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ISOTOPE KILOWATT PROGRAM
FUELED CAPSULE DESIGN AND EVALUATION
A SAFETY ANALYSIS

K. W. Haff

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ISOTOPE DEVELOPMENT CENTER

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Isotopes Division

MAY 1971

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ABSTRACT

A large heat source capsule design for the Isotopes Kilowatt Program meets the containment criteria for safe operation in terrestrial systems and probable accident conditions. The capsule presented here meets all the requirements of operational safety and the particular hazards to which it might be exposed in its operational environment and transportation to and from its use site.

SUMMARY

The universal criterion to which all radioisotope-fueled devices must adhere is the absolute containment of the fuel under all credible conditions where its release could endanger life or property.

Lanes,¹ in discussing the safety considerations of isotopic SNAP (Systems for Nuclear Auxiliary Power) devices, has stated that the design of these units must be directed toward withstanding a "maximum credible accident." He states further that "the goal of a contractor developing a SNAP unit must be to design a fuel capsule that can withstand this environment [of the maximum credible accident], and, . . . to be able to conclusively demonstrate the achievement of this goal."

In 1968, Oak Ridge National Laboratory began work on a program to evaluate various types of isotopic energy-conversion systems for the production of 1 to 10 kW of electric power for terrestrial (to include undersea) applications. Task I of this program,² which was completed in 1969, was a parametric and engineering analysis of four radioisotope fuels, $^{144}\text{Ce}_2\text{O}_3$, ^{90}SrO , $^{90}\text{SrTiO}_3$, and ^{60}Co metal, and several types of energy-conversion devices.

Task II, of which this work is a part, is concerned with a more detailed engineering study of three radioisotope energy-conversion system concepts, organic Rankine, steam Rankine and thermoelectric, that were selected as a result of the information developed in Task I. A typical set of performance and dimensional data³ for a reference design 5-kW(e) organic Rankine cycle system is given in Table 1.

Table 1. Performance and Dimensional Data for the
Reference Design 5-kW(e) Isotope-Powered
Organic Rankine Cycle Energy Conversion System

Plant Performance

Isotope heat output, beginning of life [kW(th)]	34
Isotope heat output, end of life [kW(th)]	30
Net power output, beginning of life [kW(e)]	5.7
Net power output, end of life [kW(e)]	5.0
Design life (years)	5

Fuel Capsules

Fuel material	$^{90}\text{SrTiO}_3$
Number of fuel capsules	7
Fuel capsule OD (in.)	4.10
Fuel pellet OD (in.)	3.40
Fuel capsule length (in.)	39.8
Fuel length (in.)	38.4
Fuel capsule center-line spacing (in.)	5.65

Heat Block-Shield

Material	Iron
Diameter over fin tips (in.)	40.5
Height (in.)	59.2
Fin height (in.)	2.50
Fin thickness (in.)	0.50
Fin center-line spacing (in.)	2.50
Number of fins	45
Radiation dose at surface (mr/hr)	200
Heat block-shield assembly weight (lb)	17,200

Heat Block-Shield and Fuel Temperatures

Normal Operation	
Maximum fuel temperature (°F)	1940
Maximum cladding temperature (°F)	1400
Maximum block temperature (°F)	1250
Block surface temperature (°F)	875
Shipping	
Maximum fuel temperature (°F)	1580
Maximum cladding temperature (°F)	1020
Maximum block temperature (°F)	870
Block surface temperature (°F)	480
Accident Conditions (loss-of-coolant)	
Maximum fuel temperature (°F)	2400
Maximum cladding temperature (°F)	1890
Maximum block temperature (°F)	1810
Block surface temperature (°F)	1360

Table 1. continued

Heat Loss During Normal Operation (kW)	3
Boiler	
Heat load (kW)	31-27
Temperature (°F)	613-600
Pressure (psia)	51.6-45.6
Total vapor flow rate (lb/hr)	500-436
Boiler tube linear heat rating (Btu/hr.ft)	1885-1640
Average heat flux (Btu/hr.ft ²)	9730-8480
Number of tubes	12
Center-line diameter of tubes (in.)	31
Outer tube OD (in.)	1.050
Outer tube ID (in.)	0.742
Inner tube OD (in.)	0.540
Inner tube ID (in.)	0.302
Vapor riser OD (in.)	0.840
Vapor riser ID (in.)	0.546
Boiler drum OD (in.)	8.625
Boiler drum ID (in.)	7.981
Maximum radiation dose rate in boiler tubes (R/hr)	3.5
Maximum radiation dose rate in boiler drum (R/hr)	0.15

In the interest of economy, both from the standpoint of design effort and fabrication and loading facilities, a single capsule concept has been developed that will satisfy the requirements of all three systems. A parametric study of fuel capsule dimensions conducted in Task I did not reveal any particular advantages for a specific size. However, heat transfer studies of several heat-block configurations indicated that a large capsule was more desirable. The capsule size chosen, on the basis of experience with the SNAP-21 and SNAP-23 programs, is one which can be fabricated utilizing existing facilities and technology. The basic capsule is 4.100 in. in diameter and 40.400 in. long and has a wall thickness of 0.325 in. The bottom cap of the capsule is 0.780 in. thick and is electron beam welded with a minimum penetration of 0.120 in. The top cap is 1.060 in. thick and is a threaded design for ease of assembly in a hot cell. The cap will have four 3-3/4-in.-diam threads and will be plasma arc seal welded after closure with a minimum penetration of 0.055 in. The capsule is designed to meet the requirements of 10 CFR 71 (ref. 4), IAEA Safety Series No. 6 (ref. 5), and IAEA Safety Series No. 33 (ref. 6).

The bottom cap rests on a 0.045-in.-wide ledge to reduce shear stress on the electron beam weld, and the top cap rests on a 0.073-in.-wide ledge to reduce shear stress on the threads. The support provided by these ledges is ignored in the stress calculations as an additional safety factor. Also ignored in the stress calculations is the support provided the capsule by the fuel material. Twice the number of threads required have been built into the top cap.

The fuel capsule is constructed of a corrosion-resistant superalloy (Hastelloy C-276). It is designed to withstand pressures to 10,000 psi (equivalent of 22,500-ft depth in seawater with a density of 64 lb/ft³) without exceeding its yield strength and to withstand corrosion by seawater for 300 years. Hastelloy C-276 was chosen as the encapsulating material because of its demonstrated corrosion and oxidation resistance, its excellent strength and ductility, and its demonstrated compatibility with the selected fuel form $^{90}\text{SrTiO}_3$.

Cobalt-60 metal, $^{144}\text{Ce}_2\text{O}_3$, ^{90}SrO , and $^{90}\text{SrTiO}_3$ were considered as possible fuels for multikilowatt heat sources;² $^{144}\text{Ce}_2\text{O}_3$ was eliminated during the very early phases of the program because of its short (0.78 year) half-life.

In large heat sources the fuel must be arranged to provide adequate heat-transfer paths from the interior of the capsule array to the outer surface to prevent overheating and possible melt down of the capsules should any of the active heat-removal systems fail during transport or use. In the cases of ^{90}SrO and ^{60}Co metal, this design philosophy of passive heat rejection under loss-of-coolant conditions results in the fuel capsules having to be spread out in a large volume and in the effective power density being not much greater than that of the $^{90}\text{SrTiO}_3$ fuel.

The half-life of ^{60}Co is a limitation at conversion-system lifetimes (from initial fueling) of about 2 years. The amount of excess fuel at the beginning of life in order to have the rated power level at the end of life creates significant excess heat discharge and temperature control problems.

Of all the fuels, $^{90}\text{SrTiO}_3$ is the best characterized in isotopic power applications, since it has been used in over fifty thermoelectric devices. The procedures for preparation and encapsulation are well developed as a result of several AEC programs, and the fuel has been accepted by safety and regulatory groups for a wide variety of terrestrial (including under-sea) applications. The fuel is suitable for both short- and long-mission applications. Therefore, the capsule design for this program has been one utilizing $^{90}\text{SrTiO}_3$ as a fuel. A summary of fuel properties is given in Appendix I.

A system and capsule designed for a $^{90}\text{SrTiO}_3$ fuel can be fueled with $^{90}\text{SrF}_2$ with essentially no — or at least very little — modification, since it is expected that the AEC will be routinely removing all the ^{90}Sr and ^{137}Cs from the fuel reprocessing wastes at its Hanford plant prior to solidification of the remaining wastes for long-term storage. This is being done as part of the Hanford Waste Management Program to minimize waste mobility. It is planned, by about 1975, to routinely convert the separated ^{90}Sr to solid form, probably $^{90}\text{SrF}_2$, and encapsulate the solid in Hastelloy C-276 cans. Depending on accounting procedures, the separated $^{90}\text{SrF}_2$ could be considered as paid for up to that point. This would be a significant reduction in fuel costs for isotopic power units.

Fuel for the system is recovered from reactor fuel reprocessing as a waste material. After it has been separated and purified, the product is converted to the highly stable strontium titanate in a powder form. At

this point, the radioactive content is determined by radiochemical analysis and the heat quality of the powder is determined by calorimetry. The quantity required for a fuel pellet is then hot-pressed at approximately 3500 psi with nickel screens located along the height of the pellet at approximately 0.3-in. intervals. The nominal pellet dimensions for this capsule will be 3.400-in. diameter by 1.920-in. height; the pellet will contain six 24-mesh by 0.014-in.-diam nickel wire screens (Fig. 1). Calorimetry will again be performed to verify the thermal output of each pellet. The pellets [20 per source, approximately 4860 W(th)] will then be loaded into the fuel capsule. All these operations will be performed in a hot cell.

An inspection of the finished capsule and capsule materials will be made. The capsule body will be fabricated of welded pipe of specified size, and the end caps will be fabricated of plate material as in the SNAP-23 program. The inspection will include examination of the raw materials to ensure that they meet quality standards and a complete dimensional inspection of the fabricated component parts. The assembled and fueled capsule will be leak tested to ensure its leak tightness.

Fig. 1. Isotope Kilowatt Program Fuel Pellets.

DESIGN CRITERIA

The capsule for the Isotope Kilowatt Program is designed for complete containment of the fuel in seawater at pressures up to 10,000 psi (equivalent to 22,500-ft depth of seawater with a density of 64 lb/ft³) without exceeding its yield point at operating temperature for 300 years and under conditions of a 1-hr fire test as prescribed in the code of the National Fire Protection Association. Much broader design requirements were imposed to ensure containment of the fuel under "maximum credible accident" situations. The safety aspects of the fuel capsule governed the design to provide a fuel capsule with a very high degree of fuel containment integrity.

The design, shown in Fig. 2, consists of a cylindrical shell with the bottom cap welded in place and the top cap of a screw-thread design which is seal welded. The capsule shell is formed from welded Hastelloy C-276 pipe and the end caps are machined from Hastelloy C-276 plate.

Electron beam welding was selected as the closure weld for the bottom cap because of ORNL experience gained in the SNAP-21 and SNAP-23 programs. Equipment and techniques for welding and inspection of this particular type of joint which requires 0.120-in. penetration were developed in these programs. This part of the capsule assembly and inspection will be performed outside a hot cell. The top cap is a screw-thread design. This design was selected because of experience gained in loading the Sentinel

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Fig. 2. Isotope Kilowatt Program Fuel Capsule.

generator capsules. The Sentinel generator capsule has been approved for use in the deep sea by regulatory agencies. Since the weld is only a seal weld and not a structural weld, the only inspection required is a leak test. The weld penetration required is 0.055 in. Assurance of this weld penetration is given by qualification of the weld procedure in a simulated capsule, both before and after the actual seal weld is made. A plasma arc weld procedure will be used. Both the simplified inspection and the in-cell plasma arc weld are less expensive than an in-cell electron beam weld and ultrasonic inspection at the present time. The weld integrity of the bottom cap will be verified by ultrasonic inspection in out-of-cell facilities. It is anticipated that in the near future in-cell electron beam welding and ultrasonic inspection facilities will be permanently installed in operating cells, and this procedure may be available for sealing the top closure of this capsule. Should that be the case, the top closure would be redesigned identically to the bottom closure and the analysis and inspection requirements of the bottom closure and cap would also apply to the redesigned top closure.

