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March 1986

Radioisotope Thermoelectric Generators Emplaced in the Deep Ocean

Recover or Dispose In Situ?

H. V. Weiss
J. F. Vogt

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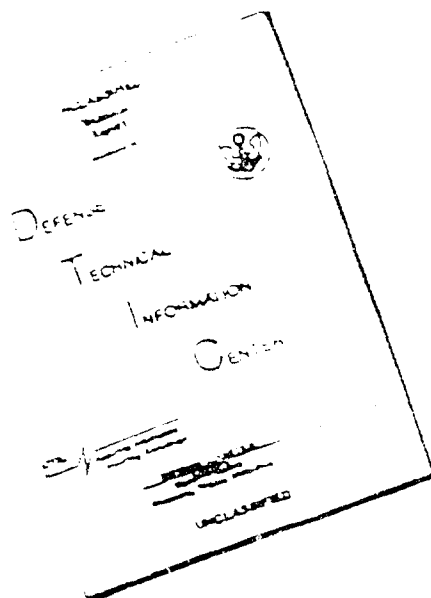
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INTRODUCTION

In 1970 and 1977 the Navy emplaced a total of six radioisotope thermoelectric generators (RTGs) in the deep ocean. These devices were installed to provide power for acoustical transponders that served as geodetic benchmarks.

The fuel capsules of the RTGs are designed to retain their integrity for at least 300 years during exposure to seawater at 10,000 psi. They are fueled with radioactive strontium-90, whose half-life (27.7 years) is such that only a small fraction (5.5×10^{-4}) of the initial radioactivity remains at the end of this 300-year interval.

The purpose of this report is to consider the risk to man of in situ disposal of the RTGs versus recovery for ultimate disposal at a terrestrial site. A description of the RTGs, their emplacement sites, and their ability to contain the strontium-90 while exposed to a deep-ocean environment are provided. For in situ disposal, the strontium-90 concentration in seawater is calculated and the resulting dose to man estimated. Summaries of earlier safety analyses which considered in situ disposal are also included. For disposal at a terrestrial site, recovery of the RTGs from the deep oceans must utilize the submersible vehicle TRIESTE. Descriptions of this vehicle, a typical mission, and an attempted RTG recovery are included. Also, a general appraisal of the risks involved in the recovery and terrestrial disposal of the RTGs is provided. Finally a conclusion is drawn regarding the merits of the disposal alternatives.

RTG DESCRIPTIONS

Each RTG consists of a strontium-90 titanate heat source, thermoelectric generator, thermal insulation, biological shielding, and a pressure vessel/housing. Thermal energy generated within the heat source as a result of the radioactive decay process is converted into low-voltage dc electrical power within the thermoelectric generator. Thermal insulation is included to channel the heat flow through the thermoelectric generator and minimize parasitic heat losses. Although the beta particle emissions from strontium-90 and its

daughter, yttrium-90, are absorbed within the fuel and fuel capsule, bremsstrahlung radiation is produced in the process, and this circumstance requires shielding. These components are enclosed in a pressure vessel/housing which has the proven ability to withstand at least 20,000 ft of ocean depth.

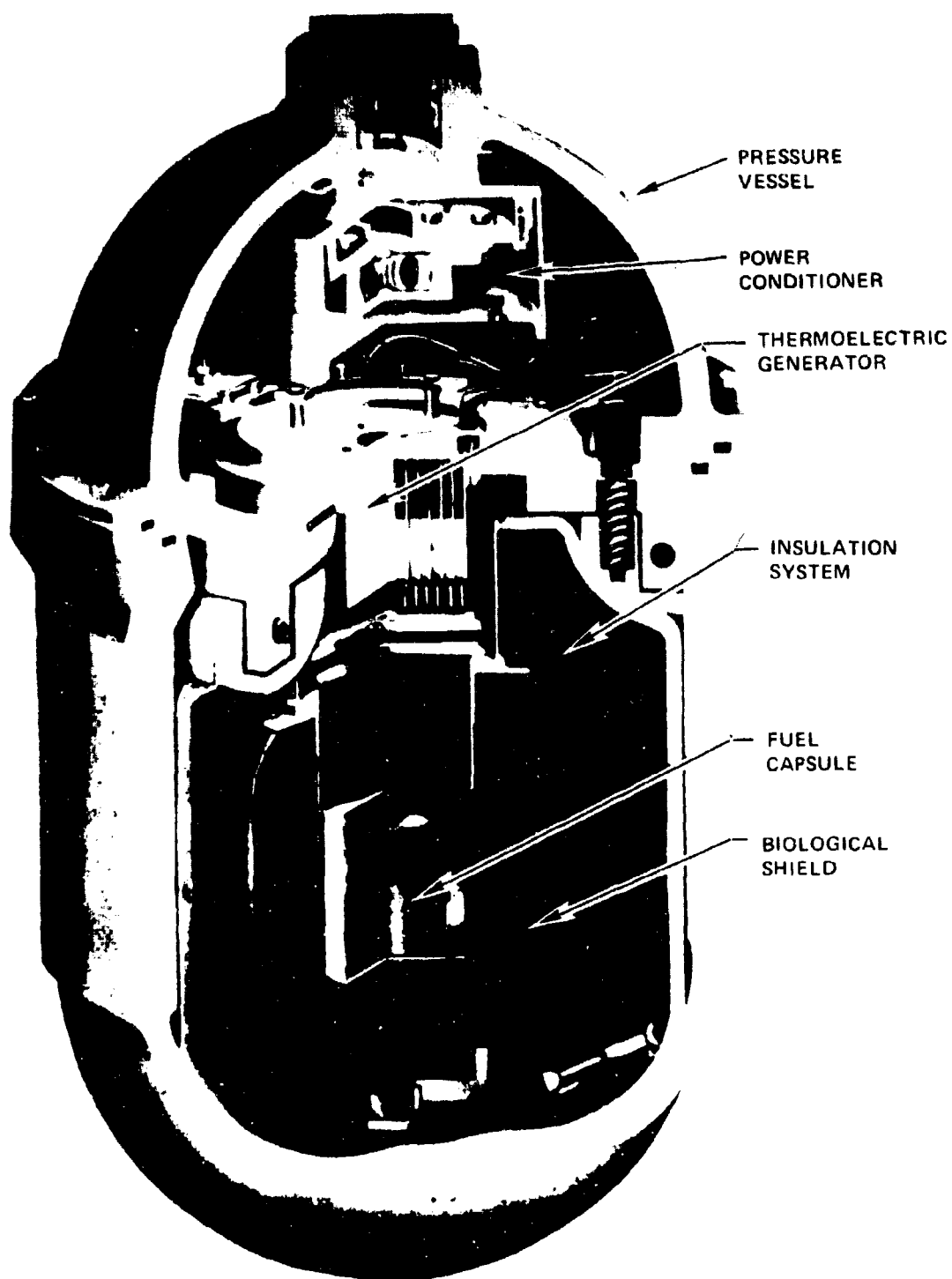
Three different models of RTGs, designated as SNAP-21, URIPS-P1, and RG-1, produced by the 3M Company, Aerojet-General Corporation, and General Atomic Company, respectively, were deployed. A diagram of each appears in Fig 1, 2, and 3. Each conforms in principle to the description given above and varies only in detail (Ref 1, 2, 3).

