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CALIFORNIUM-252 NEUTRON SOURCES FOR MEDICAL APPLICATIONS

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ABSTRACT

Californium-252 neutron sources are being prepared to investigate the value of this radionuclide in diagnosing and treating diseases. A gram of ^{252}Cf emits 2.34 x 10^{12} neutrons per second through spontaneous fission.

A source resembling a cell-loaded radium needle was developed for neutron therapy. Four micrograms of ^{252}Cf were electrodeposited on a platinum-iridium wire, 0.51 millimeter in diameter and 20 millimeters in length, and the wire was doubly encapsulated. Since therapy needles are normally implanted in the body, very conservative design criteria were established to prevent leakage of radioactive material.

A more intense source, containing 100 micrograms of ^{252}Cf was prepared for neutron radiography experiments. This source is pelletized ^{252}Cf oxide in a platinum metal matrix doubly encapsulated in stainless steel. The active source volume was approximately 6 cubic millimeters.

Methods are being developed to prepare very intense californium sources that could be used eventually for neutron radiography and for diagnosis by neutron activation analysis.

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INTRODUCTION

The possibility of using neutrons for radiotherapy was recognized soon after their discovery.(1) Recently, better understanding of the physical and biological interactions of neutrons with tissue has lent impetus to research in this field.(2)

Californium-252 sources are being developed to investigate the value of this radionuclide in diagnosing(3) and treating diseases.(4,5) The nuclide is encapsulated in needles and afterloading cells and tubes, which can be implanted in tissue, inserted into body cavities, or used as surface applicators. Californium-252 therapy sources resemble cell-loaded radium sources except that Cf_2O_3 is uniformly electrodeposited on the source rod or fixed in a platinum matrix (inside the cell) instead of being loosely mixed with an inert filler in the cell. These neutron sources can be handled in the same manner as other radiotherapy sources, and the problems of radiation protection are straightforward.(6)

More intense californium-252 sources can be prepared in a variety of geometries for use in neutron radiography and diagnosis by neutron activation analysis.(7)

CHARACTERISTICS OF CALIFORNIUM-252

Californium-252 is a trivalent actinide with an effective half-life of 2.57 years and emits 2.34×10^{12} neutrons per second per gram (4.4×10^9 neutrons per second per curie) by spontaneous fission.(8) The average neutron energy of the fission spectrum (Fig. 1) is 2.3 MeV. Gamma production rate is 1.3×10^{13} photons per second per gram, exclusive of internal conversion X-rays. Gamma dose rate is 1.4×10^2 R per hour per gram at one meter. The gamma spectrum is shown in Fig. 2. Californium-252 emits 1.9×10^{13} alpha disintegrations per second per gram (6.11 MeV per disintegration).

Heat emission due to alpha decay is 39.07 watts per gram. Pressure produced by helium from alpha decay and by fission gases in a therapy source containing 10 micrograms of ^{252}Cf (5.4 millicurie) approximates 9 psig at body temperature 37°C and 11 psig at autoclave temperature 115°C (at infinite decay).

SOURCE PREPARATION PROCEDURES

Californium sources for medical therapy are prepared by electrodeposition of $^{252}Cf(OH)_3$, and sources for radiography are prepared by coprecipitation of $^{252}Cf(OH)_3$ with $Fe(OH)_3$. Both methods require hyperpure californium. Organic degradation products of ion exchange materials, ammonium alpha hydroxy isobutyrate used to separate californium from other actinides and lanthanides, and inorganic salts from process equipment and glassware corrosion interfere seriously in the production of uniform, adherent californium sources in high yield.

Californium-252 Purification

To purify californium, the tripositive elements are scavenged by ferric hydroxide and then the actinides are extracted from 12M LiCl-0.1M HCl to 0.61M tri-isooctylamine in diethyl benzene by a laboratory-scale Tramex(9) process. Actinides are then stripped from the extractant with 8M HCl and dried in platinum ware. Organic residues are wet ashed with a mixture of concentrated HNO_3 and H_2O_2.

Californium is separated from residual salts by sorption on a column of di-2-ethylhexyl phosphoric acid (HDEHP) on a diatomaceous earth support from 0.10M HNO_3.(10) Californium is eluted from the HDEHP column with 4M HNO_3, and the solids-free product is stored in HCl-leached fused quartz to avoid silicate contamination.

This procedure has been used successfully for more than a year to recover californium from spent electrolytes and from waste solutions from ferric hydroxide coprecipitation, and to purify it of organic and inorganic impurities after ion exchange separations. Californium obtained by this method produces consistent yields in the electrodeposition process of greater than 85% on cylindrical cathodes with surface areas of 0.63 cm^2. Yields drop to 65% when cathode surface area is reduced to 0.3 cm^2.

Electrodeposition

Electrodeposition is generally considered to be one of the best techniques to produce thin, uniformly distributed films of radioelements on small, flat discs for the measurement of nuclear constants, for reactor or particle accelerator irradiation experiments, and for isotopic analysis by alpha particle or fission counting and alpha-energy measurements.(11,12) Excellent reviews and thorough studies of the electrodeposition of several individual actinides and lanthanides have been made to establish methods of producing disc sources for a variety of uses.(13,14,15)

Not many investigations have been reported, however, on the electrodeposition of californium.(16) None were found which attempted to produce thin, uniform, adherent films on cylindrical cathodes with surface areas of 0.3 to 0.6 cm^2.

At this Laboratory, californium is electrodeposited from aqueous solution in a simple cell (Fig. 3) with a specially prepared cathode. Since the cathode becomes the source, it must withstand considerable handling during the electrodeposition and still not exceed the very small dimensional tolerances required to fit inside the therapy source cell. After experimenting with various metals, an alloy of 90% platinum-10% iridium was chosen for the cathode because it is hard enough to assure a very straight source and is inert to acid corrosion and flaking. The portion of the Pt-Ir wire that serves as the cathode is sandblasted to increase the surface area and to provide a more adherent deposit.