The major considerations in the design of the capsule are:

<u>Hazard</u>	<u>Occurrence</u>	<u>Requirement</u>
Pressure	In-service	14,505 psi
Crushing	Transportation	Unknown
Impact	Transportation	Free fall terminal velocity from 30 ft
Thermal	Transportation or storage fire	2000°F for 30 min
Vibration	Transportation	Various
Thermal Shock	In-service	1400°F to 32°F instantaneous immersion held for 10 min
Corrosion	In-service	Seawater
Oxidation	In-service or fire	2000°F in air
Puncture	Transportation	7 kg from a height of 1 meter

CAPSULE DESCRIPTION

The fuel capsule is a right circular cylinder 4.100 in. in diameter by 40.400 in. overall length with a wall thickness of 0.325 in. and will contain approximately 4860 W(th) of $^{90}\text{SrTiO}_3$. This wall thickness was determined by means of stress calculations, hydrostatic tests on SNAP-23 capsules, and the seawater corrosion rate of Hastelloy C-276. The corrosion rate of this alloy is 10^{-4} in./year (ref. 7); therefore, there could be 0.030 in. of corrosion penetration in 300 years. The corrosion rate also governs the depth of penetration of the seal weld on the top cap (0.055 in.) and the structural weld on the bottom cap (0.120 in.).

To reduce shear stress on the bottom welded joint and the top threaded joint, the top and bottom caps rest on shoulders machined into the cylindrical body of the capsule. These shoulders are 0.073 in. and 0.045 in. wide for the top and bottom, respectively. The top and bottom caps are raised 0.060 in. above the weld areas so that the weld bead will not interfere with assembly of the capsule into the heat block or cask and so that the overall length of the capsule is accurately known. The detailed drawing of the capsule is shown in Fig. 2.

CALCULATIONS

Strength calculations for the fuel capsule are not indicative of the capacity of the fueled capsule to withstand its total environment, since for conservatism the capsule was assumed to stand alone in the analysis. When the pellets are placed in the capsule, they will very nearly fill the internal volume. Under high external pressure some elastic deformation of the capsule wall will take place. On the diameter there can be a maximum of 0.050-in. total space between capsule and fuel. Since pressure is assumed to be uniformly applied, the maximum wall movement would be 0.025 in. at which time support from the fuel would become effective. In the longitudinal direction the space can amount to 0.160 in. total. In reality this much space will not be available since the 20 fuel pellets vary slightly in density, and some will be higher than the design height. Any excess space that is left after fueling will be filled with Hastelloy C-276 spacers. Assuming that the entire space is available, the two end caps can deflect up to 0.080 in. at their centers before contact with the fuel occurs. Once contact has been established, the fuel begins to pick up any additional load imposed on the capsule. The compressive strength of $^{90}\text{SrTiO}_3$ is about 19,000 psi, and once the capsule deforms about the fuel the load-carrying capability of the combination becomes extremely large because no plastic flow of the fuel can take place.

The fuel capsule for the Isotopes Kilowatt Program has been designed to withstand the total environment to which it will credibly be exposed even under accident conditions without relying on any support from the fuel. This discussion above is intended to point out the factor of safety included in the design. Other safety features that are not included in the design calculations are an excess of greater than twice the number of threads required in the top cap design and the support ledges for the top and bottom cap which act to reduce shear stress on the closures. The excess threads are included to allow for deflection in the top cap. When any deflection in the cap occurs due to an external pressure, the top thread contact area tends to be lessened because of a pulling-away effect. The shearing effect on that particular thread is then transferred to the excess threads and to the support ledge.

While it is not a requirement of the work statement of this project, the capsule is expected to withstand the requirement for external pressure suggested in the IAEA guide for the design of radioisotopic power generators.⁶ This requirement states that "the capsule shall be shown to be able to resist an external pressure of 1000 bars, i.e., 10^8 Newtons per square metre."

This translates to 987 atmospheres or 14,505 psi. This is not expected to create a problem in terms of rupture of this capsule since it is designed to withstand 10,000 psi and remain in the elastic region, i.e., all stresses are less than the yield stress. In the event of pressurization to 14,505 psi, the capsule would be expected to experience some yield but not failure. Tests⁸ conducted at ORNL on SNAP-23 were performed at pressures of 16,100 psi without failure of the capsule. Some plastic deformation did occur, but even this was minimized by support afforded the capsule by the fuel simulant.

The stress calculations due to external pressure are summarized in Table 2. Values of 10,000 and 14,505 psi for external pressure were used in the calculations. In the detailed stress calculations, the numbers in parentheses to the right of the stress values are for an external pressure of 14,505 psi.

Table 2. Summary of Calculated Values^a for
Isotope Kilowatt Program Capsule

	External Pressure	
	10,000 psi	14,505 psi
Stresses in Caps		
Top Cap, pressure side (psi)	-30,666	-44,481
Top Cap, fuel side (psi)	19,272	27,954
Bottom Cap, pressure side (psi)	-48,345	-70,124
Bottom Cap, fuel side (psi)	33,737	48,936
Stress in Bottom Cap Weld (psi)	22,058	31,995
Required Thickness of		
Threaded Cap (in.)	0.424	0.615
No. of Threads Required	1.42	1.609
Rotation of Threaded Cap		
Due to Pressure (in.)	0.0084	0.0122
Stresses in Cylinder Wall		
Circumferential stress (psi)	-62,860	-91,180
Longitudinal stress (psi)	-34,250	-49,680
Radial stress (psi)	-5,644	-8,187
Maximum Load Capsule Can Support (lb)		45,134
Maximum Puncture Load on 1-in.-diam Capsule Can Support (lb)		6,118
Deflection in Cylinder Wall Caused by Maximum Load of 6,118 lb on 1-in.-diam Area (in.)		0.0202
Dynamic Load Due to 7-kg Bar Dropped From One Meter (lb)		1,841

^aValues were calculated using 10,000 and 14,505 psi for the external pressures.

Glossary of Terms Used in Calculations

- λ_c = capsule wall flexibility parameter (dimensionless)
 t_c = capsule wall thickness (in.)
 R = radius (in.)
 R_{ID} = inside capsule radius (in.)
 δ = ledge width (in.)
 ν = Poisson's ratio (in./in.)
 c = ratio t_c/t_h' (dimensionless)
 t_h' = distance from ledge to bottom of capsule (in.)
 Q_O = shear force at joining structure (lb/in.)
 P = pressure (psi)
 M_O = moment at joining structure (lb)
 S = stress (psi)
 t_h = thickness of cap (in.)
 $a = t_h' - (t_w/2)$
 t_w = thickness of weld (in.)
 t_{th} = thickness of threaded cap (in.)
 S_y = yield stress (psi)
 N = number of threads (dimensionless)
 A_s = area of contact between threads (in.)
 n = number of threads per inch (threads/in.)
 L_e = length of engagement of threads (in.)
 $K_{n_{max}}$ = maximum minor diameter of internal threads (in.)
 $E_{s_{min}}$ = minimum basic pitch diameter (in.)
 A_t = tensile stress area of threads (in.²)
 D = diameter of threads of cap (in.)
 θ = rotation of threaded cap due to external pressure (if unrestrained by seal weld) (radians)
 r = rotation of threaded cap due to external pressure (if unrestrained by seal weld) (in.)
 E = modulus of elasticity (psi)
 R_2 = average radius of threaded cap (in.)
 a = inside radius of cylinder (in.)
 b = outside radius of cylinder (in.)
 r_c = radius of cylinder at which stress is calculated (in.)

S_H = hoop strength = yield strength (psi)
 $A = 12(1 - \nu^2)$
 w = axial load (lb/linear in.)
 l = length of capsule (in.)
 W = total axial load (lb)
 b_c = radius of area over which load acts (in.)
 $\text{Max } y$ = maximum deflection in cylinder wall due to applied force (in.)
 t = time (sec)
 s = distance of fall (ft)
 g = acceleration due to gravity (ft/sec²)
 v = velocity (ft/sec)
 k = spring constant (lb/ft)
 I = moment of inertia (in.⁴)
 D_m = major diameter (in.)
 d = minor diameter (in.)
 W_m = dynamic deflection of beam (ft)
 m_2 = mass of striking object (lb)
 F = force (lb)
 $G(p_i)$ = function of p_i
 $\bar{x}_i$ = fraction of length subjected to stress (p_i) and strain (ϵ_i^*) or less (dimensionless)
 p_y = compressive yield stress (psi)
 p_i = compressive stress (psi)
 ϵ_i^* = compressive strain corresponding to p_i (in./in.)
 x_i = length of capsule subjected to stress (p_i) and strain (ϵ_i^*) or less (in.)
 ρ = density (lb/in.³)

Capsule Wall Flexibility Parameter

$$\lambda_c = \sqrt[4]{[3(1 - \nu^2)R^2]/t_c^2}$$

$$t_c = 0.280 \text{ in.}$$

$$R = R_{ID} + \delta + t_c/2 = 1.91 \text{ in.}$$

$$\delta = 0.045 \text{ in.}$$

$$R_{ID} = 1.725 \text{ in.}$$

$$\nu = 0.32$$

$$\lambda_c = \sqrt[4]{[3(1 - 0.32^2)R^2]/t_c^2}$$

$$\lambda_c = 3.346$$

Shear Force at Joining Structure

$$Q_o = \left\{ \frac{c^3 \lambda_c^3 + 2(2 - \nu)c^3 \lambda_c + 2(2 - \nu)(1 + \nu)}{2c^3 \lambda_c^2 + [(1 - \nu)c^4 + (1 + \nu)]\lambda_c + (1 - \nu^2)c} \right\} \frac{PR}{4}$$

$$c = t_c/t_h' = 0.3889$$

$$Q_o = 5697 \text{ lb} \quad (8263 \text{ lb})$$

Moment at Joining Structure

$$M_o = \left\{ \frac{2c^3 \lambda_c^3 + (1 - \nu)c^4 \lambda_c^2 + 2(2 - \nu)(1 + \nu)}{2c^3 \lambda_c^2 + [(1 - \nu)c^4 + (1 + \nu)]\lambda_c + (1 - \nu^2)c} \right\} \frac{PR^2}{8\lambda_c}$$

$$M_o = 2013 \text{ lb} \quad (2920 \text{ lb})$$

Stress Due to Pressure (Top)

$$S_R = S_T = - \frac{3PR_{ID}^2(3 + \nu)}{8t_h^2}$$

$$t_h = 1.00 \text{ in.}$$

$$S_R = S_T = -37,047 \text{ psi} \quad (-53,737 \text{ psi})$$

Stress Due to Pressure (Bottom)

$$S_R = S_T = -60,893 \text{ psi} \quad (-88,325 \text{ psi})$$

$$t_h = 0.780 \text{ in.}$$

Stress Due to M_O (Top)

$$S_R = S_T = \frac{6M_O}{t_h^2} = 12,078 \text{ psi} \quad (17,519 \text{ psi})$$