The fuel consists of hot-pressed strontium-90 titanate. The hot-pressed pellet is sealed in a stainless steel liner. Final encapsulation is within a nickel alloy, Hastelloy C or Hastelloy C-276, both highly resistant to the corrosive action of seawater. All of the capsules conform to the requirements listed in the International Atomic Energy Agency Safety Series No. 33, "Guide to the Safe Design, Construction, and Use of Radioisotope Power Generators for Certain Land and Sea Applications." Fuel, fuel liner, and fuel capsule characteristics are shown in Table 1.

IN SITU DISPOSAL

SITE DESCRIPTIONS

The location, emplacement date, depth, radioactivity level at the time of emplacement, and model of each RTG as well as the name of each manufacturer are listed in Table 2. The three URIPS-P1 RTGs reside at depths of 16,119-16,169 ft in the Pacific Ocean. The others are situated in the North Atlantic, a SNAP-21 at a depth of 14,400 ft, and two of the RG-1 models at depths of 10,344 and 10,860 ft.



SNAP-21 10 WATT SYSTEM

Figure 1. SNAP-21.

1 WATT(e) URIPS-P1, LEAD SHIELD

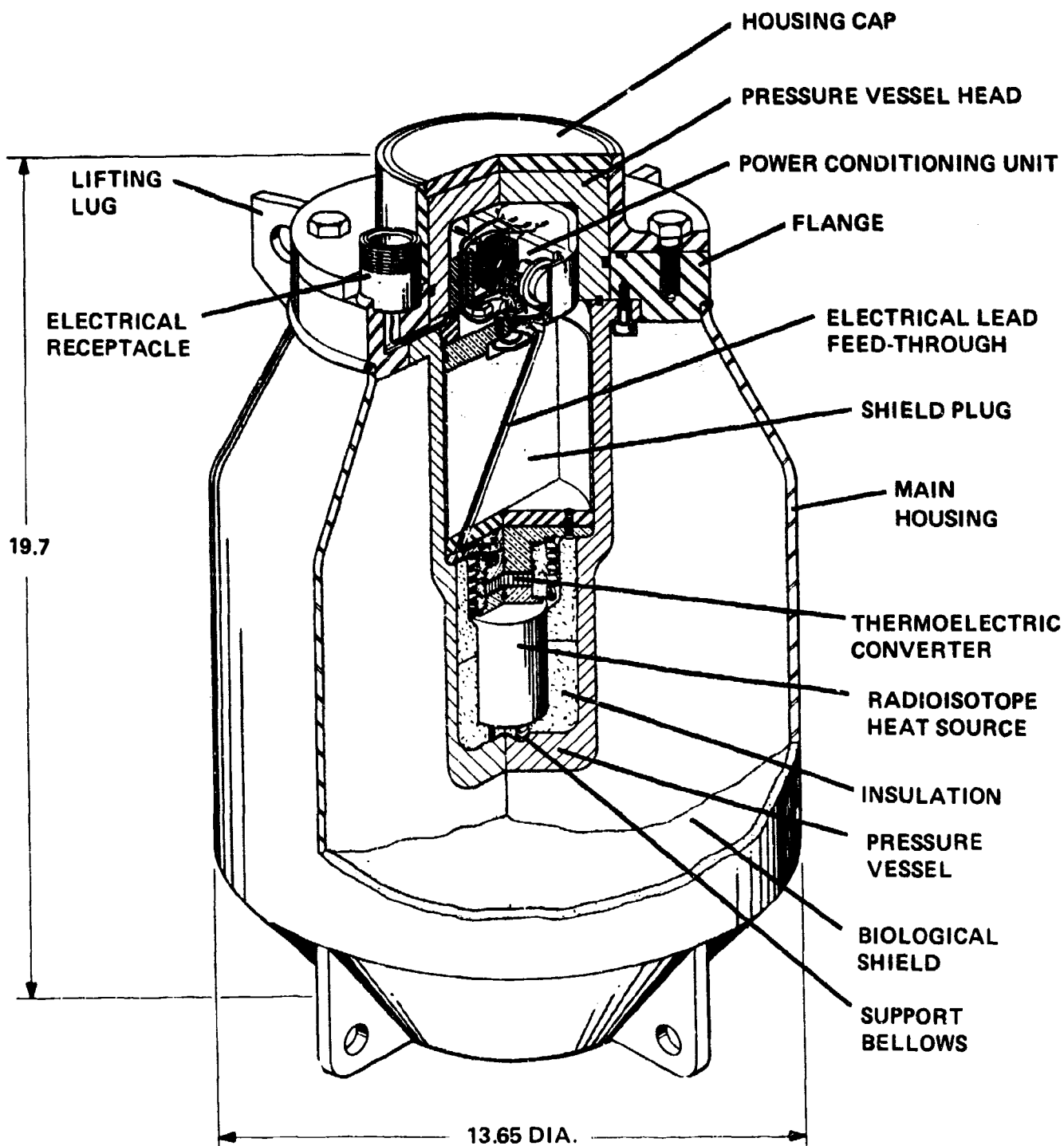
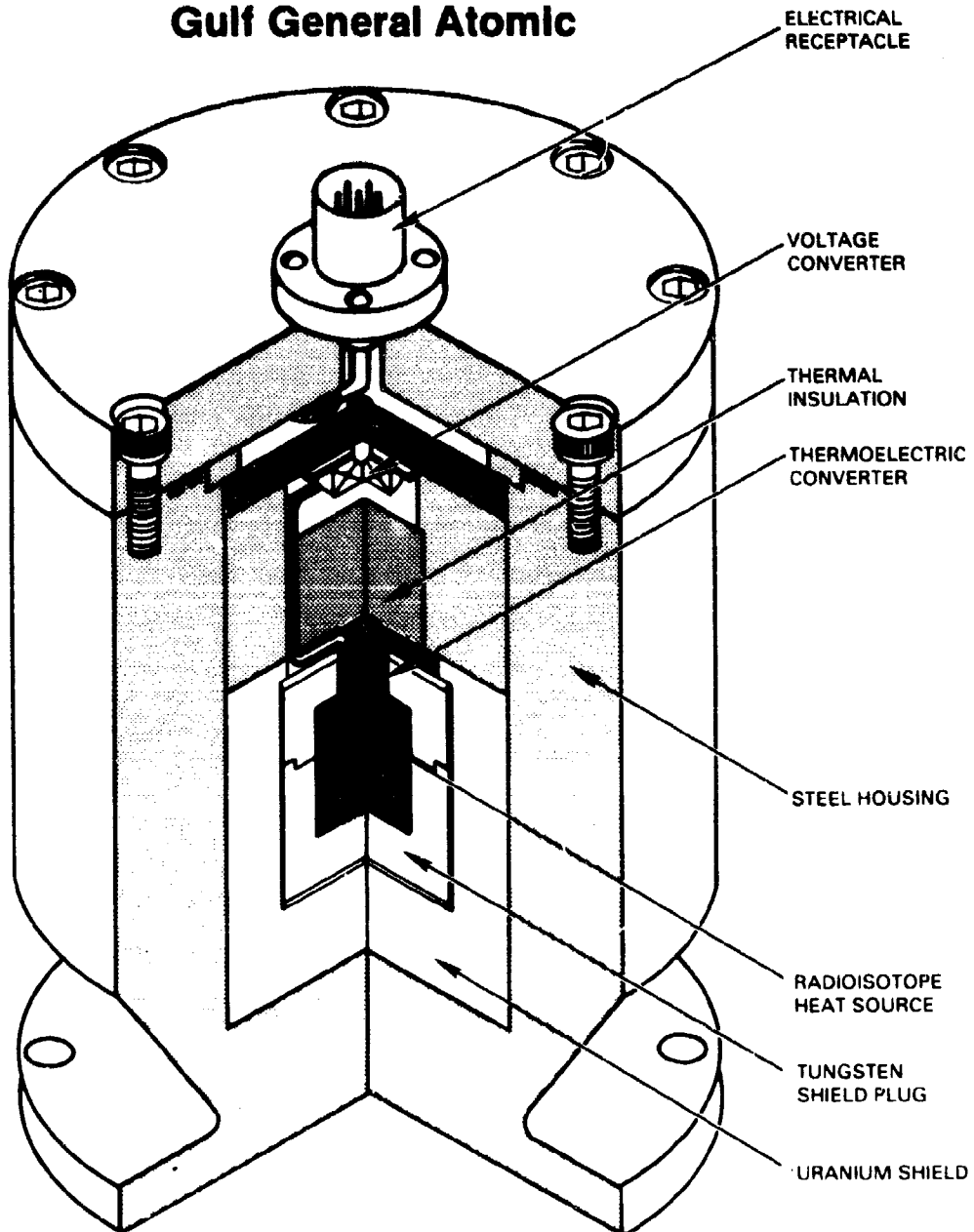