Californium is electrodeposited by electrolytic base formation from an aqueous solution that is about 0.01M ammonium nitrate and 0.10M nitric acid. Hydrogen ions are removed from the cathode region causing precipitation of $Cf(OH)_3$.

$$\begin{array}{l} 6\,H_2O + 6\,\bar{e} \rightarrow 3\,H_2 + 6\,OH^- \\ 2\,Cf^{3+} + 6\,OH^- \rightarrow 2\,Cf(OH)_3 \\ \hline 2\,Cf^{3+} + 6\,H_2O + 6\,\bar{e} \rightarrow 2\,Cf(OH)_3 + 3\,H_2 \end{array}$$

Nitric acid is reduced by hydrogen ions at the cathode.

$$H^+ + NO_3^- + H_2O + 2\,\bar{e} \rightarrow HNO_2 + 2\,OH^-$$

$$HNO_2 + 4\,H_2O + 6\,\bar{e} \rightarrow NH_3 + 6\,OH^-$$

Although hydrogen ions are formed at the anode by the destruction of water

$$2\,H_2O \rightarrow 4\,H^+ + O_2 + 4\,\bar{e}$$

the net hydrogen depletion as the electrolysis proceeds gradually reduces the acidity of the electrolyte from pH greater than 1 to pH 5-6. About one minute prior to discontinuing the current, the electrolyte is made basic (pH 8-9) so that the $Cf(OH)_3$ deposit is not immediately dissolved from the cathode when the current stops.

Procedural Notes and Discussion

General (Fig. 3). Medical sources containing up to 5 micrograms of ^{252}Cf are prepared in exhausted enclosures (glove boxes) to contain radioactive contamination. The electrolysis cells are enclosed in 8-inch cubes of an acrylic plastic covered with 1/32-inch-thick cadmium. These enclosures, as well as portable cadmium-covered plastic blocks, are used inside the glove box as neutron shields. Sources containing more than 5 micrograms of ^{252}Cf must be prepared in a shielded facility equipped for remote manipulation.

Electrodes. The helical anode is 16 B & S gage pure platinum wire. The coil is constructed so that the anode-to-cathode distance is 5 millimeters across the entire length of the cathode (source) area. A variable speed electric stirrer, capable of turning from a few revolutions per minute to about 60 rpm turns the anode during deposition. A typical cathode is made of 90% Pt-10% Ir alloy, is 0.51 millimeter in diameter (24 Brown and Sharpe gage wire), 80 millimeters in length, and has a cathode surface (source area) sandblasted to a length of 20 millimeters. However, a 90% Pt-10% Ir wire of any desired B & S gage can be used. The anode and cathode are degreased in acetone or trichloroethylene vapors, rinsed in 1M HNO_3, and flamed to red heat (800°C) prior to use.

After the cathode is inserted through the cell base "Teflon"* liner and positioned so that the desired source area is exposed to electrolyte, the assembled cell is filled with distilled water and tested for leaks around the cathode seal and cell threads.

Electrolyte. Although californium can be electrodeposited from a chloride medium with good yields, a dilute nitrate system, about 0.01M NH_4NO_3 and 0.10M HNO_3, produced more consistent, higher yields and more uniform sources. Addition of uranium carrier decreased deposition time and increased yields.(12) Molecular plating(17) from an organic electrolyte (isopropanol) at voltages up to 200 V did not offer any advantages over deposition from aqueous media. Films formed by molecular plating from an organic electrolyte were generally neither adherent nor uniform.

Time and Current Density. The electrolyte is strongly acid (about pH 1) at the start of deposition. Over a period of 2-1/2 to 3 hours at current densities of 280 ma per square centimeter (5-8 V DC), the electrolyte gradually approaches neutrality (pH 5-6).

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* "Teflon" - Trademark of Du Pont.

Current density and time vary with the amount of californium to be deposited. The following conditions consistently produce the most uniform, adherent sources in a reasonable period of time.

Cathode Surface Area, cm^2	Current Density, ma/cm^2	Time, hr:min
0.3	370	1:00
	465	2:00
0.6	280	1:00
	560	1:30

It is difficult to electrodeposit more than 5 micrograms of ^{252}Cf on a cylindrical cathode of 0.6 cm^2 during a single deposition.

If it is necessary to make a more intense source, the cathode from the initial deposition is flamed (to convert the hydroxide to the oxide), and is used again as the cathode in a second deposition with freshly prepared electrolyte and hyperpure $^{252}Cf(NO_3)_3$.

After the deposition is complete, the electrolyte is made alkaline (pH 8-9) by the addition of concentrated NH_4OH and the current is discontinued. Spent electrolyte is pipetted to a recovery flask and the cell carefully disassembled.

Encapsulation. The californium-bearing cathode is heated slowly and carefully to red heat inside the glove box using the oxygen-butane flame of a microtorch. This converts the $Cf(OH)_3$ to Cf_2O_3 and reduces the platinum black to platinum metal. The deposit is also more adherent perhaps because the heat annealed the sandblasted surface of the Pt-Ir cathode.

Wet and dry smear tests were conducted with cathodes containing nanogram quantities of ^{252}Cf. Acetone and saline solution (0.025% by weight) were used in the wet tests. About 5% of the $^{252}Cf_2O_3$ was removed by the initial smear - wet or dry - but after that, less than 0.01% was transferable.

The californium-bearing end of the cathode is inserted into a Pt-Ir cell. After the inert section of the cathode wire is cut off, a Pt-Ir plug is inserted and sealed in place with silver braze alloy (flow point 855°C). Integrity of the source cell is verified by the procedure discussed in "Safety Tests". The sealed cell is then enclosed either in a therapy needle (Fig. 4), an afterloading cell (Fig. 5), or afterloading tube (Fig. 6).