Stress Due to M_O (Bottom)

$$S_R = S_T = 19,852 \text{ psi} \quad (28,795 \text{ psi})$$

Stress Due to Q_O (Top)

$$S_R = - \frac{Q_O}{t_h} = -5697 \text{ psi} \quad (-8263 \text{ psi})$$

Stress Due to Q_O (Bottom)

$$S_R = -7304 \text{ psi} \quad (-10,594 \text{ psi})$$

Total Stresses in Top and Bottom S_{1PT} (Top - Pressure Side)

$$S_{1PT} = -37,047 + 12,078 - 5697$$

$$S_{1PT} = -30,666 \text{ psi} \quad (-44,481 \text{ psi})$$

S_{1FT}(Top - Fuel Side)

$$S_{1FT} = 37,047 - 12,078 - 5697$$

$$S_{1FT} = 19,272 \text{ psi} \quad (27,954 \text{ psi})$$

S_{1PB}(Bottom - Pressure Side)

$$S_{1PB} = -60,893 + 19,852 - 7304$$

$$S_{1PB} = -48,345 \text{ psi} \quad (-70,124 \text{ psi})$$

S_{1FB}(Bottom - Fuel Side)

$$S_{1FB} = 60,893 - 19,852 - 7304$$

$$S_{1FB} = 33,737 \text{ psi} \quad (48,936 \text{ psi})$$

Stress in Weld

$$S_w = \frac{M_o}{at_w} + \frac{Q_o}{t_w}$$

$$a = t_h' - (t_w/2) = 0.660$$

$$S_w = -25,417 + 47,475$$

$$S_w = 22,058 \text{ psi} \quad (31,995 \text{ psi})$$

Required Thickness of Threaded Cap

$$t_{th} = R_2[3P(3 + \nu)/8S_y]$$

$$S_y = 55,000 \text{ psi}$$

$$p = 10,000 \text{ psi}$$

$$\nu = 0.32 \text{ in./in.}$$

$$R_2 = 1.875 \text{ in.}$$

$$t_{th} = 0.424 \text{ in.} \quad (0.615 \text{ in.})$$

Number of Threads Required

$$N - 1 = \frac{\pi P R_1}{S_y A_s}$$

$$A_s = 3.1416 n L_e K_{n_{\max}} \left[(1/2n) + 0.57735 (E_{s_{\min}} - K_{n_{\max}}) \right]$$

$$L_e = \frac{2A_t}{3.1416 K_{n_{\max}} \left[(1/2) + 0.57735 n (E_{s_{\min}} - K_{n_{\max}}) \right]}$$

$$A_t = 0.7854 [D - (0.9743/n)]^2$$

$$D = 3.75 \text{ in.}$$

$$n = 8 \text{ threads/in.}$$

$$A_t = 10.34 \text{ in.}$$

$$K_{n_{\max}} = 3.6147 \text{ in.}$$

$$E_{s_{\min}} = 3.6688 \text{ in.}$$

$$L_e = 2.428 \text{ in.}$$

$$A_s = 20.68 \text{ in.; } A_s / \text{thread} = 2.58$$

$$N - 1 = 0.42 \quad (0.609)$$

$$N = 1.42 \quad (1.609)$$

Rotation of Head Due to Pressure

$$\theta = \frac{3P(1 - \nu)}{2E(t_{th}/R_2)^3}$$

$$\theta = 4.48 \times 10^{-3} \text{ radians}$$

$$r = \frac{(0.00448)(3.75)}{2}$$

$$r = 0.0084 \text{ in.} \quad (0.0122 \text{ in.})$$

Stresses in Cylinder Wall Remote from EndsCircumferential Stress

$$S_{p_1} = -P \left(\frac{b^2(a^2 + r_c^2)}{r_c^2(b^2 - a^2)} \right)$$

$$b = 2.05 \text{ in.}$$

$$a = 1.725 \text{ in.}$$

$$r_c = [(b - a)/2] + a = 1.8875 \text{ in.}$$

$$S_{p_1} = -6.286 \times 10^4 \text{ psi} \quad (-9.118 \times 10^4 \text{ psi})$$

Longitudinal Stress

$$S_{p_2} = -P \left(\frac{b^2}{b^2 - a^2} \right)$$

$$S_{p_2} = -3.425 \times 10^4 \text{ psi} \quad (-4.968 \times 10^4 \text{ psi})$$

Radial Stress

$$S_{p_3} = -P \left(\frac{b^2(r_c^2 - a^2)}{r_c^2(b^2 - a^2)} \right)$$

$$S_{p_3} = -5.644 \times 10^3 \text{ psi} \quad (-8.187 \times 10^3 \text{ psi})$$

To determine resistance to crushing, a uniform axial load was assumed along the cylinder.

Maximum Load to Produce a Hoop Stress Equal to the Yield Stress

$$S_H = -0.492A^{1/8}wR^3\ell^{-1/2}t_c^{-5/4}$$

$$S_H = -5.5 \times 10^4 \text{ psi} \quad \ell = 40.280 \text{ in.}$$

$$A = 12(1 - \nu^2) \quad R = 2.050 \text{ in.}$$

$$\nu = 0.32 \quad t_c = 0.325 \text{ in.}$$

$$w = - \frac{S_H \ell^{1/2} t_c^{5/4}}{(0.492)A^{1/8}R^{3/4}}$$

$$w = 75,500 \text{ lb/linear in.}$$

$$W = w\ell = 3,041,140 \text{ lb}$$

Maximum Load to Produce a Circular Bending Stress Equal to Yield Stress

$$S_C = 1.217A^{-1/8}wR^{1/4}l^{1/2}t_c^{-7/4}$$

$$w = \frac{S_C A^{1/8} t_c^{7/4}}{1.217 R^{1/4} l^{1/2}}$$

$$w = 1120.5 \text{ lb/linear in.}$$

$$W = wl = 45,134 \text{ lb}$$

Maximum Load to Produce a Longitudinal Stress Equal to the Yield Stress

$$S_L = -0.1188A^{3/8}wR^{1/4}l^{1/2}t_c^{-7/4}$$

$$w = \frac{S_L t_c^{7/4}}{0.1188A^{3/8}R^{1/4}l^{1/2}}$$

$$w = 3496 \text{ lb/linear in.}$$

$$W = wl = 140,817 \text{ lb}$$

The capsule is therefore capable of supporting a load of 22.5 tons without exceeding its yield strength.⁹ This load is greater than the presently anticipated total system weights.

To determine resistance to puncture as required by the IAEA guide, a calculation was made of stresses produced by a load on the center of the capsule on a 1-in.-diam area.

Maximum Load on a 1-in.-diam Area to Produce a Hoop Stress Equal to the Yield Stress

$$S_H = -0.130A^{1/8}wR^{3/4}b_c^{-3/2}t_c^{-5/4}$$

$$b_c = 0.5 \text{ in.}$$

$$W = \frac{S_H b_c^{3/2} t_c^{5/4}}{0.130A^{1/8}R^{3/4}}$$

$$W = 15,920 \text{ lb}$$

Maximum Load on a 1-in.-diam Area to Produce a Circular Bending Stress Equal to the Yield Stress

$$S_C = A^{-1/8} W R^{1/4} b_c^{-1/2} t_c^{-7/4}$$

$$W = \frac{S_C A^{1/8} b_c^{1/2} t_c^{7/4}}{R^{1/4}}$$

$$W = 6118 \text{ lb}$$

Maximum Load on a 1-in.-diam Area to Produce a Longitudinal Stress Equal to the Yield Stress

$$S_1 = -0.150 A^{3/8} W R^{1/4} b_c^{-1/2} t_c^{-7/4}$$

$$W = \frac{S_1 b_c^{1/2} t_c^{7/4}}{0.150 A^{3/8} R^{1/4}}$$

$$W = 12,425 \text{ lb}$$

Maximum Deflection in Cylinder Wall Caused by Maximum Allowable Static Force of 6118 lb on 1-in.-diam Area in Center of Capsule

$$\text{Max } y = \frac{0.0820 A^{5/8} W R^{3/4} t_c^{1/2} t_c^{-9/4}}{E}$$

$$E = 1.5 \times 10^7 \text{ psi}$$

$$\text{Max } y = 0.020168 \text{ in.} = 0.001681 \text{ ft}$$

Dynamic Loading with 7000-g Bar Dropped from a Height of One Meter (Bar is 2.5 cm in diameter with rounded edges)¹⁰

Time of Free Fall

$$t = \sqrt{2s/g}$$

$$s = 1 \text{ meter} = 3.28 \text{ ft}$$

$$g = 32.16 \text{ ft/sec}^2$$

$$t = 0.204 \text{ sec}$$

Velocity at Impact

$$v = gt$$

$$v = 6.562 \text{ ft/sec}$$

Spring Constant of Capsule Considered as a Beam

$$k = 48EI/L^3$$

$$I = (\pi/64)(D_m^4 - d^4)$$

$$D_m = 4.1 \text{ in.}$$

$$d = 3.45 \text{ in.}$$

$$I = 6.917 \text{ in.}^4$$

$$E = 15 \times 10^6 \text{ psi}$$

$$L = 40.28 \text{ in.}$$

$$k = 76,204.7 \text{ lb/in.} = 914,456.7 \text{ lb/ft}$$

Maximum Dynamic Deflection of the Beam Due to Weight Being Dropped at Center

$$W_M = \frac{m_2 g}{k} \left(1 + \sqrt{1 + \frac{k v_2^2}{m_2 g^2}} \right)$$

$$m_2 = 15.432 \text{ lb}$$

$$g = 32.16 \text{ ft/sec}^2$$

$$k = 914,456.7 \text{ lb/ft}$$

$$v_2 = 6.562 \text{ ft/sec}$$

$$W_M = 0.0275 \text{ ft} = 0.33 \text{ in.}$$

Force Applied to Capsule

$$\text{Work} = \text{Work}$$

$$FD = fd = F W_M$$

$$F = 1840.6 \text{ lb}$$

This force is less than the maximum allowable force of 6118 lb. Therefore, no damage will result to the capsule from the drop of this bar onto the capsule.

Distortion of Capsule Due to 30-ft Free Fall onto its End¹⁰

$$\ln (\bar{x}_i)^2 = G(p_i) - G(p_1)$$

$$x_i = \bar{x}_i \ell$$

$$G(p_i) = \frac{1}{p_y} \left[p_i (1 + \ln \epsilon_i^*) - \int_{p_y}^{p_i} \ln \epsilon_i^* dp \right] - \ln \epsilon_i^*$$

p_1 is determined from

$$\rho v_1^2 = \epsilon_1^* (p_1 - p_y)$$

$$v_1 = at = gt \quad t = \sqrt{\frac{2s}{g}} = 1.366 \text{ sec}$$

$$v_1 = 43.927 \text{ ft/sec} = 527.1 \text{ in./sec}$$

$$\rho v_1^2 = 89,193.8$$

By trial and error select strain and stress from stress-strain curve and compute $\epsilon_1^* (p_1 - p_y) = 89,193.8$. (Compressive stress-strain curve for nickel-chrome steel was used.)

$$\epsilon^* = 0.46 \text{ in./in.}, p_1 = 4.15 \times 10^5 \text{ psi}, p_y = 2.2 \times 10^5 \text{ psi}$$

$$(0.46)(4.15 \times 10^5 - 2.2 \times 10^5) = 89,700 \approx 89,193.8$$

$$\therefore \epsilon_1^* = 0.46$$

$$p_1 = 4.15 \times 10^5 \text{ psi}$$

$$p_y = 2.2 \times 10^5 \text{ psi}$$

$$G(p_1) = \frac{1}{2.2 \times 10^5} \left[(4.15 \times 10^5)(1 + \ln 0.46) - \int_{2.2 \times 10^5}^{4.15 \times 10^5} \ln 0.46 dp \right] - \ln 0.46$$

$$G(p_1) = 1.8863$$

Values of $G(p_i)$ and $\bar{x}_i$ were calculated as tabulated below:

ϵ_i^* (in./in.)	p_i (psi)	$G(p_i)$	$\bar{x}_i$	x_i (in.)	Δt (in.)
0.46	4.15×10^5	1.8863	1.0	40.280	0.3
0.435	4.00×10^5	1.8182	0.9655	38.93	0.283
0.4	3.75×10^5	1.7045	0.913	36.78	0.260
0.3	3.2×10^5	1.4545	0.8058	32.46	0.195
0.2	2.8×10^5	1.2727	0.7358	29.63	0.130
0.1	2.5×10^5	1.0841	0.6696	26.97	0.065
0.01	2.2×10^5	1	0.642	25.86	0.0065

The change in wall thickness was determined from the permanent strain induced in the material due to the compressive load. Figure 3 is a plot of the variation of permanent compressive strain in the capsule resulting from a 30-ft free fall. Figure 4 is a drawing representing the distortion of the capsule due to the impact.