Figure 2 URIPS-P1



Gulf General Atomic



1-WATT RADIOISOTOPE GENERATOR

Figure 3. RG 1.

Table 1. URIPS-P1, RG-1, and SNAP-21 RTG fuel, fuel liner, and fuel capsule characteristics (nominal values).

	URIPS-P1	RG-1	SNAP-21
Specific Activity (Ci ⁹⁰ Sr/gm SrTiO ₃)	34	33	33
Density SrTiO ₃ (gm cm ⁻³)	5.1	5.03	3.7
Fuel Dimensions (in.)			
Length	1.810	1.52	2.73
Diameter	1.560	1.70	2.71
Fuel Liner			
Composition	Type 304 L SS	Type 304 L SS	Type 304 L SS
Thickness (in.)			
Wall	0.040	0.038	0.020
Top	0.140	0.140	0.075
Bottom	0.040	0.040	0.075
Diameter* (in.)	1.670	1.776	2.767
Length* (in.)	2.14 (overall)	1.780	2.909
Fuel Capsule			
Composition	Hastelloy C	Hastelloy C	Hastelloy C-276
Thickness (in.)			
Wall	0.200	0.250	0.200
Top	0.260	0.350	0.200
Bottom	0.280	0.350	0.200
Diameter* (in.)	2.090	2.290	3.197
Length* (in.)	2.700	2.530	3.339
Weld Penetration (in.)	0.130-0.150	0.080 (min) 0.100 (typical)	0.205

*Outside

Table 2. Inventory of Navy radioisotope thermoelectric generators emplaced in the oceans.

LOCATION	DATE OF EMPLACEMENT	APPROX. DEPTH (ft)	ACTIVITY (Ci) WHEN EMPLACED	MANUFACTURER & RTG MODEL	US NAVY RTG NO.
Atlantic Ocean	21 Nov 1970	14,400	28980	3M SNAP-21	S10P2
	27 Feb 1977	10,860	7086	Gen. Atomic RG-1	37
	1 Mar 1977	10,344	6781	Gen. Atomic RG-1	38
Pacific Ocean	4 Oct 1970	16,120	7949	Aerojet Gen. Nucl. URIPS-P1	15
	5 Oct 1970	16,119	7949	Aerojet Gen. Nucl. URIPS-P1	16
	2 Oct 1970	16,169	7949	Aerojet Gen. Nucl. URIPS-P1	18

IMPACT OF STRUCTURAL COMPONENTS

The major components of the RTGs consist of metals such as lead, tungsten, a molybdenum/uranium alloy, and copper. The total of the aggregates for the heaviest of the RTGs (SNAP-21) is only 800 lb. The oceans contain from 10^{11} to 10^{13} lb of these elements. Thus the small absolute quantities of the elements involved coupled with their recognized inherent insolubility in seawater strongly indicates that no adverse environmental effect can be anticipated from their disposal in the oceans.

RADIOLOGICAL IMPACT

The outer hulls of the RTGs are designed to maintain system integrity for 50-150 years, depending on RTG model. Furthermore, based upon a corrosion rate of 10^{-4} in./year, which was determined after a 10-year ocean test (Ref 4), the fuel capsules can sustain immersion at 10,000 psi for at least 300 years without deformation. Nonetheless, a number of risk analyses have been performed that assume the worst situation and do not take advantage of these barriers, but rather consider rupture of the capsule and exposure of the strontium-90 titanate to the marine waters at the time of emplacement.