Coprecipitation

Experimental point sources of californium-252 for neutron radiography are prepared by coprecipitation of $^{252}Cf(OH)_3$ with $Fe(OH)_3$.

Hyperpure ^{252}Cf is carried on a minimum of 0.5 milligram of Fe^{3+} as a hydroxide precipitate. After centrifugation and removal of the supernate, the precipitate is transferred to a cone (Fig. 7) of 1.5-mil-thick platinum which has been hammer-welded to a thin (24 B & S gage) Pt-Ir wire to facilitate remote handling in a shielded facility. After dehydrating the precipitate under an infrared lamp, and heating to 200°C in a furnace, the cone is folded into a thin tube and placed in a pelletizer (Fig. 7) by drawing the Pt-Ir wire to which the folded cone is attached through the pelletizer base. The source pellet is then formed by inserting the ram and applying pressure. The source is removed from the pelletizer and slowly heated to red heat (800°C) in a furnace to convert remaining hydrous oxide to Fe_2O_3 and Cf_2O_3. At approximately 75% compaction, the active volume of the source is about six cubic millimeters after pelletizing and heating.

The source pellet, with its wire still attached, is inserted into a primary capsule (Fig. 8) which is sealed with silver braze alloy (flow point 855°C). This primary capsule is enclosed in an outer capsule (Fig. 9) which is sealed by welding. Outer capsules are designed to user specifications.

Calibration

A manganese-bath method is used to determine the rate of neutron emission from the sources. The source is placed at the center of a cylindrical plastic tank (42 inches in diameter and 39 inches tall) that contains 900 liters of 0.45M $MnSO_4$. After a timed irradiation to activate manganese atoms to ^{56}Mn, the tank is stirred thoroughly and a sample of the $MnSO_4$ solution is assayed with a counter calibrated for ^{56}Mn. Corrections are made for the leakage of neutrons from the tank and the capture of neutrons by hydrogen, oxygen, and sulfur atoms in the solution. Calibration of this system was validated with a californium-252 source previously calibrated at the National Bureau of Standards. The precision of the determination of the neutron emission rate is estimated to be approximately 5%.

SAFETY TESTS

Californium-252 sources are designed and tested during and after construction to eliminate the possibility of leakage and to minimize the consequences of capsule rupture.

Therapy Sources

Leak, dimensional, corrosion, mechanical, and metallographic tests are used to verify the soundness of encapsulation techniques.

In addition, a similar group of tests showed that therapy source components were not affected by exposure to fast and thermalized neutrons from nuclear reactors equivalent to a 5-year exposure from 10 micrograms of ^{252}Cf.

Encapsulated dummy source cells and sheaths were pressurized separately in 30-psi helium for 30 minutes. Leak tests on individual pieces in a helium leak detector whose lower detection limit is 2.4×10^{-9} cubic centimeters of helium per second indicated no leaks. (Leak tests are performed in this manner on each source when it is made.)

Seal integrity of a therapy source made in July, 1966 was tested in May, 1968 by smear and helium leak tests. Neither smearable contamination nor measurable helium leaks were detected.

The sealed source cells and sheaths were weighed to the nearest 0.1 mg. Length and diameter were measured to the nearest one-thousandth of an inch. There were no measurable changes in weight or dimensions as a result of exposure to fast and thermalized neutrons.

Each type of source component was exposed to water and to cold and warm saline solution (0.025% sodium chloride by weight) for periods up to five months to test for leakage, changes in weight, or evidence of corrosion. Specimens were thoroughly examined at 50X magnification for evidence of deterioration of seals or corrosion but none was observed.

Sets of sealed dummy sources were divided into two groups. One group was irradiated and examined further by leak, mechanical, and metallographic tests. The other group was not irradiated and was examined by the same mechanical and metallographic tests.

The first group was exposed to 8.8×10^{13} nvt (neutron fluence) at the Health Physics Research Reactor, an unshielded assembly at Oak Ridge National Laboratory, to simulate the fast neutron exposure from the ^{252}Cf inside the cell of a therapy source. The same group of sources was exposed again to a thermalized neutron spectrum in a reactor at the Savannah River Laboratory, since the sources will be in a moderating medium most of the time, i.e., in tissue or a storage shield which will thermalize the neutrons produced by spontaneous fission of the ^{252}Cf. The neutron fluence in the second irradiation was 9.72×10^{14} nvt.

The irradiated group was again pressurized and leak tested. No leaks were found.

The mechanical property tests most commonly used to evaluate the quality of ductile metal products include hardness tests, bending tests, and visual metallography.(18) Irradiated and nonirradiated sources were examined with these three tests.

Diamond-point hardness, elastic deformation (yield strength), and plastic deformation (ultimate strength) tests showed no detectable changes after the needles were irradiated.

Specimens were prepared for visual metallography by mounting, cutting, grinding, polishing, and etching procedures. They were then photographed and examined in the metallograph. Sections of the sheath cap, wall, and point, and cell wall and cell cap silver braze alloy joint were examined. There were no differences between irradiated and nonirradiated specimens.

Radiography Source

Pressure created in the inner capsule by helium from alpha decay and fission gas buildup in a 100-μg ^{252}Cf source will be 4.8 atm (70.7 psig) at 30°C (at infinite decay).

Stress calculations assumed the capsules were single, hollow, thick-walled cylinders with well-bonded seals. Metallurgical examination of test specimens verified these assumptions. Maximum calculated safe pressures were 8525 psi for the inner capsule and 7653 psi for the outer capsule, both limited by allowable circumferential stress.