Fig. 3. Variation of Permanent Compressive Strain Along Length of Isotopes Kilowatt Program Capsule Due to 30-ft Free Fall.

Fig. 4. Isotopes Kilowatt Program Capsule Shape After Impact from 30-ft Free Fall.

SELECTION OF CAPSULE MATERIAL

Hastelloy C-276 was selected as the encapsulation material because of its good high-temperature properties and corrosion resistance to seawater. Since high temperatures from fire conditions are a primary threat to fuel containment, the relative inertness of Hastelloy C-276 at high temperatures is important.

Stellite Division, Cabot Corporation, investigated the air oxidation of Hastelloy C-276 (ref. 9) for 100 hr at static conditions. Tables 3 and 4 summarize their results. These data indicate that the air oxidation of Hastelloy C-276 is not appreciable until $\geq 2150^{\circ}\text{F}$.

Table 3. Results of Air Oxidation 100-hr Test of Hastelloy Alloy C-276

Temperature ($^{\circ}\text{F}$)	Oxidation Rate (mils/year)	
	Continuous	Intermittent
1800	9.5	9.7
1900	19.2	15.7
2000	142	253

Table 4. Weight Change of Hastelloy C-276 at 2150°F

Duration of Test Period (continuous)	Weight Change (mg/cm^2)
15 min	5.2
30 min	9.0
1 hr	13.3
2 hr	18.4
6 hr	23.6

Additional data taken by the author emphasizes the strong temperature dependency for oxidation of Hastelloy C. Table 5 summarizes the results of prolonged exposure of 24 identical Hastelloy C coupons in flowing air at 1832°F and 2000°F .

Compatibility between $^{90}\text{SrTiO}_3$ and Hastelloy C has been demonstrated by several operational SNAP systems, notably the SNAP-7 series. Inspection of the SNAP-7A fuel capsules did not reveal any evidence of chemical incompatibility of the fuel and capsule after 6 years of operation at 540°C .

Table 5. Oxidation of Hastelloy C

Exposure Time (months)	Percent Weight Loss Due to Oxidation at Environmental Temperatures of	
	1832°F (1000°C)	2000°F (1093°C)
1	0.05 (gain)	22.43
2	0.03	26.97
3	0.05	44.07
4	0.69	48.5
5	0.61	52.83
6	0.9	75.4
7	1.2	70.15
8	0.84	78.9
9	2.39	88.5
10	0.69	86.45
11	1.01	80.7
12	1.36	87.2

In other tests by the ORNL Metals and Ceramics Division,¹¹ specimens of Hastelloy C have been exposed to nonradioactive SrTiO₃ for periods of 1000, 5000, and 10,000 hr at 1100°C and for 10,000 hr at 900°C. The data indicate that ⁹⁰SrTiO₃ is compatible with Hastelloy C. Weight changes were small and no gross interactions were apparent. Table 6 is a summary of the type and depth of reaction in superalloys exposed to nonradioactive strontium compounds at 1100°C. Table 7 is a summary of 900°C results. At the present time there are no data on compatibility samples exposed to radioactive materials at the temperatures of interest here. While data available from the nonradioactive tests and from the lower temperature units that have been built do not indicate that any problems exist, the missing data should be obtained. These data will be obtained early in the development program prior to building the unit.

Some loss of strength and ductility occurred in aged samples of Hastelloy C heat treated at 900 and 1100°C. This was apparently due to the increase in grain size and the amounts of various phases that precipitate as a result of the particular heat treatment. However, as pointed out previously, once the capsule deforms about the fuel, the load-carrying capability of the combination becomes extremely large and no further plastic flow of the combination can occur. Table 8 is a summary of these data.

Kubose et al.^{7,12} of the Naval Radiological Defense Laboratory (NRDL) have conducted a number of studies to evaluate seawater corrosion of SNAP container alloys. Laboratory and in-situ ocean tests were performed on SNAP-21 materials and electrically heated simulated fuel capsules. The effects of internal heat, high hydrostatic pressure, and ionizing radiation were investigated.¹³ The results of these studies indicate that the fuel capsule corrosion rate is very low (10⁻⁴ in./year). Galvanic coupling effects were also investigated and the fuel capsule (Hastelloy C-276) corrosion rate was found not to be significantly increased (3.8 x 10⁻¹

Table 6. Type and Depth of Reaction in Superalloys
Exposed to Nonradioactive Strontium Compounds at 1100°C

Fuel	Haynes Alloy No. 25						Hastelloy C						Type 316 Stainless Steel					
	1,000 hr		5,000 hr		10,000 hr		1,000 hr		5,000 hr		10,000 hr		1,000 hr		5,000 hr		10,000 hr	
	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)	Type ^a Reaction	Depth (mil)
BARE FUEL																		
SrTiO ₃	SV	10	SV	15	SV	12	SR	<1	SR	<1	SR	<1	SV	2	SR	<1	SR	<1
									SV	<1	GB	<1			SV	2	SV	2
Sr ₂ TiO ₄	SR	<1	SR	1	SR	2	SR	<1	SR	1	SR	1	None		SV	2	SV	4
			GB	1	GB	2												
SrO	GB	5	GB	7	GB	8	GB	4	GB	10	GB	10	GB	3	GB	5	GB	4
	SV	10					TG	4	TG	10	TG	10	TG	3	TG	5	TG	4
PLATINUM-JACKETED FUEL																		
SrTiO ₃									RZ	5	RZ	5						
											SV	30						
Sr ₂ TiO ₄									RZ	5	SR	2						
											SV	20						
SrO									GB	8	GB	8						
									TG	8	TG	8						
									SV	10	SV	30						

^aSV - subsurface voids, SR - surface roughening, GB - grain boundary attack, TG - transgranular attack, and RZ - reaction zone.

Table 7. Type and Depth of Reaction in Superalloys Exposed to Nonradioactive Strontium Compounds for 10,000 hr at 900°C

Fuel	Haynes Alloy No. 25		Hastelloy C		Type 316 Stainless Steel	
	Type ^a	Depth	Type ^a	Depth	Type ^a	Depth
	Reaction	(mil)	Reaction	(mil)	Reaction	(mil)
BARE FUEL						
SrTiO ₃	SV	5	SV	4	SR	3
					GB	3
Sr ₂ TiO ₄	SR	<1	SR	<1	None	
SrO	GB	2	GB	5	None	
	TG	2	TG	5		
			SL	1		
PLATINUM-JACKETED FUEL						
SrTiO ₃			SV	10		
Sr ₂ TiO ₄			SV	3		
SrO			GB	3		
			TG	3		
			SL	1		
			SV	10		

^aSV - subsurface voids, SR - surface roughening, GB - grain boundary attack, TG - transgranular attack, and SL - surface layer.

Table 8. Results of Room-Temperature Tensile Tests on Aged Hastelloy C

Treatment	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Elongation in 1 in. (%)
Anneal 1 hr at 1100°C	88,000	130,000	30
Anneal 1 hr at 1100°C + age 10,000 hr at 900°C	60,000	105,000	7
Anneal 1 hr at 1100°C + age 1000-10,000 hr at 1100°C	50,000	93,000	7 ^a

^aAverage of three tests at 1000, 5000, and 10,000 hr.

mil/year).¹⁴ The studies considered the most adverse exposure conditions, and corrosion of the fuel capsule is expected to be of no serious consequence.

Ocean exposure of two SNAP-21 bare fuel capsules is in progress¹⁵ at the Naval Undersea Research and Development Center (NVC). Two fuel capsules were prepared for this experiment and are in a shore-based seawater exposure tank.

The thermal shock requirement of IAEA Safety Series No. 33 is adequately met by this capsule as demonstrated in the heat treating and quenching of weld test specimens (see Appendix II) and thermal shock tests made on the SNAP-21 capsules by 3M Company.¹⁶ In these tests two SNAP-21 capsules were heated to 1850°F and immersed in water at 50°F. No failure modes were found.

The physical and chemical properties of Hastelloy C-276 are described in detail in Appendix II.

FUELING

A typical fueling procedure involves hot-pressing $^{90}\text{SrTiO}_3$ powder at a pressure of 3500 psig in a furnace heated to 2372°F. Nickel wire screens are inserted into the powder to reinforce the pressed pellet and to provide heat transfer paths out of the pellet to eliminate thermal stressing of the pellet. Figure 2 is a drawing of the fuel pellet configuration to be used in the Isotopes Kilowatt Program source. The pellets are inserted in the Hastelloy C-276 capsule, the top cap is inserted, and the capsule is seal welded, cleaned as required to remove external contamination, and leak tested. The capsule is then ready for insertion into the heat exchanger.

The operations described above are conducted in shielded facilities having 3 to 4 ft of concrete shielding. All manual operations are performed using in-cell hoists and masterslave manipulators.

CAPSULE INSPECTION

Battelle Northwest Laboratory has conducted extensive research and development of ultrasonic techniques of inspecting radioisotope fuel capsules.¹⁷ This research has resulted in the development of a high efficiency, spherically focused, broadband, ultrasonic transducer ideally suited for isotopic source testing and has already been applied to SNAP-21 and SNAP-23. This technique will be used to inspect the capsule bottom electron beam weld.

The sample to be analyzed is immersed in a liquid coupling medium on a turntable. The transducer is movable in lateral motions on the x- and y-axes. Therefore, a complete surface scan of the fuel capsule can be accomplished.

Data are recorded as a plane view of the capsule weld area as shown in Fig. 5. Each continuous line

Fig. 5. Recording of Ultrasonic Response from SNAP-21 Capsule Calibration Standard with Various Hole Sizes.

represents one circumferential path around the capsule, and the spacing represents a 0.006-in. index along the capsule axis. The lines are skewed so that a vertical deflection of the recorder pen (caused by discontinuity indications) can be detected.

The high sensitivity of the ultrasonic technique permits establishment of the following acceptance criteria for the bottom cap weld of the capsule. The depth of weld penetration is referred to as the longitudinal direction, and the circumferential path around the capsule is referred to as the transverse direction. Rejectable conditions are defined for welds with discontinuities having components in these two directions. Defects occurring within a 5° circumferential band are considered to be in the same longitudinal plane. These conditions assume an ultrasonic test sensitivity such that a signal equal to or greater than that received from the bottom of a 0.015-in.-diam electro-discharge-machined hole will be recorded. These criteria ensure a minimum thickness of weld from the exterior of the fuel of 0.120 in.

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Fig. 6. Fuel Capsule Bottom Cap Weld Zones.

Since the defects in the outer portion of the weldment are considered more critical than those appearing deeper, the acceptance criteria considered this aspect by dividing the weld into two zones as shown in Fig. 6.

The following conditions shall be cause for rejection:

1. Longitudinal Discontinuities

- a. Outer Weld Zone — An aggregate of discontinuities with components in a longitudinal plane totaling 0.040 in. or greater.
- b. Full Depth of Joint — An aggregate of discontinuities with components in a longitudinal plane totaling 0.070 in. or greater.

2. Transverse Discontinuities

- a. Outer Weld Zone — Any single discontinuity with a transverse component greater than 0.250 in. or an aggregate of discontinuities with transverse components totaling greater than 0.300 in. per inch of transverse length.

The threaded top cap seal weld will be leak tested to ascertain sealing of the capsule. A krypton leak test will be used. A detailed procedure of this test and a sample calculation are included in Appendix III. In this test the tracer gas (^{85}Kr) is incorporated into the capsule. The tracer gas escaping through a leak is collected in a chamber and is analyzed by conventional counting techniques. The leak rate is then calculated from the counting rate. The sensitivity of this leak test method is about 10^{-8} to 10^{-10} cm^3/sec (STP). Acceptance criteria for the Isotopes Kilowatt Program capsule will be less than 10^{-6} cm^3/sec (STP).