In 1964 a safety analysis (Ref 5) conducted by the Irradiated Fuels Branch, Division of Materials Licensing, U.S. Atomic Energy Commission, of a SNAP 7E RTG with a heat source containing 3.1×10^4 Ci of strontium-90 titanate concluded that "using available strontium titanate solubility data and diffusion data for radioactive material in great depths of seawater, we have made calculations which show that a man could live and feed indefinitely in the environment which would exist at a distance of 1 meter from the SNAP 7E without attaining his maximum permissible body burden of 2 microcuries--we conclude that even if the SNAP 7E were not recovered and did release its strontium-90 titanate for dissolution it would not endanger the health and safety of the public."

Another analysis (Ref 6) considered a rupture of the SNAP-21 fuel capsule. In this case the initial strontium-90 titanate inventory was exposed to

seawater. For the purpose of this analysis, the solubility of strontium titanate was taken as $1 \text{ mg cm}^{-2} \text{ day}^{-1}$, although previous experimental work had shown that this compound dissolves initially at a rate of 0.5 and $0.7 \text{ mg cm}^{-2} \text{ day}^{-1}$ in the absence or presence of sediment and that the rate diminishes to 0.09 and $0.16 \text{ mg cm}^{-2} \text{ day}^{-1}$ at the end of 180 days (Ref 7). With this rate, diffusion into the ocean environment was calculated by Mikhail (Ref 8) using the Carter-Okubo model and assuming a continuously releasing source. Expressed in terms of iso-contours, a maximum permissible concentration (MPC) was contained within a volume of $3.57 \times 10^2 \text{ m}^3$. To convey the biological significance of the contaminated patch, a comparison was drawn between the volume of contaminated seawater and the volume of seawater required to support production of an annual supply of seafood for an individual receiving his entire protein supply from seafood. For this analysis it was assumed that the release occurred in California coastal waters (average depth of 30 m), where a kilogram of seafood is produced in 10^4 m^3 . The protein requirement for an individual is satisfied upon ingesting 75 kg year^{-1} , which is the amount contained in 150 kg of raw seafood. This quantity of seafood demands a volume of $1.5 \times 10^6 \text{ m}^3$ for its support. Therefore the water contaminated at an MPC level or greater constitutes only 3×10^{-4} of the volume required to produce the annual protein supply for a single individual. This example indicates the trivial nature of the problem even if rupture of the fuel capsule is considered to occur at the time of emplacement.

In the present evaluation another approach was undertaken to analyze the risk to man. Two cases were considered. In the first, it was assumed that fuel was exposed to seawater at the time of RTG emplacement. In the second case, it was assumed that the RTG would contain the fuel for at least 300 years. The analysis is based upon methodology proposed by the U.S. Nuclear Regulatory Commission (NRC) for the estimation of doses to man from discharges of radioactive material to the hydrosphere (Ref 9).

In this method the concentration of a radionuclide in aquatic foods is assumed to be directly related to the concentration of the nuclide in seawater. To estimate this concentration, the results of Shepherd's studies on the dispersion of radioactive materials in a closed and finite ocean were

applied. Shepherd developed a model to estimate equilibrium concentrations of radionuclides in seawater arising from a disposal site located on the bottom of the deep ocean (Ref 10). This model was later used as the basis for the London Dumping Convention. Shepherd suggests that safety assessments of deep sea disposals should be based on the long-term average concentration reached in a well-mixed ocean. This approach presumes that the initial release rate is maintained indefinitely, makes no allowances for mixing time, and assumes that the only removal process is radioactive decay. Thus, the methodology is deemed extremely conservative. Shepherd shows that the "well-mixed" average concentration is greater than the equilibrium concentration in biologically productive coastal waters.

To calculate the well-mixed average concentration in seawater, a measure of the quantity of strontium-90 that dissolves from each heat source per unit of time is required. This quantity was computed from the information available on the dimensions of each fuel pellet (Table 2) and a solubility rate, taken as $1 \text{ mg cm}^{-2} \text{ day}^{-1}$. These values together with the specific surface concentration in the ocean (Ci m^{-3} per unit release in Ci s^{-1}) provided by Shepherd for a nuclide with the half-life of strontium-90 afforded computation of the strontium-90 well-mixed average concentration. In addition, a safety factor of ten was imposed upon the well-mixed average concentration to allow for the improbable event of a continuing rapid upwelling of the deep waters (Ref 10).

The well-mixed average concentration in each of the oceans was computed. The concentrations derived for the situation where fuel is exposed to seawater at the time of RTG emplacement were 1.64×10^{-2} and $5.0 \times 10^{-3} \text{ pCi kg}^{-1}$ for the North Atlantic and North Pacific Oceans, respectively. An example of the calculations is given in Appendix A. It should be noted that the RTGs were functional at the time of emplacement; thus fuel exposure at this time is contrary to fact. The concentrations are reduced by a factor of 5.5×10^{-4} were fuel, more realistically, to be exposed to seawater at least 300 years later.

With these concentrations, the annual dose to man was calculated as prescribed by NRC Regulatory Guide 1.109 (Ref 9). Bioaccumulation data, consumption rates of fish and other edible marine life for the maximum exposed individual, and ingestion dose factors for adults, teenagers, and children were taken from Tables A-1, E-5, E-11, E-12, and E-13, respectively, of NRC Regulatory Guide 1.109. An example of the calculations appears in Appendix B.

Annual doses to man for each of the situations considered are shown in Table 3. An example of the calculations is given in Appendix B. Even where the doses were calculated for an unrealistically premature exposure to seawater, the values are orders of magnitude below acceptable limits for the whole body. See Table 4.

TERRESTRIAL DISPOSAL

For ultimate disposal of the RTGs at a terrestrial site, recovery by the manned submersible TRIESTE would be required. Only this vehicle is certified for operation at these depths. A description of the TRIESTE, a general mission profile, and a recovery attempt are presented in detail to convey the complexities and risks associated with recovery and terrestrial disposal.

VEHICLE DESCRIPTION

The TRIESTE is a self-propelled bathyscaph and consists of two main assemblies, a buoyancy chamber (float) and a cabin (sphere). The overall length and height of the vehicle is about 78 by 27 ft, and it displaces 268 tons at the surface. The craft is designed to ascend and descend by weight control. This control is accomplished by discharging shot ballast or by valving off aviation gasoline (AVGAS) to make the vehicle lighter or heavier than the surrounding water.

The float hull is essentially a hydrodynamically shaped container which houses ballast (BB-size iron shot) and AVGAS (66,000 gal) and serves as support for batteries, propulsion motors, sensors and other devices and equipment. End compartments in the float are floodable, and when filled with seawater the craft has a slight negative buoyancy.

Table 3. Dose (rem/yr) to the maximally exposed individual of an age group, for hypothetical capsule rupture and fuel release at the time of RTG deployment (A) and 300 years later (B).