A dummy source was dropped onto a steel plate from heights of 30 and 66 feet. No significant damage occurred to the dummy source as a result of these tests.

FUTURE PLANS

Methods are being developed to prepare very intense californium sources that could be used eventually for neutron radiography and for diagnosis by neutron activation analysis.

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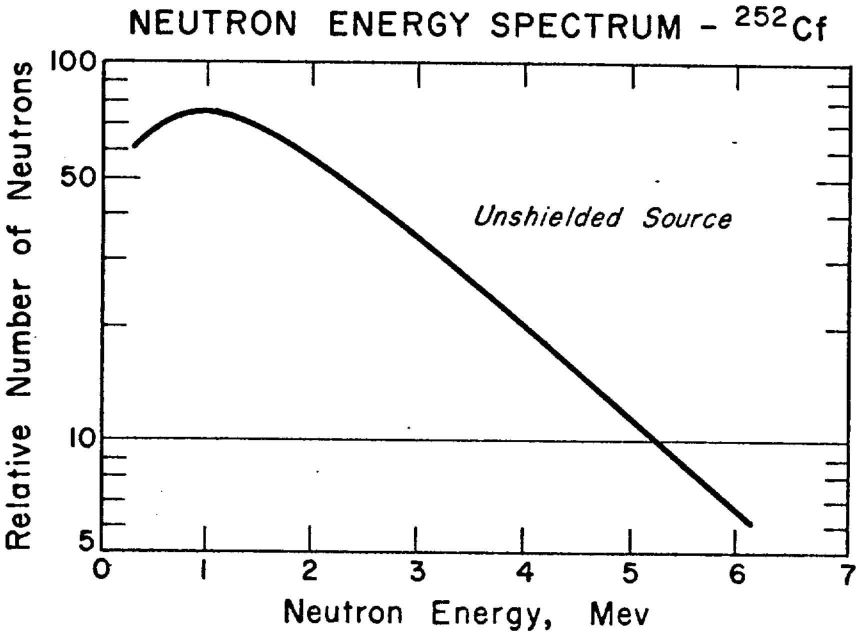