To assure the depth of penetration of the seal weld of the top cap, pre- and post-test welds shall be made on simulated capsules. These test welds are to be sectioned in at least four places upon completion and the depth of penetration of the weld verified. In this way the welding parameters of the capsule seal weld shall be verified and the seal weld shall be assumed of equal depth of penetration as the test welds. A depth of penetration of less than 0.055 in. in either of the test welds will be cause for rejection of the capsule weld and rewelding of the capsule shall be accomplished with test welds again being made as before.

APPENDIX I

Properties of $^{90}\text{SrTiO}_3$ (ref. 18)1. Half-life: 26.6 y2. Composition

a. Radionuclidic abundance

<u>Isotope</u>	<u>% Abundance</u>
^{90}Sr	55.0
^{88}Sr	43.9
^{86}Sr	1.1

These values were obtained by a mass-spectrometric analysis of fission-product strontium. Average molecular weight of fission-product strontium is 89.08.

b. Radiochemical purity

The principal radionuclide other than ^{90}Sr is ^{89}Sr ($T_{1/2} = 50.5$ d), whose content depends on the length of time since reactor discharge, as shown in the following table.

Calculated Ratios of $^{89}\text{Sr}/^{90}\text{Sr}$ Activities as a Function of Cooling Time Since Reactor Discharge with an Irradiation Time of 200 Days

<u>Cooling time, days</u>	<u>Ratio of activities $^{89}\text{Sr}/^{90}\text{Sr}$</u>
50	29
100	15
200	4.0
300	1.10
400	0.30

The ratio of ^{89}Sr to ^{90}Sr activities will decrease by a factor of ~ 2.0 for each 50 days of cooling time.

c. Chemical composition*

(1) Range of composition

<u>Cation</u>	<u>Maximum, wt %</u>	<u>Minimum, wt %</u>
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0

One gram of ^{90}Sr will produce an average of 0.0232 g of ^{90}Zr after one year's decay.

*Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

(2) Average chemical composition

<u>Metal oxide</u>	<u>Content, wt %</u>	<u>Titanate compound</u>	<u>Content, wt %</u>
SrO	52.5	SrTiO ₃	92.5
CaO	2.3	CaTiO ₃	5.6
BaO	0.5	BaTiO ₃	0.8
MgO	0.4	MgTiO ₃	1.1
TiO ₂	44.3		

The strontium metal content of pure fission-product SrTiO₃ is 48.16%.

The strontium metal content of average fission-product SrTiO₃ is 44.55%.

The as-processed SrTiO₃ will contain 24.5% ⁹⁰Sr. The ¹⁴⁴Ce constitutes 0.03% of the radioactivity at a maximum. The ¹³⁷Cs has been found to be as high as 0.003% of the total activity. The ¹⁰⁶Ru activity has not been found. These activities can be neglected compared to the bremsstrahlung radiation.

3. Specific Power

- a. 0.247 w/g of pure SrTiO₃ (26.5% ⁹⁰Sr metal)
0.235 w/g of average SrTiO₃ (24.5% ⁹⁰Sr metal)

It is assumed that there are 139 Ci/g of ⁹⁰Sr and 148.9 Ci of ⁹⁰Sr per thermal watt.

- b. 36.8 Ci of ⁹⁰Sr per gram of pure SrTiO₃ (26.5% ⁹⁰Sr metal)
34.1 Ci of ⁹⁰Sr per gram of average SrTiO₃ (24.5% ⁹⁰Sr metal)

4. Radiation

- a. Alpha particles

None

- b. Beta particles

<u>Nuclide</u>	<u>Max E, Mev</u>	<u>Av E, Mev</u>	<u>Abundance, %</u>	<u>w/kCi</u>	<u>Particles w⁻¹ sec⁻¹</u>
⁹⁰ Sr	0.546	0.1963	100	1.164	5.51 x 10 ¹²
⁹⁰ Y	2.284	0.9365	100	<u>5.551</u>	5.51 x 10 ¹²
Total power				6.715	

- c. Gamma

None

d. Bremsstrahlung

The high-energy bremsstrahlung photons from ^{90}Sr and ^{90}Y in matrices of SrO and SrTiO_3 are given in Tables 1-4. Sources of ^{90}Sr - ^{90}Y activities require slightly more shielding than sources of ^{137}Cs - ^{137}Ba activities because of the high energy of some of the bremsstrahlung radiation from ^{90}Y which emits a 2.27-Mev beta particle.

e. Neutrons

None

5. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

6. Compatibility with Materials of Containment

The compatibilities of various inactive strontium compounds with a number of container materials were determined and have been summarized in the following table.

Source material and exposure	Container material								
	Superalloys				Refractory metals				
	Hastelloy X	Haynes 25	Ni-o-nel	N-155	Mo	Nb	Ta	W	TZM
Strontium metal (Sr)									
1000°C, 1000 hr	SR	NR	SR	MR	NR		SR	NR	NR
1000°C, 5000 hr		MR		MR			SR	NR	
1000°C, 10,000 hr		MR	MR	MR	NR		SR	SR	
Strontium oxide (SrO)									
1000°C, 1000 hr	SR		SR	SR	NR	NR	SR	SR	
1850°C, 168 hr					SR	MR	SR	SR	
Strontium-9% beryllium oxide (SrO -9% BeO)									
1000°C, 1000 hr		MR	MR	SR	NR			NR	NR
Strontium fluoride (SrF_2)									
1000°C, 1000 hr	SR	SR	SR	SR	NR		SR	SR	
Strontium disilicide (SrSi_2)									
1000°C, 168 hr	DR	DR	DR	DR	DR		DR	DR	DR
Strontium titanate (SrTiO_3)									
1000°C, 1000 hr	SR	SR	SR	SR	NR		NR	NR	NR
1850°C, 1000 hr					NR	SR	SR	NR	MR
Legend: NR - Negligible or no reaction (compatible) SR - Slight reaction									
DR - Destructive reaction (incompatible) MR - Major reaction									

A number of reactions were dependent on time and temperature; for example, Haynes 25 with strontium metal showed no attack at 1000°C up to 1000 hr but fell into the major reaction classification after 5000 and 10,000 hr at 1000°C. This indicates that Haynes 25 should probably not be considered for use with strontium metal at temperatures >1000°C and times >5000 hr.

For periods up to 1000 hr at 1000°C, strontium metal showed little or no reaction with any metal except N-155, in which areas of severe subsurface void formation were found up to 22 mils.

At 1000°C SrO showed only slight surface oxidation reaction with most of the metals.

Strontium fluoride (SrF_2) showed very little attack with the metals tested.

At 1000°C SrSi_2 showed extensive reaction with Hastelloy X, Haynes 25, Ni-0-nel, and N-155. Molybdenum, tantalum, and TZM were resistant to penetration by silicon metal which formed from the dissociation of SrSi_2 at 1000°C.

Strontium titanate was compatible with all the container materials exposed at 1000°C. Molybdenum and tungsten were compatible at 1850°C, while niobium and tantalum had a slight reaction at this temperature. TZM reacted to a depth of 5 mils for a major reaction classification.

More extensive compatibility tests of Haynes 25, Hastelloy C, and type 316 stainless steel with inactive SrTiO_3 and Sr_2TiO_4 have not indicated any serious interactions after 1000 and 5000 hr at 1100°C. However, these materials were attacked to a maximum depth of 0.007 in. when exposed to SrO under the same conditions. It is believed that these latter results are due to reaction of the container materials with water vapor or excess oxygen dissolved in the SrO. Mechanical properties tests of specimens exposed to all three strontium compounds did not reveal any deterioration when compared with control specimens heat treated in argon under similar conditions of time and temperature.

7. Thermophysical Properties

a. Density

5.11 g/cm³ for pure SrTiO_3
5.03 g/cm³ for average SrTiO_3

b. Coefficient of thermal expansion

$\alpha = 11.2 \times 10^{-6}/^\circ\text{C}$ (100-700°C)

The coefficient of expansion of SrTiO_3 has been determined up to 1400°C with a Brinkman Model 5440 dilatometer. To simulate a typical radioactive strontium fuel, samples were prepared with a composition of 92 wt % Sr, 3.7 wt % Ca, 3.7 wt % Ba, and 0.3 wt % Mg. The hot-pressed SrTiO_3 sample was 1 in. in length and contained 5% excess TiO_2 over the stoichiometric ratio of $\text{SrO} \cdot \text{TiO}_2$.

The following table gives the values obtained for the mean coefficient of expansion for SrTiO_3 for the temperature intervals shown. The mean coefficient of expansion, A_m , is defined as

$$A_m(t_0, t) = \Delta l / l \Delta t ,$$

where

$A_m(t_o, t)$ = mean coefficient of expansion in the temperature interval, Δt , from t_o to $t^\circ\text{C}$,

Δt = temperature interval,

Δl = change in sample length over Δt ,

l = sample length at temperature $t_o^\circ\text{C}$.

Temperature interval, $^\circ\text{C}$	Mean linear coefficient of expansion for SrTiO_3
0-100	$10.8 \times 10^{-6}/^\circ\text{C}$
0-200	$10.7 \times 10^{-6}/^\circ\text{C}$
0-300	$10.7 \times 10^{-6}/^\circ\text{C}$
0-400	$10.8 \times 10^{-6}/^\circ\text{C}$
0-500	$10.9 \times 10^{-6}/^\circ\text{C}$
0-600	$11.0 \times 10^{-6}/^\circ\text{C}$
0-700	$11.1 \times 10^{-6}/^\circ\text{C}$
0-800	$11.2 \times 10^{-6}/^\circ\text{C}$
0-900	$11.3 \times 10^{-6}/^\circ\text{C}$
0-1000	$11.4 \times 10^{-6}/^\circ\text{C}$
0-1100	$11.6 \times 10^{-6}/^\circ\text{C}$
0-1200	$11.7 \times 10^{-6}/^\circ\text{C}$
0-1300	$12.0 \times 10^{-6}/^\circ\text{C}$
0-1400	$12.1 \times 10^{-6}/^\circ\text{C}$

c. Specific heat and enthalpy

(1) Specific heat in $\text{cal g}^{-1} ^\circ\text{C}^{-1}$

$$0.154 + 0.96 \times 10^{-5}T - 2.54 \times 10^{-3}T^{-2} \quad (^\circ\text{K})$$

(2) Enthalpy in cal/mole

$$H_T - H_{298} = 28.23T + 0.88 \times 10^{-3}T^2 + 4.66 \times 10^{-5}T^{-1} - 10,058 \quad (^\circ\text{K})$$

d. Temperatures of phase transformations

(1) Melting point

2040°C

(2) Boiling point

$2500\text{--}3000^\circ\text{C}$

(3) Phase changes at 1440 and 1640°C

e. Latent heats of phase transformations

ΔH vaporization = 71 kcal/mole (calculated from Trouton's rule)

f. Vapor pressure

g. Thermal conductivity

(1) $\text{SrO}:\text{TiO}_2 = 1.00$

The following equation was derived from data by a method of least mean squares:

$$1/k = 55.76 + 0.0673T \text{ (}^\circ\text{K)}$$

where k is the thermal conductivity in $\text{cal cm}^{-1} \text{ sec}^{-1} \text{ }^\circ\text{C}^{-1}$. The data covered the range 350 to 900°C . The useful range of equation is 200 to 1400°C .

Thermal conductivity, ^a $\text{cal cm}^{-1} \text{ sec}^{-1} \text{ }^\circ\text{C}^{-1}$	Temperature, $^\circ\text{C}$
0.0114 ± 0.0015	200
0.0099 ± 0.0003	400
0.0088 ± 0.0001	600
0.0078 ± 0.0001	800
0.0071 ± 0.0002	1000
0.0065 ± 0.0003	1200
0.0060 ± 0.0003	1400

^aDetermined on theoretically dense pellets of stoichiometric SrTiO_3 with a composition of 51.03 wt % SrO , 1.92 wt % BaO , 2.42 wt % CaO , 0.28 wt % MgO , and 44.35 wt % TiO_2 simulating a freshly prepared Hanford product.