A. Release at time of deployment

	BONE		TOTAL BODY		LOWER LARGE INTESTINE	
	ATLANTIC	PACIFIC	ATLANTIC	PACIFIC	ATLANTIC	PACIFIC
Adult	1.77×10^{-5}	5.38×10^{-6}	4.33×10^{-6}	1.32×10^{-6}	5.10×10^{-7}	1.56×10^{-7}
Teenager	1.47×10^{-5}	4.49×10^{-6}	3.63×10^{-6}	1.11×10^{-6}	4.13×10^{-7}	1.26×10^{-7}
Child	1.33×10^{-5}	4.07×10^{-6}	3.39×10^{-6}	1.03×10^{-6}	1.80×10^{-7}	5.47×10^{-8}

B. Release 300 years after deployment

Adult	9.74×10^{-9}	2.96×10^{-9}	2.38×10^{-9}	7.26×10^{-10}	2.81×10^{-10}	8.58×10^{-11}
Teenager	8.09×10^{-9}	2.47×10^{-9}	2.00×10^{-9}	6.11×10^{-10}	2.27×10^{-10}	6.93×10^{-11}
Child	7.32×10^{-9}	2.24×10^{-9}	1.85×10^{-9}	5.67×10^{-10}	9.88×10^{-11}	3.01×10^{-11}

Table 4. Dose-Limiting regulations and recommendations.

GROUP	DOSE LIMIT
Individual Members of the Public or Occasionally Exposed Individuals	0.5 rem in any one year (Ref 11,12)
Population (as a whole)	0.17 rem average per person per year (Ref 12)

The sphere is occupied by the operators. This chamber is the major pressure-resistant part of the vehicle and is designed for operation at depths exceeding 20,000 ft. Its pressure is maintained at 1 atm. Operating controls, monitoring devices, and an independent life support system are contained within this chamber. An observation window is oriented forward and slightly downward for providing a view of the ocean floor.

Silver-zinc storage batteries power the propulsion motors, lights, and the scientific and operational equipment.

GENERAL MISSION PROFILE

A mission profile (Ref 13) is presented to describe the considerations, risks, and sequence of steps that enter into the successful recovery of an object by TRIESTE. The preferred and more simplified method of operation includes support by a surface vessel dedicated exclusively to TRIESTE activities. This description will assume its availability, although the USS PT LOMA, which has served this function, currently is under other assignment.

Pre-mission planning focuses upon the mission site, methods of locating the object, water depth, bottom topography, sediment characteristics and the projected approach to be followed in the recovery. According to the plan developed, a suite of inboard and outboard equipment is selected for installation on the TRIESTE.

A provisioning phase involves the logistics of supplying expendable items such as AVGAS, various oils, ballast, nitrogen gas, and a number of other consumables. The transit phase aboard the POINT LOMA is used to prepare the TRIESTE for its assigned task. During this period project planning and command instructions are also reviewed. The TRIESTE crew receives final briefings on the task, and POINT LOMA personnel are instructed in detail to ensure a safe operation.

Upon arrival at the diving area all systems and equipment are examined with comprehensive and detailed check-off lists. Various lines, supply hoses,

cabling and rigging for AVGAS, shot ballast, and communications are readied. Boats are launched to provide assistance in moving the TRIESTE out of the POINT LOMA. The well of the POINT LOMA is flooded, and the hawser boats pull the TRIESTE to a point about 500 ft astern.

Service lines between the POINT LOMA and TRIESTE are connected by divers, AVGAS tanks are filled, and shot ballast unloaded. During this period divers from the POINT LOMA check underside arrangements and open gates on the shot valves. Simultaneously, within the sphere, electronic and battery tests, shot valve readings, and other details are checked.

When TRIESTE is readied for the dive, its ballast tanks take on water and it begins descent. The rate of descent (about 2.5 ft/s) is controlled by venting AVGAS or discharging bursts of shot. If the vehicle descends at an angle, correction is managed by release of shot from the fore or aft tank as required. When the vehicle is approximately 1200 ft from the bottom, the release of shot ballast is accelerated to reduce the descent rate to about 1 ft/s. If the vehicle is properly trimmed, the descent is almost stopped when a 250-lb trail ball suspended 15-30 ft below the vehicle touches bottom. The TRIESTE then rides the trail ball line to the bottom.

The hull of the TRIESTE is relatively thin. Thus it is essential that the vessel not collide with any feature of the ocean bottom. Navigation on the bottom is primarily conducted through use of a navigation computer and the outboard sensor suite coupled to the computer. A manual mode is also available. TV cameras, searchlights, and visual observations are also used as aids to navigation.

Upon completion of the recovery, preparation for ascent is initiated. Check-off procedures are performed, which include monitoring breathing gas, carbon dioxide levels, and humidity. The vehicle is trimmed, and the ascent is started by dropping shot. The rate of ascent is carefully monitored and controlled by further shot release at 5- to 8-s intervals. During ascent all of the nonessential systems are shutdown to conserve power.

When the vehicle breaks surface, divers board to establish phone communications. Water is blown from the two end tanks to create slight positive buoyancy, causing the vehicle to rise sufficiently to provide an exit for the crew. AVGAS is pumped back to the POINT LOMA, and the tanks are purged with nitrogen gas to discharge the residual flammable vapors. Up to 5000 gal of AVGAS remain in the TRIESTE, and strict precautions must be observed to prevent static electricity and sparking.

Finally the POINT LOMA is flooded, docking procedures are carried out basically by the same steps as described for undocking, except in reverse order, and the return transit completes the mission.

Clearly, a TRIESTE mission is a major undertaking that poses certain recognized risks. The launching of the vehicle and support boats, diver activities with numerous lines in the water, the transfer of flammable AVGAS, operation at great depths in environments of unknown topography, dependency on an independent life support system, and recovery of the crew upon surfacing are but a few of the non-trivial tasks involved.

RECOVERY ATTEMPT BY TRIESTE

In August 1978 the TRIESTE and POINT LOMA were requested to recover the three URIPS-P1 RTGs located near Midway Island. In the recovery plan developed for this event, an RTG was to be secured to the TRIESTE and carried to the surface. (Sketches of the RTG system and pre-dive recovery hardware appear in Fig 4 and 5.) The bow winch cable was to be lowered and a hook at its terminus grasped by the manipulator arm. The hook was to pass around one or two of the standframe legs of the RTG and then snapped onto the bow winch cable. An alternate point of attachment was the RTG's power adapter assembly.

Once hookup was accomplished, the bow winch was to lift the RTG from the bottom. If problems were encountered with the bow winch, the centerline lift rig was to be used. Plans also considered the possibility of securing a second RTG on the same dive—time, battery power, and the availability of the centerline lift rig permitting.