FIG. 1 NEUTRON ENERGY SPECTRUM OF ^{252}Cf

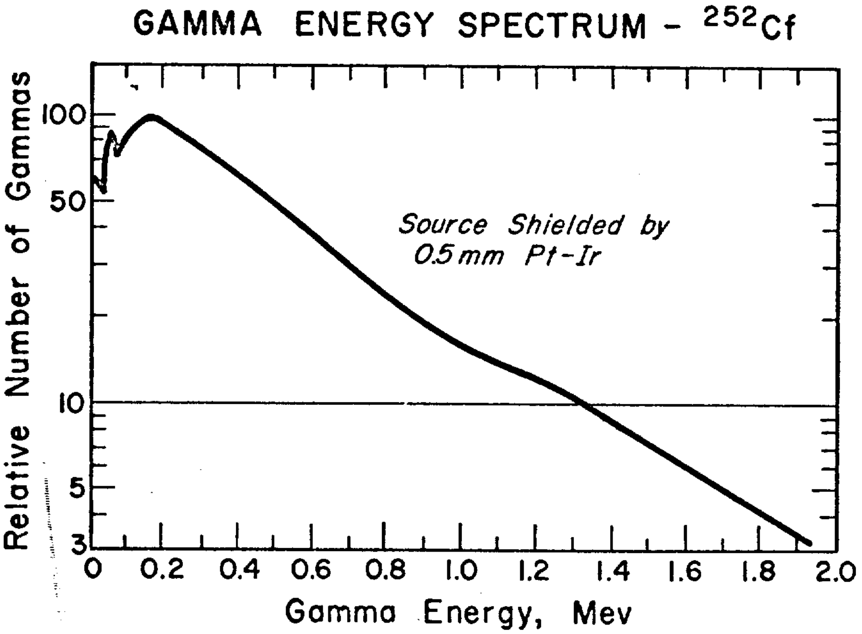


FIG. 2 GAMMA ENERGY SPECTRUM OF ^{252}Cf

Figure 3

CALIFORNIUM ELECTRODEPOSITION APPARATUS

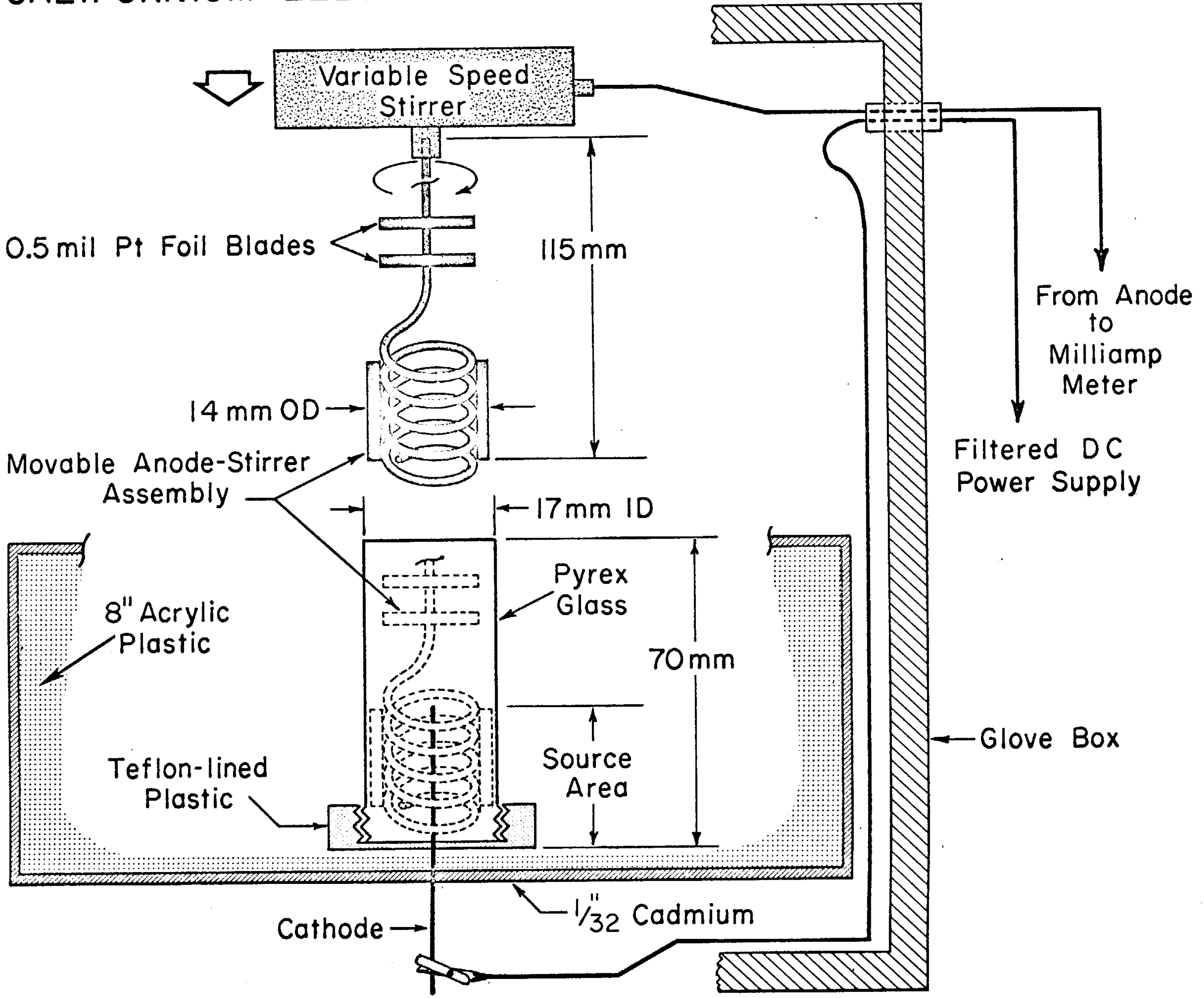
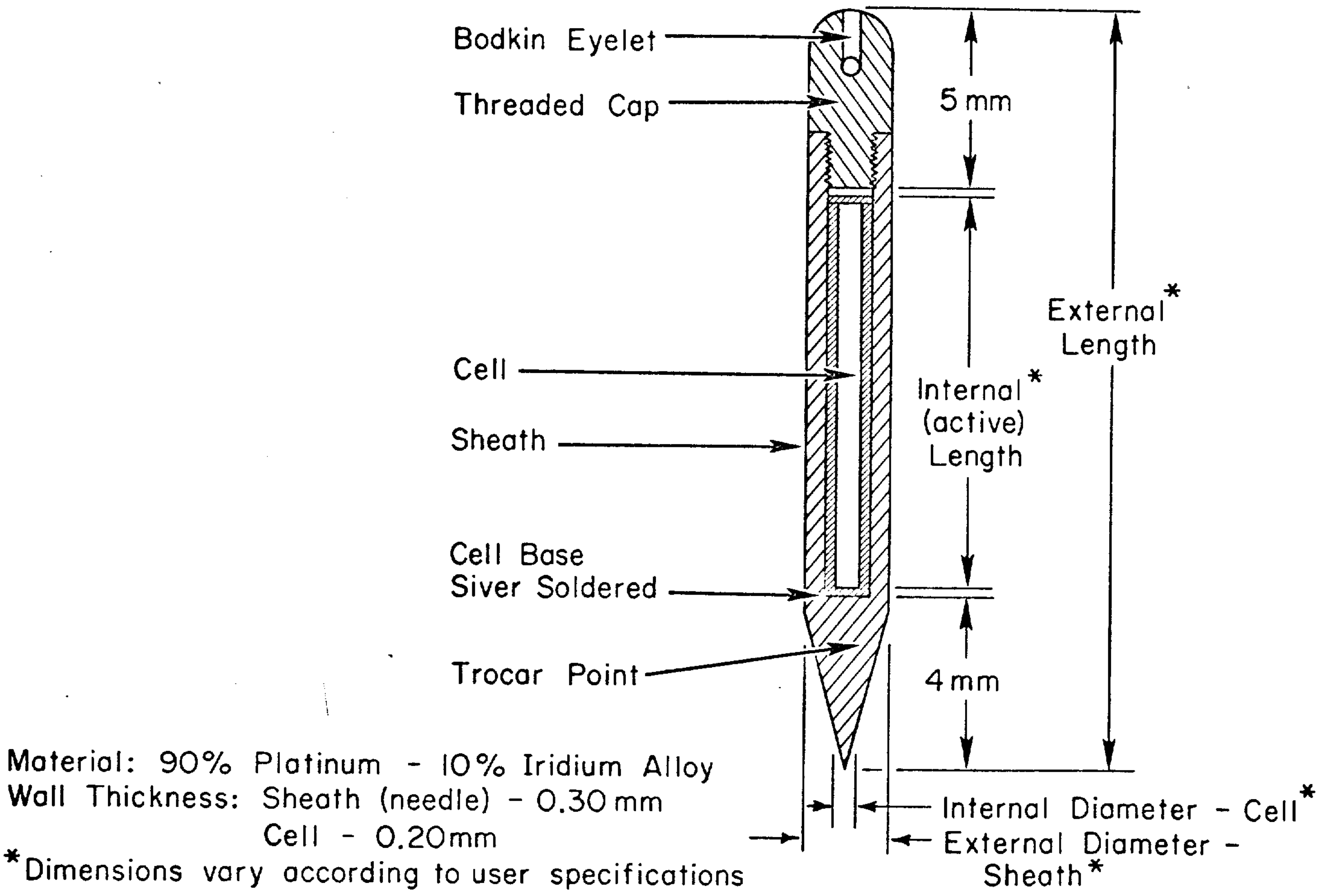