(2) Thermal conductivity of various SrO-TiO_2 compositions

The curves in Fig. 1 were obtained by interpolating the data for the stoichiometric SrO , Sr_2TiO_4 , SrTiO_3 , and TiO_2 .

(3) Thermal conductivity of radioactive strontium titanate

Data were obtained on three hot-pressed pellets having 92, 92, and 98% theoretical densities with $\text{TiO}_2/\text{alkaline-earth oxide}$ mole ratios of 0.86, 0.95, and 1.25. The ages of the SrTiO_3 in the pellets were 0.5, 3.5, and 4.25 years. It was found that the age of SrTiO_3 and the variation in pellet composition and theoretical density did not have an effect on the results within the limit of experimental error. A single equation for the thermal conductivity as a function of temperature was derived from the data by the method of least mean squares:

$$1/k = 82.65 + 0.112T \text{ (}^\circ\text{K)}$$

where k is the thermal conductivity in $\text{cal cm}^{-1} \text{ sec}^{-1} \text{ }^\circ\text{C}^{-1}$.

Fig. 1. Thermal Conductivity of Various SrO-TiO₂ Compositions.

The data were measured over a range of 350 to 850°C and are considered usable from 200 to 1400°C. Values of k as a function of temperature are given below at the 95% confidence level.

Thermal conductivity, cal cm ⁻¹ sec ⁻¹ °C ⁻¹	Temperature, °C
0.00737 ± 0.00090	200
0.00632 ± 0.00025	400
0.00554 ± 0.00015	600
0.00493 ± 0.00016	800
0.00444 ± 0.00023	1000
0.00403 ± 0.00028	1200
0.00370 ± 0.00031	1400

h. Thermal diffusivity

(1) 100% dense inactive SrTiO_3 pellet

Thermal diffusivity, ^a cm^2/sec	Temperature, $^{\circ}\text{C}$
0.0151	200
0.0124	400
0.0107	600
0.0093	800
0.0083	1000
0.0075	1200
0.0068	1400

^aThese values were calculated by dividing the thermal conductivity by the product of the specific heat and the density.

(2) Thermal diffusivity of radioactive strontium titanate (94.7% of theoretical density)

Thermal diffusivity, ^a cm^2/sec	Temperature, $^{\circ}\text{C}$
0.01068	200
0.00869	400
0.00739	600
0.00645	800
0.00574	1000
0.00511	1200
0.00461	1400

^aThese values were calculated by dividing the thermal conductivity by the product of the specific heat and the density.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

m. Crystallography

Cubic: $a = 3.899 \text{ kX}$

n. Solubilities

Leach rates were determined on five $^{90}\text{SrTiO}_3$ fuels having densities ranging from 62 to 92% of theoretical. The low

density samples were recovered from SNAP-7A fuel capsules after seven years of operation. The high density samples were prepared by hot pressing. The samples were intact after an immersion of 76 days in distilled water. The data were fitted to a single equation by a method of least squares and are presented in Fig. 2 with the 95% confidence limits. A single equation to represent the data is as follows:

$$\ln R = -0.5235 \ln T - 2.5987$$

where

R = leach rate, $\text{mg cm}^{-2} \text{ day}^{-1}$

T = time, days.

Fig. 2. Leach Rate of ⁹⁰SrTiO₃ as a Function of Time.

o. Diffusion rates

8. Mechanical Properties

a. Hardness

b. Crush strength

19,100 lb/in.²

c. Bend strength

43 lb/in.²

9. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

$$\Delta H_f^\circ = -399 \text{ kcal/mole}$$

(calculated from available data)

(2) Free energy of formation

$$\Delta F_f^\circ = -379 \text{ kcal/mole}$$

(calculated from available data)

(3) Entropy

$$S_{298}^\circ = 26.0 \text{ eu}$$

b. Chemical reactions and reaction rates

(1) Oxygen - no reaction

(2) Nitrogen - no reaction

(3) Water - decomposes

(4) Inorganic acids - soluble

10. Biological Tolerances

Maximum Permissible Body Burdens and Maximum Permissible Concentrations
for Radionuclides in Air and in Water for Occupational Exposure

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max permissible burden in total body, q(μ Ci)	Max permissible concentrations, μ Ci/cm ³			
			For 40-hr week		For 168-hr week	
			Water	Air	Water	Air
⁹⁰ Sr (β^-)	<u>Bone</u>	<u>2</u>	<u>4×10^{-6}</u>	<u>3×10^{-10}</u>	<u>10^{-6}</u>	<u>10^{-10}</u>
	(Sol) { Total Body	<u>20</u>	10^{-5}	9×10^{-10}	4×10^{-6}	3×10^{-10}
	GI (LLI) ^a		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
	(Insol) { <u>Lung</u>			<u>5×10^{-9}</u>		<u>2×10^{-9}</u>
	GI (LLI) ^a		<u>10^{-3}</u>	2×10^{-7}	<u>4×10^{-4}</u>	6×10^{-8}

^aThe abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

11. Shielding Data

Bremsstrahlung dose rates from ⁹⁰Sr power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 w with iron, lead, and uranium shielding are given in Figs. 3-6 for a SrTiO₃ matrix. These sources require significant shielding because of the high energy of some of the photons from the bremsstrahlung radiation.

Fig. 3. Bremsstrahlung Dose Rates from Unshielded Isotopic Power Sources of Strontium-90 (Strontium Titanate) as a Function of Distance from Center of Source.

Fig. 4. Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

Fig. 5. Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

Fig. 6. Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point of separation of distance = 100 cm.

Table 1. Production of Bremsstrahlung Photons
from Strontium-90 Beta in Strontium Oxide Matrix

Maximum beta-particle energy		0.545 Mev
Average beta-particle energy		0.201 Mev
Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons $w^{-1} \text{ sec}^{-1}$
0.020 $\pm$ 0.01	1.378×10^{-2}	7.58×10^{10}
0.040 $\pm$ 0.01	5.523×10^{-3}	3.04×10^{10}
0.060 $\pm$ 0.01	2.998×10^{-3}	1.65×10^{10}
0.080 $\pm$ 0.01	1.841×10^{-3}	1.01×10^{10}
0.100 $\pm$ 0.01	1.208×10^{-3}	0.66×10^{10}
0.120 $\pm$ 0.01	8.239×10^{-4}	0.45×10^{10}
0.140 $\pm$ 0.01	5.759×10^{-4}	3.17×10^9
0.160 $\pm$ 0.01	4.086×10^{-4}	2.25×10^9
0.180 $\pm$ 0.01	2.923×10^{-4}	1.61×10^9
0.200 $\pm$ 0.01	2.099×10^{-4}	1.15×10^9
0.220 $\pm$ 0.01	1.505×10^{-4}	0.83×10^9
0.240 $\pm$ 0.01	1.074×10^{-4}	0.59×10^9
0.260 $\pm$ 0.01	7.604×10^{-5}	0.42×10^9
0.280 $\pm$ 0.01	5.315×10^{-5}	2.92×10^8
0.300 $\pm$ 0.01	3.654×10^{-5}	2.01×10^8
0.320 $\pm$ 0.01	2.458×10^{-5}	1.35×10^8
0.340 $\pm$ 0.01	1.609×10^{-5}	0.88×10^8
0.360 $\pm$ 0.01	1.016×10^{-5}	0.56×10^8
0.380 $\pm$ 0.01	6.135×10^{-6}	3.37×10^7
0.400 $\pm$ 0.01	3.491×10^{-6}	1.92×10^7
0.420 $\pm$ 0.01	1.835×10^{-6}	1.01×10^7
0.440 $\pm$ 0.01	8.638×10^{-7}	0.48×10^7
0.460 $\pm$ 0.01	3.456×10^{-7}	1.90×10^6
0.480 $\pm$ 0.01	1.065×10^{-7}	5.86×10^5
0.500 $\pm$ 0.01	2.007×10^{-8}	1.10×10^5
0.520 $\pm$ 0.01	1.000×10^{-9}	5.50×10^3
0.540 $\pm$ 0.01	0.000	
Total bremsstrahlung energy, Mev/beta particle		1.411×10^{-3}

Table 2. Production of Bremsstrahlung Photons
from Yttrium-90 Beta in Strontium Oxide Matrix

Maximum beta-particle energy		2.27 Mev
Average beta-particle energy		0.944 Mev
Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons $w^{-1} \text{ sec}^{-1}$
0.100 $\pm$ 0.05	6.152×10^{-2}	3.38×10^{11}
0.200 $\pm$ 0.05	2.415×10^{-2}	1.33×10^{11}
0.300 $\pm$ 0.05	1.281×10^{-2}	0.70×10^{11}
0.400 $\pm$ 0.05	7.674×10^{-3}	4.22×10^{10}
0.500 $\pm$ 0.05	4.894×10^{-3}	2.69×10^{10}
0.600 $\pm$ 0.05	3.234×10^{-3}	1.78×10^{10}
0.700 $\pm$ 0.05	2.181×10^{-3}	1.20×10^{10}
0.800 $\pm$ 0.05	1.485×10^{-3}	8.17×10^9
0.900 $\pm$ 0.05	1.014×10^{-3}	5.58×10^9
1.000 $\pm$ 0.05	6.887×10^{-4}	3.79×10^9
1.100 $\pm$ 0.05	4.630×10^{-4}	2.55×10^9
1.200 $\pm$ 0.05	3.00×10^{-4}	1.65×10^9
1.300 $\pm$ 0.05	1.973×10^{-4}	1.09×10^9
1.400 $\pm$ 0.05	1.231×10^{-4}	0.68×10^9
1.500 $\pm$ 0.05	7.337×10^{-5}	4.04×10^8
1.600 $\pm$ 0.05	4.117×10^{-5}	2.26×10^8
1.700 $\pm$ 0.05	2.125×10^{-5}	1.17×10^8
1.800 $\pm$ 0.05	9.740×10^{-6}	5.36×10^7
1.900 $\pm$ 0.05	3.728×10^{-6}	2.05×10^7
2.000 $\pm$ 0.05	1.058×10^{-6}	5.82×10^6
2.100 $\pm$ 0.05	1.670×10^{-7}	9.19×10^5
2.200 $\pm$ 0.05	4.768×10^{-9}	2.62×10^4
Total bremsstrahlung energy, Mev/beta particle		2.814×10^{-2}

Table 3. Production of Bremsstrahlung Photons
from Strontium-90 Beta in Strontium Titanate Matrix

Maximum beta-particle energy		0.545 Mev
Average beta-particle energy		0.201 Mev
Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons $w^{-1} \text{ sec}^{-1}$
0.020 $\pm$ 0.01	1.009×10^{-2}	5.55×10^{10}
0.040 $\pm$ 0.01	4.044×10^{-3}	2.22×10^{10}
0.060 $\pm$ 0.01	2.195×10^{-3}	1.21×10^{10}
0.080 $\pm$ 0.01	1.348×10^{-3}	7.41×10^9
0.100 $\pm$ 0.01	8.845×10^{-4}	4.86×10^9
0.120 $\pm$ 0.01	6.034×10^{-4}	3.32×10^9
0.140 $\pm$ 0.01	4.217×10^{-4}	2.32×10^9
0.160 $\pm$ 0.01	2.993×10^{-4}	1.65×10^9
0.180 $\pm$ 0.01	2.141×10^{-4}	1.18×10^9
0.200 $\pm$ 0.01	1.537×10^{-4}	8.45×10^8
0.220 $\pm$ 0.01	1.103×10^{-4}	6.07×10^8
0.240 $\pm$ 0.01	7.871×10^{-5}	4.33×10^8
0.260 $\pm$ 0.01	5.571×10^{-5}	3.06×10^8
0.280 $\pm$ 0.01	3.895×10^{-5}	2.14×10^8
0.300 $\pm$ 0.01	2.678×10^{-5}	1.47×10^8
0.320 $\pm$ 0.01	1.801×10^{-5}	0.99×10^8
0.340 $\pm$ 0.01	1.179×10^{-5}	6.48×10^7
0.360 $\pm$ 0.01	7.448×10^{-6}	4.10×10^7
0.380 $\pm$ 0.01	4.497×10^{-6}	2.47×10^7
0.400 $\pm$ 0.01	2.559×10^{-6}	1.41×10^7
0.420 $\pm$ 0.01	1.345×10^{-6}	0.74×10^7
0.440 $\pm$ 0.01	6.333×10^{-7}	3.48×10^6
0.460 $\pm$ 0.01	2.534×10^{-7}	1.39×10^6
0.480 $\pm$ 0.01	7.807×10^{-8}	4.29×10^5
0.500 $\pm$ 0.01	1.472×10^{-8}	8.10×10^4
0.520 $\pm$ 0.01	7.336×10^{-10}	4.03×10^3
0.540 $\pm$ 0.01	0.000	
Total bremsstrahlung energy, Mev/beta particle		9.924×10^{-4}