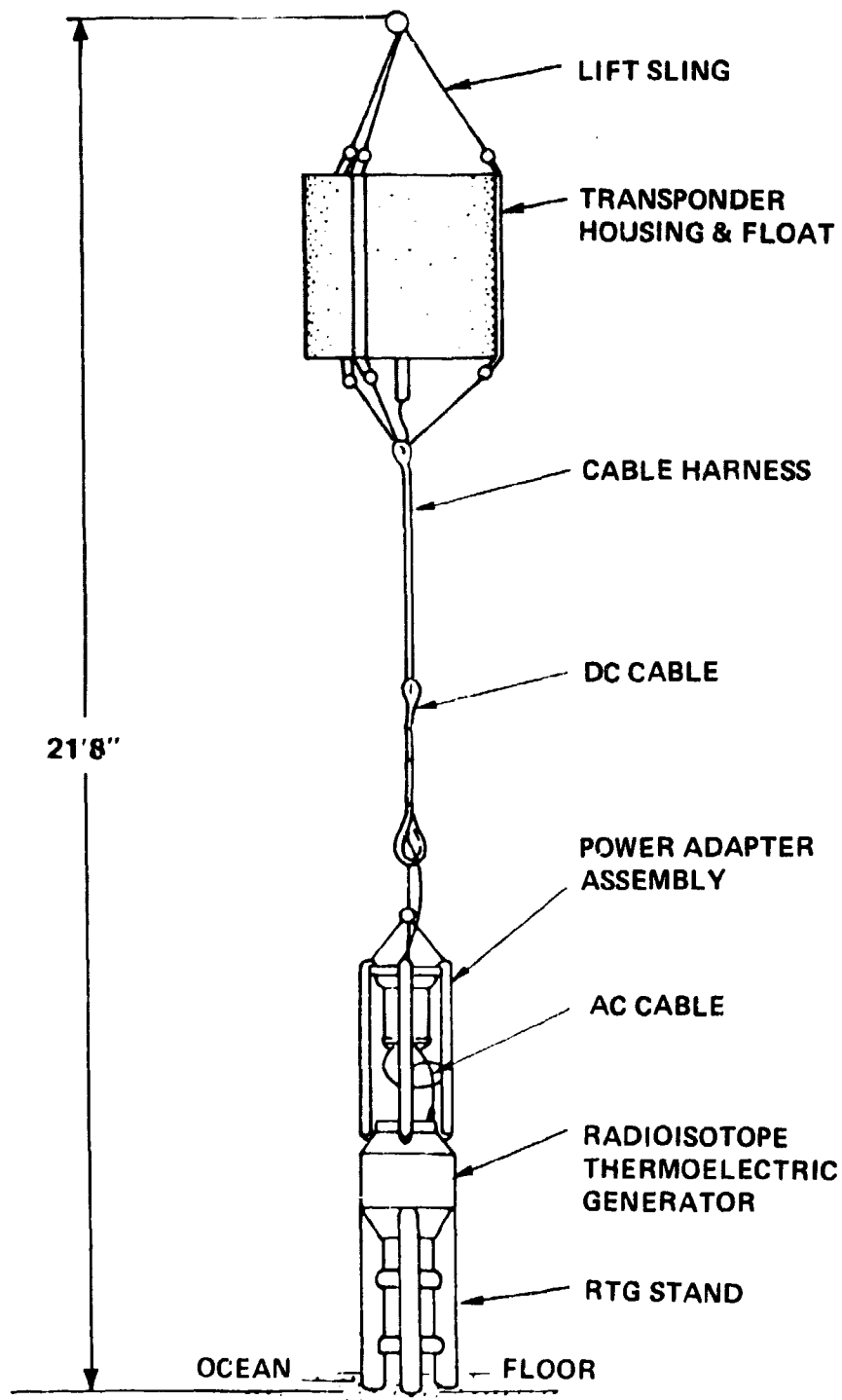


Figure 4. Deep ocean transponder system

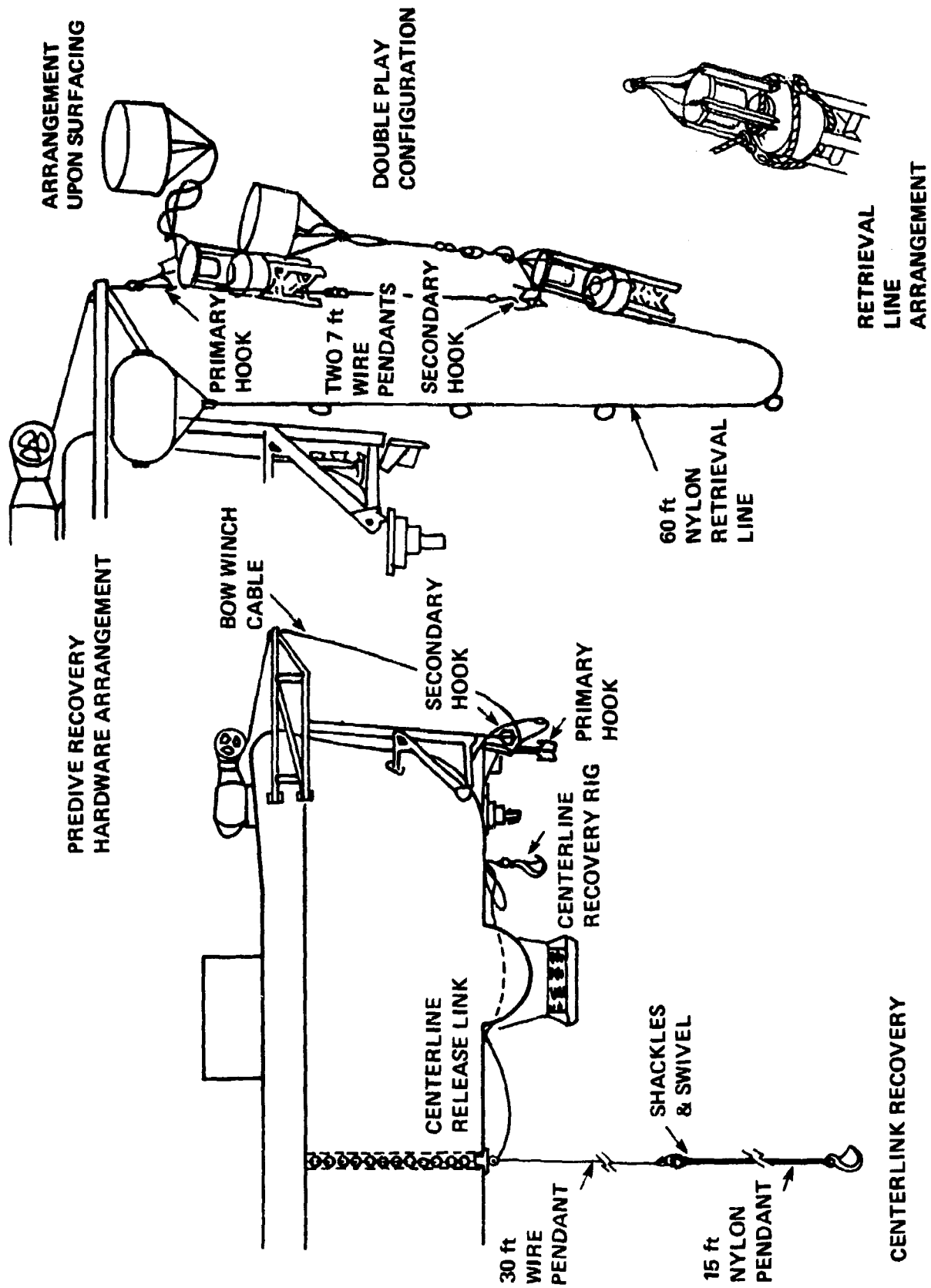


Figure 5. Midway RTG recovery equipment.

The POINT LOMA sailed from Pearl Harbor on 17 August and arrived on station the evening of 21 August. Evaluation of the accuracy of various means of navigation was immediately undertaken, and by 22 August the location of the POINT LOMA had been accurately defined.

The TRIESTE was prepared for launch on 23 August; however, the prevailing sea state prevented launch until 28 August. Pre-dive checkouts were conducted, and the descent started at 1000 on 29 August. The bottom was reached 1 1/2 hours later. After making contact with a sonobuoy, information was received from the surface tracking party to establish the position of the TRIESTE. Within 1/2 hour one of the RTGs was observed. The distance to the RTG was closed carefully, since movement of the vehicle produced dense clouds of silt that required about an hour to clear. About two-thirds of the RTG system was observed to be embedded in the sediment (Fig 6), and the only accessible lift points were the wire rope bridle and part of the power adapter assembly. When the manipulator arm was used to attempt to loosen and lift the RTG from the silt, a bridle cable fitting snapped. Upon