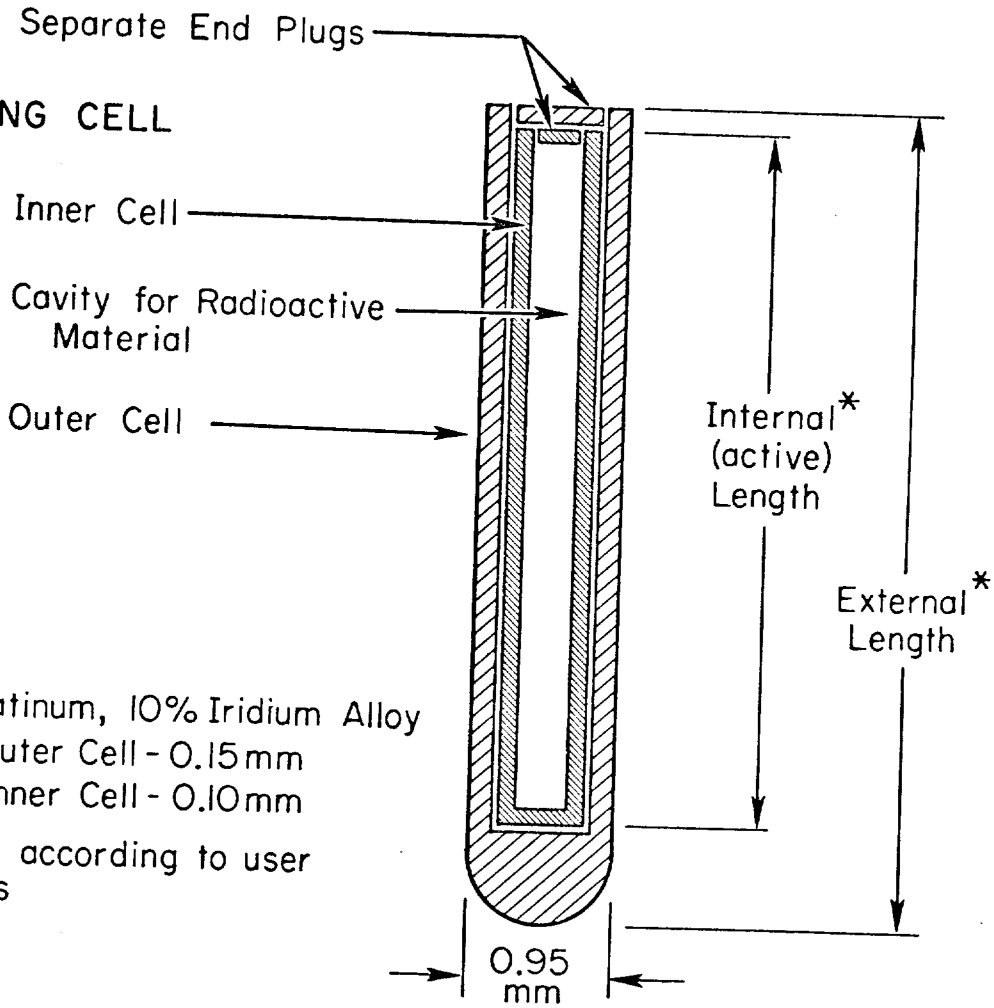
Figure 4

CELL-LOADED NEEDLE



Material: 90% Platinum - 10% Iridium Alloy
Wall Thickness: Sheath (needle) - 0.30 mm
Cell - 0.20mm
*Dimensions vary according to user specifications