Table 4. Production of Bremsstrahlung Photons
from Yttrium-90 Beta in Strontium Titanate Matrix

Maximum beta-particle energy	2.27 Mev	
Average beta-particle energy	0.944 Mev	

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons $w^{-1} \text{ sec}^{-1}$
0.100 $\pm$ 0.05	4.537×10^{-2}	2.50×10^{11}
0.200 $\pm$ 0.05	1.782×10^{-2}	0.98×10^{11}
0.300 $\pm$ 0.05	9.456×10^{-3}	5.20×10^{10}
0.400 $\pm$ 0.05	5.665×10^{-3}	3.12×10^{10}
0.500 $\pm$ 0.05	3.613×10^{-3}	1.99×10^{10}
0.600 $\pm$ 0.05	2.389×10^{-3}	1.31×10^{10}
0.700 $\pm$ 0.05	1.611×10^{-3}	0.89×10^{10}
0.800 $\pm$ 0.05	1.098×10^{-3}	6.04×10^9
0.900 $\pm$ 0.05	7.493×10^{-4}	4.12×10^9
1.000 $\pm$ 0.05	5.092×10^{-4}	2.80×10^9
1.100 $\pm$ 0.05	3.425×10^{-4}	1.88×10^9
1.200 $\pm$ 0.05	2.264×10^{-4}	1.25×10^9
1.300 $\pm$ 0.05	1.460×10^{-4}	8.03×10^8
1.400 $\pm$ 0.05	9.110×10^{-5}	5.01×10^8
1.500 $\pm$ 0.05	5.434×10^{-5}	3.00×10^8
1.600 $\pm$ 0.05	3.050×10^{-5}	1.68×10^8
1.700 $\pm$ 0.05	1.576×10^{-5}	8.67×10^7
1.800 $\pm$ 0.05	7.220×10^{-6}	3.97×10^7
1.900 $\pm$ 0.05	2.764×10^{-6}	1.52×10^7
2.000 $\pm$ 0.05	7.850×10^{-7}	4.32×10^6
2.100 $\pm$ 0.05	1.239×10^{-7}	6.81×10^5
2.200 $\pm$ 0.05	3.540×10^{-9}	1.95×10^4
Total bremsstrahlung energy, Mev/beta particle	2.078×10^{-2}	

APPENDIX II*

Properties of Hastelloy Alloy C-276

Outstanding Corrosion Resistance in the As-Welded Condition—HASTELLOY alloy C-276 is an improved wrought version of HASTELLOY alloy C. Alloy C-276 has the same excellent corrosion resistance as alloy C with vastly improved fabricability. This alloy resists the formation of grain-boundary precipitates in the weld heat-affected zone, thus making it suitable for most chemical process applications in the as-welded condition. Alloy C-276 also has excellent resistance to pitting, stress-corrosion cracking and to oxidizing atmospheres up to 1900 deg. F.

HASTELLOY alloy C-276 has exceptional resistance to a wide variety of chemical process environments. These include strong oxidizers such as ferric and cupric chlorides, hot contaminated mineral acids, solvents, chlorine and chloride-contaminated media (organic and inorganic), dry chlorine, formic and acetic acids, acetic anhydride, and sea water and brine solutions. It is also one of the few materials that will resist the corrosive effects of wet chlorine gas, hypochlorite, and chlorine dioxide solutions.

Precipitation Characteristics—The precipitation characteristics of alloy C-276 indicate that a much greater time is required to form precipitates in the grain boundaries than is required for alloy C. Precipitation occurs in alloy C in less than 10 seconds over a temperature spread from about 1500 deg. F. to over 1850 deg. F. Precipitation does not occur in alloy C-276 until after several minutes, and then in a very narrow temperature range for short-time precipitate formation compared to alloy C.

Fabricated by a Variety of Methods—HASTELLOY alloy C-276 can be forged, hot-upset, and impact extruded. Although the alloy tends to work-harden, it can be successfully deep-drawn, spun, press formed or punched. All of the common methods of welding can be used to weld HASTELLOY alloy C-276, although the oxy-acetylene process is not recommended when the fabricated item is intended for use in corrosion service. Special precautions should be taken to avoid excessive heat input when welding with submerged-arc. Fluxes containing carbon or silicon should not be used when welding alloy C-276 by the submerged-arc method.

Detailed fabricating information is available in the booklet, F-30,126, "Fabrication of HASTELLOY Alloys."

Heat-Treatment—Wrought forms of HASTELLOY alloy C-276 are furnished in the solution heat-treated condition unless otherwise specified. This heat-treatment insures maximum ductility, corrosion resistance and machinability. Alloy C-276 is solution heat-treated at 2100 deg. F. and rapid quenched. Parts which have been hot-formed should be solution heat-treated prior to final fabrication.

CHEMICAL COMPOSITION, PER CENT

Nickel	Cobalt	Chromium	Molybdenum	Tungsten	Iron	Silicon	Manganese	Carbon	Others
Balance	2.50*	14.50-16.50	15.00-17.00	3.00-4.50	4.00-7.00	0.05*	1.00*	0.02*	V-0.35* P-0.03* S-0.03*

*Maximum

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PHYSICAL PROPERTIES

Physical Property	Temp., deg. C.	Metric Units	Temp., deg. F.	British Units
Density	22	8.90 g./cu. cm.	72	0.321 lb./cu. in.
Melting Temperature	1323-1371		2415-2500	
Electrical Resistivity	24	130 microhm-cm.	75	51 microhm-in. (779 ohms per cir. mil. ft.)
Mean Coefficient of Thermal Expansion	24-93	11.2 microns/m. - deg. C.	75-200	6.2 microinches/in. - deg. F.
	24-204	12.0 microns/m. - deg. C.	75-400	6.7 microinches/in. - deg. F.
	24-316	12.8 microns/m. - deg. C.	75-600	7.1 microinches/in. - deg. F.
	24-427	13.2 microns/m. - deg. C.	75-800	7.3 microinches/in. - deg. F.
	24-538	13.4 microns/m. - deg. C.	75-1000	7.4 microinches/in. - deg. F.
	24-649	14.1 microns/m. - deg. C.	75-1200	7.8 microinches/in. - deg. F.
	24-760	14.9 microns/m. - deg. C.	75-1400	8.3 microinches/in. - deg. F.
	24-871	15.9 microns/m. - deg. C.	75-1600	8.8 microinches/in. - deg. F.
Thermal Conductivity	24-927	16.0 microns/m. - deg. C.	75-1700	8.8 microinches/in. - deg. F.
	-168	0.072 watt-cm./cm. ² - deg. C.	-270	50 Btu-in./ft. ² -hr. - deg. F.
	-73	0.087 watt-cm./cm. ² - deg. C.	-100	60 Btu-in./ft. ² -hr. - deg. F.
	-18	0.094 watt-cm./cm. ² - deg. C.	0	65 Btu-in./ft. ² -hr. - deg. F.
	38	0.103 watt-cm./cm. ² - deg. C.	100	71 Btu-in./ft. ² -hr. - deg. F.
	93	0.112 watt-cm./cm. ² - deg. C.	200	77 Btu-in./ft. ² -hr. - deg. F.
	204	0.130 watt-cm./cm. ² - deg. C.	400	90 Btu-in./ft. ² -hr. - deg. F.
	316	0.151 watt-cm./cm. ² - deg. C.	600	104 Btu-in./ft. ² -hr. - deg. F.
	427	0.170 watt-cm./cm. ² - deg. C.	800	117 Btu-in./ft. ² -hr. - deg. F.
	538	0.192 watt-cm./cm. ² - deg. C.	1000	132 Btu-in./ft. ² -hr. - deg. F.
	649	0.210 watt-cm./cm. ² - deg. C.	1200	145 Btu-in./ft. ² -hr. - deg. F.
	760	0.231 watt-cm./cm. ² - deg. C.	1400	159 Btu-in./ft. ² -hr. - deg. F.
	871	0.251 watt-cm./cm. ² - deg. C.	1600	173 Btu-in./ft. ² -hr. - deg. F.
Specific Heat (Calculated)	1000	0.268 watt-cm./cm. ² - deg. C.	1800	185 Btu-in./ft. ² -hr. - deg. F.
	1111	0.293 watt-cm./cm. ² - deg. C.	2000	195 Btu-in./ft. ² -hr. - deg. F.
Dynamic Modulus of Elasticity	Room 204 316 538 649	20.9 g./cm. ² x 10 ⁸ 19.9 g./cm. ² x 10 ⁸ 19.2 g./cm. ² x 10 ⁸ 18.6 g./cm. ² x 10 ⁸ 17.9 g./cm. ² x 10 ⁸	Room 400 600 800 1000	29.8 psi x 10 ⁶ 28.3 psi x 10 ⁶ 27.3 psi x 10 ⁶ 26.4 psi x 10 ⁶ 25.5 psi x 10 ⁶

IMPACT STRENGTH

Form	Condition	Typical Charpy V-Notch Impact Strength, ft. -lbs. at			
		-320° F	Room	392° F	752° F
Plate	Heat-treated at 2100 deg. F., Water Quenched	181	238*	239*	—
	As welded	91	219	—	187*

*Specimen did not break.

TENSILE DATA, ALL WELD METAL – 1 inch thick

Welding Process	Ultimate Tensile Strength, psi	Yield Strength at 0.2% Offset, psi	Elongation, per cent
Room Temperature			
Gas, Tungsten Arc	106,400	69,200	46
Metallic Arc, Coated Electrodes	105,500	66,400	57
Submerged Arc*	106,900	69,400	43
500 Deg. F.			
Gas, Tungsten Arc	86,700	59,200	31
Metallic Arc, Coated Electrodes	88,900	55,800	44
Submerged Arc*	93,400	59,600	38
1000 Deg. F.			
Gas, Tungsten Arc	81,600	53,700	45
Metallic Arc, Coated Electrodes	79,200	50,400	54

*Special precautions should be taken when using this method to weld alloy C 276

TENSILE DATA, WELDMENTS – 0.094 to 5/16-inch thick

Welding Process	Ultimate Tensile Strength, psi	Yield Strength at 0.2% Offset, psi	Elongation, per cent
Room Temperature			
Gas, Tungsten Arc	110,600	59,800	45
Metallic Arc, Coated Electrodes	109,500	56,000	46
Submerged Arc*	106,700	56,000	35
Gas, Metallic Arc, Pulsed	110,700	58,200	46
1000 Deg. F.			
Gas, Tungsten Arc	87,900	41,400	45
Submerged Arc*	81,300	36,100	35
Gas, Metallic Arc, Pulsed	85,100	38,900	44
1400 Deg. F.			
Gas, Tungsten Arc	69,900	37,100	28
Submerged Arc*	71,100	32,000	33

*Special precautions should be taken when using this method to weld alloy C-276.