attempting to free the RTG by grasping its power adapter assembly, hydraulic fluid was noted to be oozing from the manipulator arm, and it was secured. The RTG was subsequently lost from sight in another cloud of disturbed sediment. Repeated attempts to grapple the power adapter assembly with the bow winch hook were unsuccessful. The TRIESTE started its ascent at 1845 and surfaced 2 hours later. Since the recovery operation was severely hampered by loss of the manipulator arm, the mission was terminated.

IMPACT OF RECOVERY ON MAN

If the RTGs could be recovered from the ocean floor at this time, exposure to strontium-90 contamination is not anticipated. It is emphasized that the properties of the fuel capsule are such that exposure of strontium-90 to the environment appears improbable over the next several centuries. Nonetheless, an evaluation should be instituted by collection and analysis of waters and sediment in proximity to the RTGs before an attempted recovery. In the unlikely event that radioactivity is detected in these samples, it would be

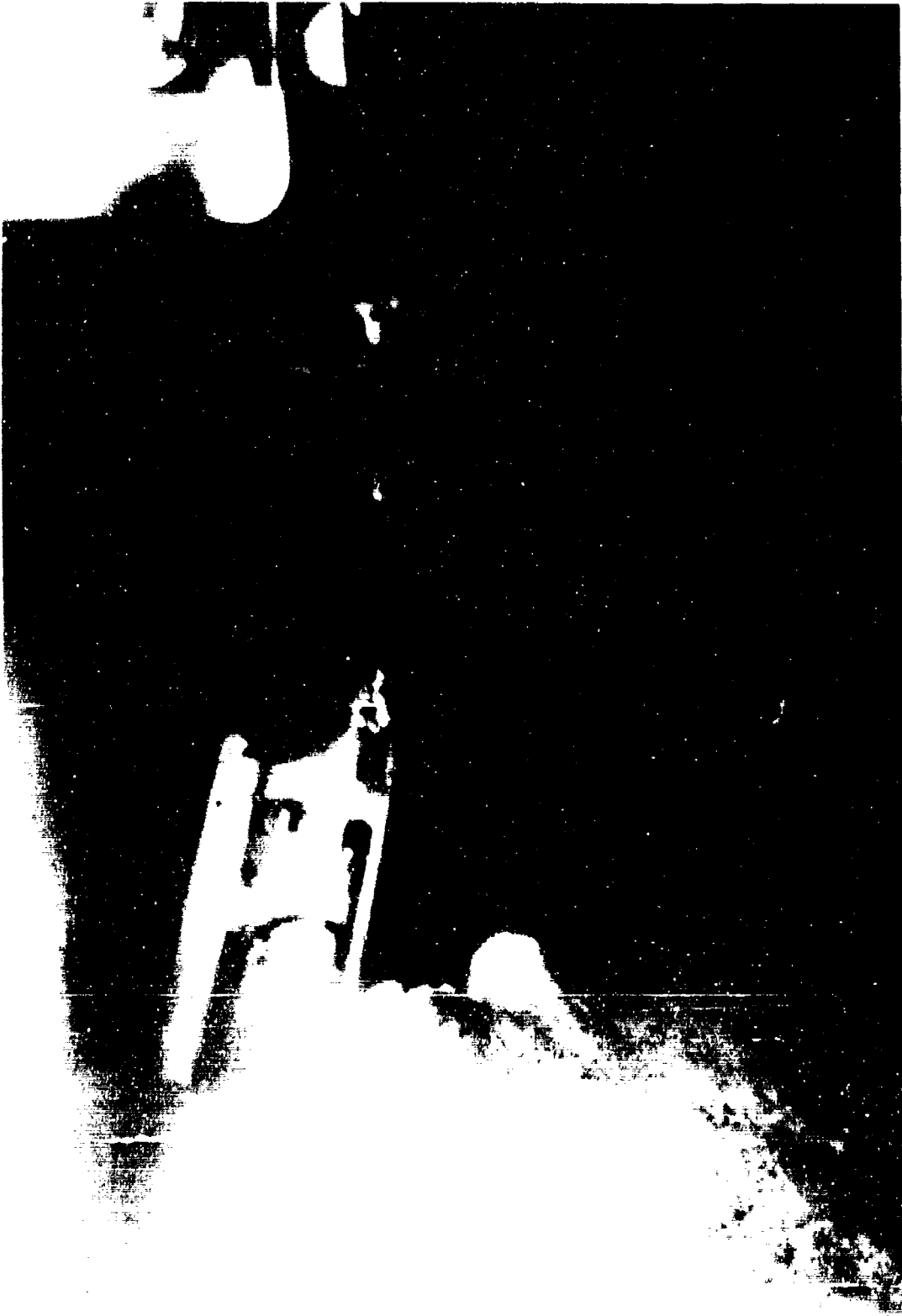


Figure 6. RTG as viewed from TRIESTE.

imprudent to recover the source unless a suitable scheme of contamination containment were devised and implemented from the onset of recovery until final disposal.