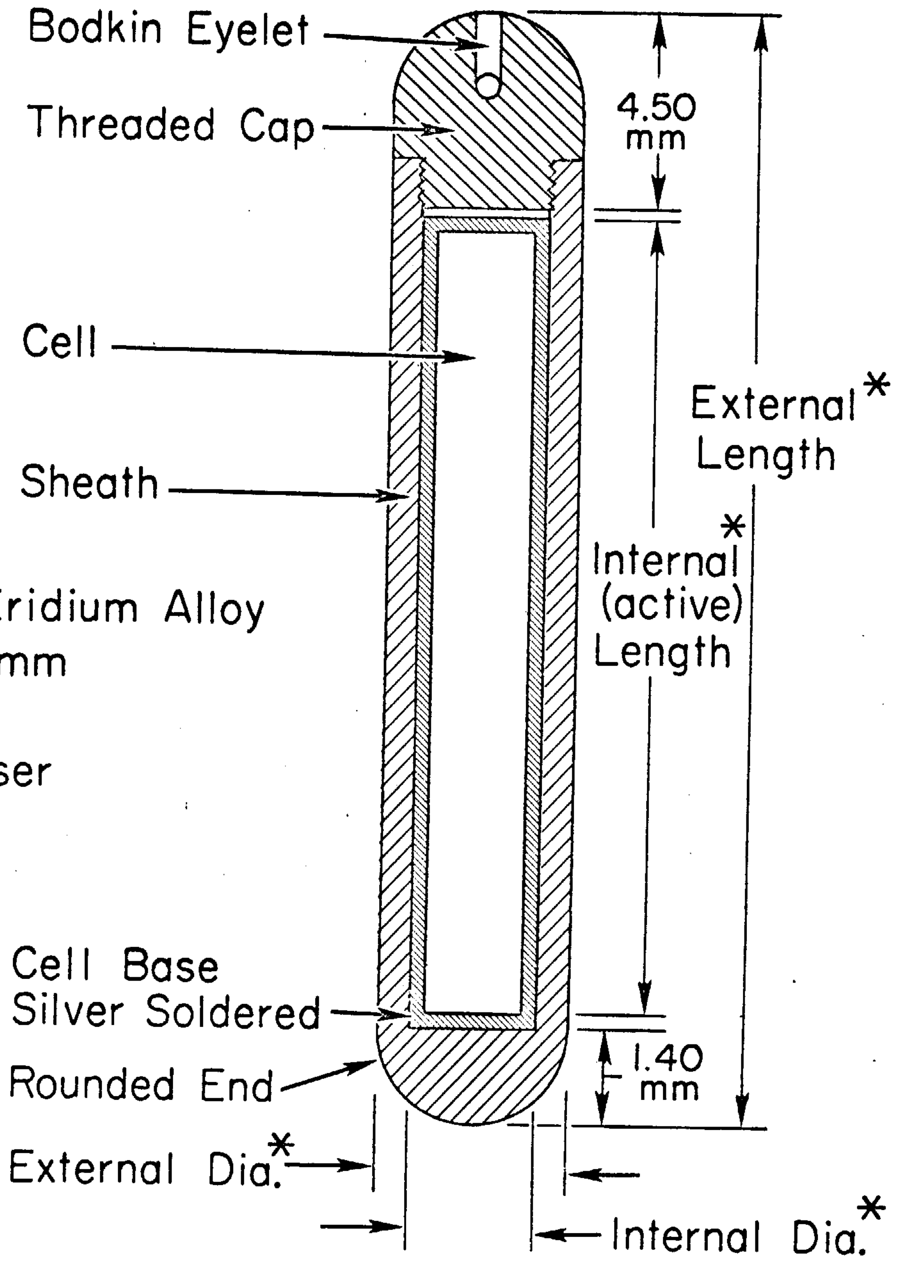
Figure 5 AFTERLOADING CELL



Material: 90% Platinum, 10% Iridium Alloy
Wall Thickness: Outer Cell - 0.15 mm
Inner Cell - 0.10 mm