TYPICAL TENSILE DATA

Form	Condition	Test Temp., deg. F.	Ultimate Tensile Strength, psi	Yield Strength at 0.2% offset, psi	Proportional Limit, psi	Elongation in 2 in., per cent
Sheet, 0.094 in. thick	Heat-treated at 2100 deg. F., Water Quenched	-320	143,100	82,500	57,500	48
		-150	128,900	69,300	45,200	51
		Room	115,600	58,400	33,000	56
		400	103,400	49,400	32,200	55
		600	101,800	45,700	35,100	64
		800	97,700	44,300	33,200	60
		1000	95,000	42,500	32,200	60
		1200	89,700	39,300	29,300	62
		1400	81,000	38,200	33,800	71
		1600	57,200	37,900	27,900	77
		1800	31,400	18,200	11,600	91
		2000	16,200	8,600	5,200	49
		2200	8,600	4,600	3,000	49
Welded Sheet, 0.094 in. thick Inert-gas, Tungsten-arc (No Filler)	Heat-treated at 2100 deg. F., Water Quenched before Welding	-320	137,500	82,000	53,400	43
		-150	128,900	71,400	44,500	41
		Room	112,600	60,000	40,500	48
		400	103,600	50,500	30,400	47
		600	96,300	45,000	29,200	46
		800	97,600	44,700	30,400	52
		1000	92,800	43,700	32,900	51
		1200	87,800	39,100	29,500	57
		1400	75,700	38,100	27,700	32
		1600	56,900	36,500	25,600	61
		1800	31,000	18,400	12,400	76
		2000	17,400	8,800	6,300	51
		2200	8,900	4,700	3,700	49
Plate, 3/4 in. thick	Heat-treated at 2100 deg. F., Water Quenched	Room	113,500	52,000	—	70
		400	101,700	44,100	—	71
		600	95,100	39,100	—	71
		800	93,800	33,500	—	75
		1000	89,600	31,700	—	74
		1200	86,900	32,900	—	73
		1400	80,700	30,900	—	78
		1600	63,500	29,900	—	92
		1800	39,000	27,000	—	127
Sheet, 0.094 in., original thickness	Cold-reduced	0 per cent				
		10 per cent				
		20 per cent				
		30 per cent				
		40 per cent				
		50 per cent				
		Room	116,900	63,000	48,400	67
		Room	129,700	92,200	66,900	48
		Room	148,100	129,100	92,800	26
		Room	169,800	157,100	108,500	15
		Room	193,800	182,900	130,300	9
		Room	210,100	195,400	144,100	7

STRESS RUPTURE DATA

Form	Condition	Test Temp., deg. F.	Stress, psi	Rupture Life, hours	Rupture Elongation, per cent
Sheet, 0.094 in. thick	Heat-treated at 2100 deg. F., Water-Quenched	1100	70,000	1626.5	27
		1200	45,000	550.5	61
		1200	50,000	292.6	58
		1200	57,000	79.1	61
		1200	60,000	70.2	61
		1200	65,000	41.7	53
		1350	25,000	297.9	91
		1350	35,000	56.2	121
		1350	37,000	7.3	72
		1350	45,000	12.5	83
		1400	30,000	9.7	104
		1500	18,000	58.5	140
		1500	20,000	41.1	152
		1500	25,000	12.8	126
		1600	7,000	1417.0	158
		1600	10,000	160.6	112
		1600	15,000	20.8	136
		1600	17,000	11.8	141
Plate, 3/8 in. thick	Heat-treated at 2100 deg. F., Water Quenched	1400	20,000	341.9	106
		1600	7,500	62.0	112
Plate, 3/4 in. thick	Heat-treated at 2100 deg. F., Water Quenched	1200	44,000	763.5	64
		1600	17,000	12.5	152
		1800	7,600	10.9	95
		1800	3,700	630.4	42

CREEP DATA, 0.094-inch SHEET*

Test Temp., deg., F.	Stress, psi	Initial Elongation, per cent	Time, hours, for total elongation of:					Total Elongation, per cent
			0.1%	0.2%	0.5%	1%	2%	
1200	57,000	10.0	—	—	—	—	—	61.2
1350	37,000	4.8	—	—	—	—	—	71.5
1350	45,000	2.9	—	—	—	—	—	83.1
1500	18,000	0.0	0.14	0.37	0.87	1.72	3.53	139.5
1500	20,000	0.05	0.04	0.18	0.57	1.21	2.50	152.4
1600	10,000	0.09	0.07	0.33	1.33	3.10	7.43	112.3
1600	15,000	0.13	—	0.04	0.15	0.34	0.84	135.6
1600	17,000	0.04	0.007	0.04	0.16	0.37	0.70	140.9

*Heat-treated at 2100 deg. F., water quenched.

OXIDATION DATA

Test Temperature, deg. F.	Average Oxidation Rate, mils per 100-hour test period	
	100 hours, continuous	100 hours, intermittent*
1800	0.11	0.11
1900	0.22	0.18
2000	1.62	2.88

*Eight periods of 3 hours and four 19-hour periods.

OXIDATION EFFECTS DURING HEAT-TREATMENT

Test Temp., deg. F.	Duration of test period (Continuous)	Weight Change mg/cm ²	Oxidation Rate, mils per test period
2150	15 min.	5.2	0.31
2150	30 min.	9.0	0.49
2150	1 hour	13.3	0.69
2150	2 hours	18.4	0.96
2150	6 hours	23.6	1.23

CORROSION DATA*

Media	Concentration, per cent by weight	Temp., deg. F.	Penetration Rate, mils per year		
			Unwelded**	As-welded***	Welded and Heat-treated**
Chromic Acid	10	Boiling	65	81	43
Formic Acid	20	Boiling	4.8	3.5	3.6
Hydrochloric Acid	10	150	21	20	21
Hydrochloric Acid	10	167	40	50	—
Hydrochloric Acid	10+0.1 FeCl ₃	167	39	45	—
Hydrochloric Acid	10+0.5 NaOCl	167	46	50	—
Hydrochloric Acid	3.5+8 FeCl ₃	190	—	5	—
Hydrochloric Acid	1.0+25 FeCl ₂	200	—	45	—
Hydrochloric Acid	0.1+2.5 FeCl ₂	150	—	nil	—
Nitric Acid	10	Boiling	16	17	17
Nitric Acid	10+3 HF	158	350	380	—
Sulfuric Acid	10	Boiling	15	14	18
Sulfuric Acid	85	167	17	17	—

*Determined in laboratory tests. It is recommended that samples be tested under actual plant conditions.

**Heat-treated at 2100 deg. F., water quenched.

***Gas tungsten-arc welded.

ACCELERATED QUALITY CONTROL CORROSION TESTS

Accelerated tests are used to assess the overall corrosion resistance of alloy C-276. Tests are conducted in an aggressive environment which is considerably more severe than that usually encountered in industrial processes. The object of the test is to determine rapidly, if the material is in the proper condition for plant service.

HCl Bend Test – Specimens are tested for one 24-hour period in boiling 10 per cent hydrochloric acid. The samples are then bent 180 degrees around a 2-T radius. Welded specimens are bent with the weld metal in tension and with the bend centered around the heat-affected zone. Bent specimens are examined at 10X for separation of grains caused by grain boundary corrosion. Typical corrosion rates for alloy C-276 are shown in the table below.

Ferric Sulfate Test – Specimens are tested for one 24-hour period in boiling 50 per cent sulfuric acid with 42 grams per liter of ferric sulfate added. The presence of grain boundary precipitates results in an accelerated corrosion attack. The maximum acceptable corrosion rate for alloy C-276 in this test is 0.040 inch per month (480 mils per year). Typical corrosion rates for alloy C-276 are shown in the following table.

Type of Test	Corrosion Rate, mils per year		
	Unwelded**	As-welded***	Welded and Heat-treated**
HCl Bend Test	225	234	229
	No grain separation noted when bent		
Ferric Sulfate Test	224	273	243

PITTING TESTS

Specimens tested in a solution of 5 per cent ferric chloride plus 10 per cent sodium chloride for one 72-hour period at room temperature. No pits were found on unwelded,** as-welded,** or welded and heat-treated** specimens.

STRESS-CORROSION

Stressed specimens were tested in a solution of boiling 42 per cent magnesium chloride representing an accelerated chloride stress corrosion cracking test. Alloy C-276 went over 1000 hours without cracking.

**Heat-treated at 2100 deg. F., water quenched.

*** Gas tungsten-arc welded.

APPENDIX III

Krypton-85 Leak Test Procedure¹⁹A. Krypton-85 Introduction

1. Insert the welded, cleaned source into a pressurization chamber and seal the chamber.
2. Evacuate the chamber and introduce a known amount of ^{85}Kr .
3. Pressurize the chamber with argon to ~3 atmospheres absolute.
4. Allow the system to stand for a pre-calculated period, with routine checks to assure that there is no gas leaking from the chamber (see example calculation).
5. Vent the chamber and remove the source.

B. Leak Test

1. Place the source in a clean test chamber and seal the chamber.
2. Fill the chamber with argon at atmospheric pressure; allow the system to stand for a pre-calculated collection period (see example calculation).
3. Attach an evacuated, calibrated ^{85}Kr counting chamber to an outlet on the test chamber and draw a fraction of the chamber atmosphere into the counting chamber.
4. Count the ^{85}Kr in the chamber and calculate the leak rate.

C. Calculations

1. The concentration of ^{85}Kr in the capsule internal atmosphere after a pressurization time of t_p seconds can be expressed as:

$$S = \frac{A_p t_p L}{V_c V_p} \mu\text{Ci}/\text{cm}^3$$

where

A_p = amount of ^{85}Kr added to the test chamber (μCi)

L = effective gas leak rate (cm^3/sec)

V_c = void volume in the capsule (cm^3)

V_p = void volume in the chamber (cm^3)

2. During a collection period of t_c seconds, the amount of ^{85}Kr leaking from the capsule into the test chamber is:

$$A_c = S t_c L \mu\text{Ci}$$

3. Since the leaked gas is collected in a closed chamber of volume V_t (cm^3), which is then sampled by means of a counting chamber of volume V_s (cm^3), the amount of ^{85}Kr in the counting chamber is:

$$A_s = \frac{A_c V_s}{V_t + V_s} \mu\text{Ci}$$

4. The ^{85}Kr in the counting chamber is determined by the counting on an instrument of efficiency e (counts/dis). So, for a count rate of C (counts/min), A_s can also be expressed by:

$$A_s = \frac{C}{2.22 \times 10^6 e} \mu\text{Ci}$$

5. By equating the two expressions for A_s and solving for A_c :

$$A_c = \frac{C(V_t + V_s)}{(2.22 \times 10^6 e)V_s} = St_c L$$

6. Substitution of the expression for S (from equation 1) into equation 5 gives:

$$L = \sqrt{\frac{C(V_t + V_s)V_c V_p}{(2.22 \times 10^6 e)V_s t_c t_p A_p}} \text{ cm}^2/\text{sec}$$

D. Example Calculation

1. Factors

The following values were determined by direct volume measurement, precalibration, and direct measurements prior to the leak testing of an actual radioactive source capsule.

$$\begin{array}{ll} V_t = 4650 \text{ cm}^3 & e = 0.01 \text{ counts/dis} \\ V_p = 690 \text{ cm}^3 & t_p = 7.42 \times 10^4 \text{ sec} \\ V_c = 60 \text{ cm}^3 & A_p = 1.05 \times 10^7 \mu\text{Ci} \\ V_s = 1070 \text{ cm}^3 & \end{array}$$

These values can be considered as constants for this particular leak test; so, the equation relating the leak rate to the collection time and count rate is:

$$L = \sqrt{\frac{1.28 \times 10^{-11} C}{t_c}}$$

2. Results

	<u>Test 1</u>	<u>Test 2</u>
Counting chamber background, counts/min	731	745
Collection time (t_c), sec	2.4×10^3	1.8×10^3
Count rate upper limit, ^a counts/min	5300	4300
Sample count rate, counts/min	786	804
Net ^{85}Kr (C), counts/min	55	59
Leak rate (L), cm^3/sec	$\sim 5 \times 10^{-7}$	$\sim 6 \times 10^{-7}$

^aFor leak of $5 \times 10^{-6} \text{ cm}^3/\text{sec}$.

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