On the other hand, the exposure rate at the surface of the RTGs ranges from 100-120 mR/hr, and at 1 m, the rate is 5-6 mR/hr. Thus, personnel involved in transferring the recovered RTGs to the deck of the support ship, packaging them in shipping containers, and securing the containers for shipment would unavoidably receive a finite radiation dose. Additionally a radiation dose would be received by those individuals involved in offloading the shipping containers from the support ship, loading them onto a vehicle for transportation to a terrestrial disposal site, unpackaging the RTGs at the disposal site, and placing them into the disposal structure. Although the number is difficult to estimate, it is conceivable that many people could be exposed. The potential for transportation accidents also exists. Though TRIESTE has an excellent safety record, several scenarios may be developed from the mission profile that present a significant degree of non-radiological risk to the TRIESTE crew and support personnel.

SUMMARY AND CONCLUSIONS

From 1970 to 1977, six RTGs with kilocurie quantities of strontium-90 titanate were deployed at depths that range from approximately 10,000 to 16,000 ft. These devices were designed to withstand the corrosive action of seawater without exposing the strontium-90 fuel to the environment for at least 300 years. At that future time, only a small fraction of radioactivity (5.5×10^{-4}) would persist. The fraction remaining is further reduced by a factor of 1.6×10^{-4} to 13×10^{-5} if the 50 to 150 years of protection afforded by the outer hull is considered. Risk evaluation using the methodology proposed by the NRC was performed for an in situ disposal. The seawater concentration required for this evaluation was calculated by a method that provides a considerable margin of safety. Also exposure of the fuel to the environment was considered to occur at the time of deployment, thus deriving no benefit from radioactive decay, although it was recognized that the RTGs

were functioning and therefore intact at that time. Even under these conservative circumstances, the results of the analysis indicate that the risk to man is insignificant.

Recovery of an RTG with the manned submersible TRIESTE was attempted in 1978. Navigation to the source was precise; however sediment character was such that much of the RTG structure was buried. A cable bridle and a portion of an assembly mounted on top of the RTG were visible above the sediment surface and available for attachment; however the bridle lacked sufficient strength to enable recovery, and due to equipment failures, the assembly could not be grasped.

The safety record of TRIESTE notwithstanding, the activities involved in a recovery mission are not without risk to its crew and support personnel; nor is recovery of the RTGs assured. Further, were the RTGs to be recovered successfully, the necessary actions involved in terrestrial disposal entail exposure of personnel to a measureable radiological dose and potential transportation accidents.

In summary, in situ disposal of the RTGs is of predictable benign consequence, while recovery for the purpose of terrestrial disposal involves significant non-radiological hazards; furthermore measurable levels of dose to personnel participating in recovery and terrestrial disposal are inevitable. Accordingly, since the in situ plan offers less risk to man than the alternative, it is recommended as the method of disposal.

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APPENDIX A

A CALCULATION OF THE STRONTIUM-90 CONCENTRATION IN THE OCEAN

The ^{90}Sr well-mixed average concentration in the North Atlantic Ocean, postulating fuel release at the time of deployment of the SNAP-21, was calculated by the following formulation:

$$C = \frac{(SA)(DR)(A)(SF)}{(V)(D)}$$

where

C is the well-mixed average concentration of ^{90}Sr in seawater of the North Atlantic Ocean (pCi/kg).

SA is the surface area of the fuel (224.14 cm^2) derived from the dimensions of the fuel given in Table 1.

DR is the dissolution rate of the strontium-90 titanate in $\text{g/cm}^2/\text{s}$ and is equal to $\frac{0.001 \text{ g/cm}^2/\text{day}}{86,400 \text{ s/day}}$.

A is the activity of the fuel (28,980 Ci) as given in Table 1.

V is the volume of the fuel (257.63 cm^3) derived from the dimensions given in Table 1.

D is the density of the strontium-90 titanate (3.7 g/cm^3) as shown in Table 1.

SF is Shepherd's Factor in pCi/kg as deduced from Fig 7 of Ref 10 and (including a safety factor of 10) is equal to:

$$\frac{1.28 \times 10^{-7} \text{ Ci/m}^3 / \text{Ci/s} \times 10^{12} \text{ pCi/Ci}}{10^3 \text{ kg/m}^3}$$

Upon substitution

$$C = 1.01 \times 10^{-2} \text{ pCi/kg.}$$

APPENDIX B

A CALCULATION OF RADIATION DOSE

The following is a calculation of the radiation dose to the bone of an adult from the ingestion of marine foods derived from North Atlantic Ocean waters contaminated with ^{90}Sr from RTGs that hypothetically ruptured at the time of their deployment.

The equation used from NRC Regulatory Guide 1.109 was

$$R_{aj} = (C)(U_a)(B)(D_{aj})$$

where

R_{aj} is the annual dose to organ j of an individual of age group a in mrem/yr.

C is the well-mixed average concentration of ^{90}Sr in the seawater (pCi/kg). The concentration calculated for the North Atlantic Ocean is 1.64×10^{-2} pCi/kg, of which 1.01×10^{-2} pCi/kg is derived from the SNAP-21 (see Appendix A) and 6.26×10^{-3} pCi/kg from the RG-1 sources.

B is the bioaccumulation factor, which is 2* for fish and 20* for invertebrates.

D_{aj} is the ingestion dose factor specific to age group and organ. For bone of an adult this factor is 7.58×10^{-3} mrem/pCi**.

*Table A-1, ** Table E-11

U_a is the intake rate for an age group (kg/yr). For an adult the intake rate of rate of fish is 21*** and of invertebrates 5***.

Thus:

$$\begin{aligned} R_{aj} &= 1.64 \times 10^{-2} [21(2)+5(20)] 7.58 \times 10^{-3} \\ &= 1.77 \times 10^{-2} \text{ rem/yr of } 1.77 \times 10^{-5} \text{ rem/yr.} \end{aligned}$$

***Table E-5 of NRC Regulatory Guide 1.109.