*Dimensions vary according to user specifications

Figure 6 AFTERLOADING TUBE



Material: 90% Platinum, 10% Iridium Alloy

Wall Thickness: Sheath - 0.50 mm
Cell - 0.20 mm

*Dimensions vary according to user specifications

PELLETIZER

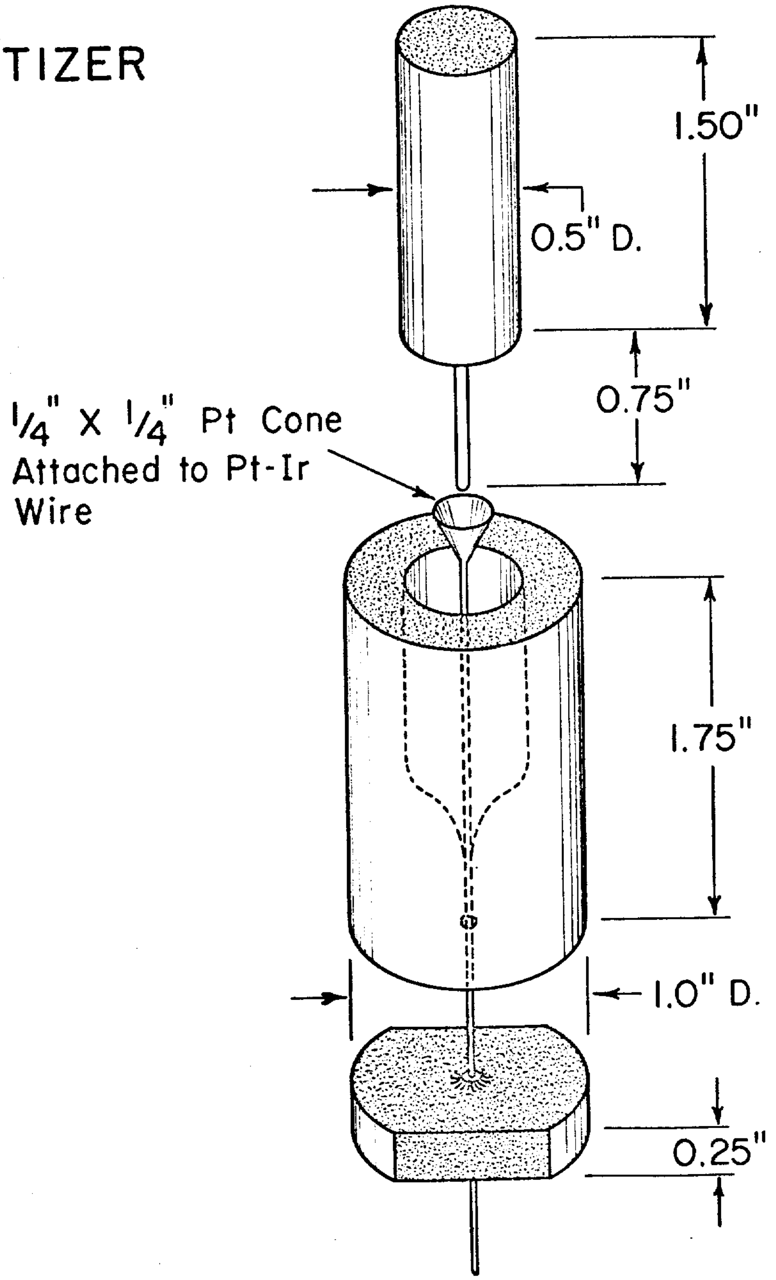


FIG. 7 PELLETIZER

^{252}Cf SOURCE INNER CAPSULE

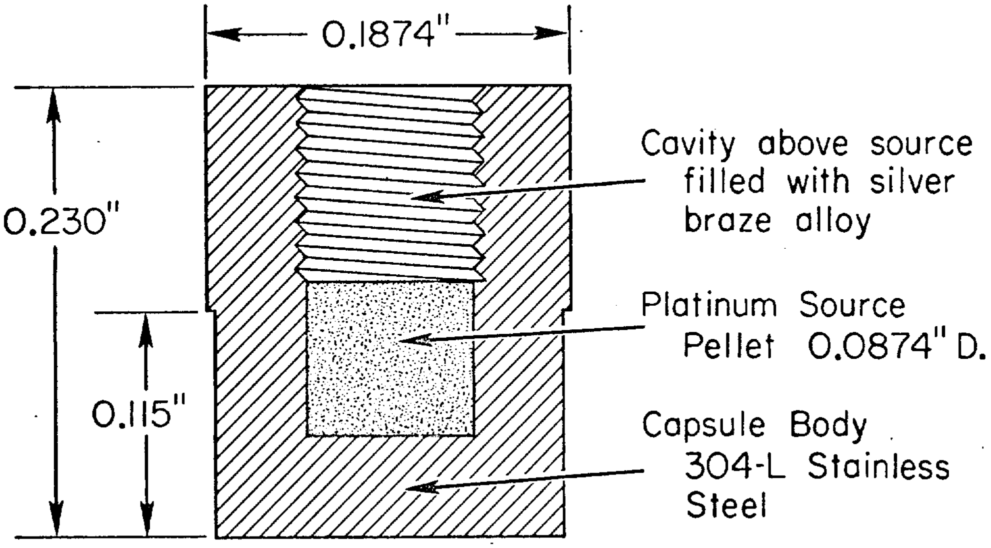


FIG. 8 ^{252}Cf SOURCE INNER CAPSULE

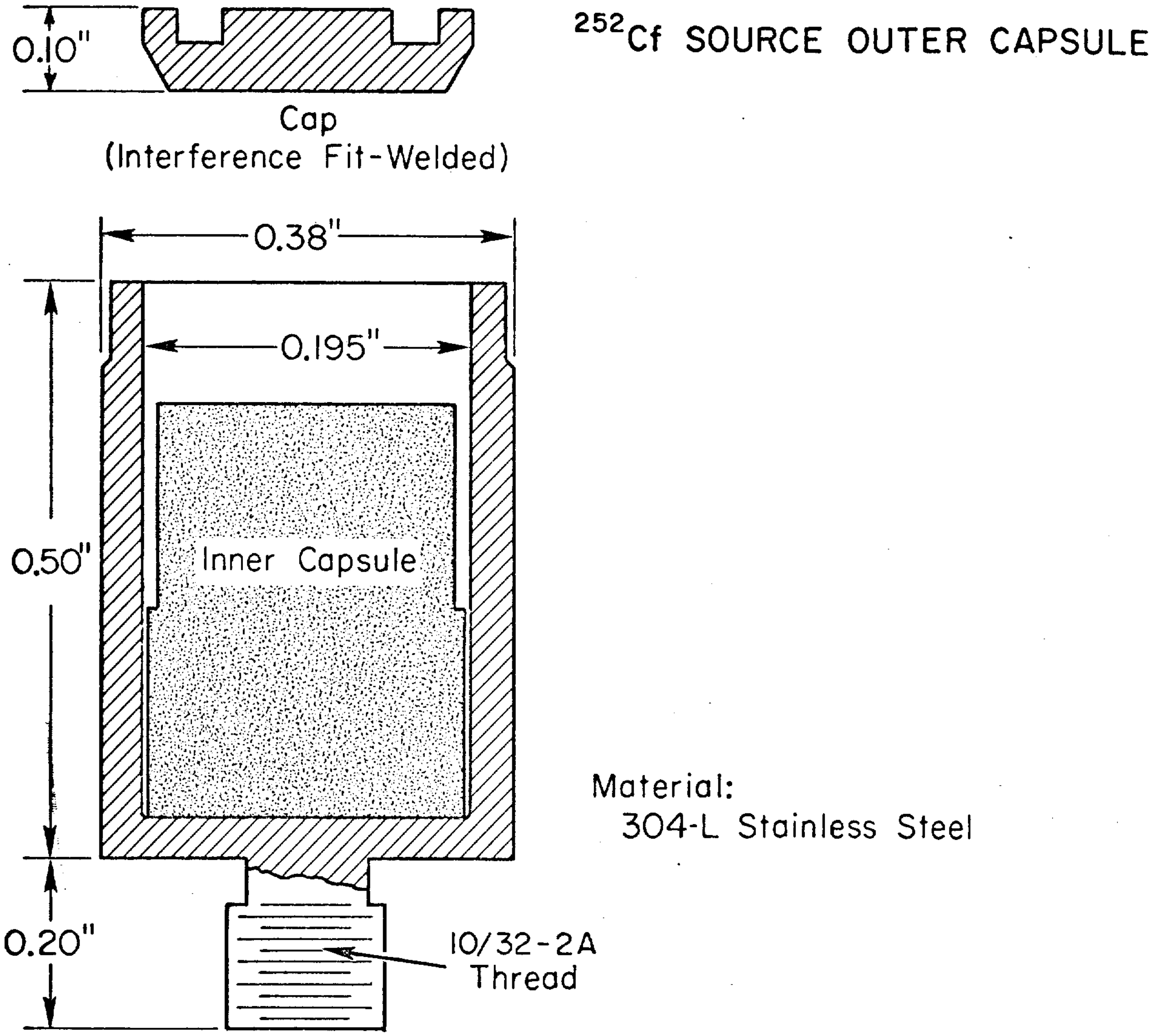


FIG. 9 ^{252}Cf SOURCE OUTER CAPSULE