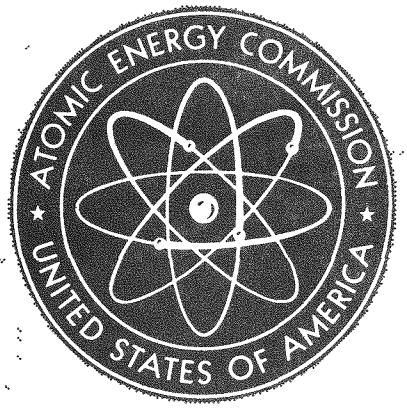

MND-P-2977

PRODUCTION OF STRONTIUM-TITANATE RADIOISOTOPE FUEL FOR SNAP 7B THERMOELECTRIC GENERATOR

Prepared by
Justin L. Bloom

April 15, 1963

Aerospace Division
Martin-Marietta Corporation
Baltimore, Maryland

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

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MND-P-2977
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TECHNOLOGY, (TID-4500, 24th Ed.)

PRODUCTION OF STRONTIUM-TITANATE RADIOISOTOPE FUEL FOR SNAP 7B THERMOELECTRIC GENERATOR

Prepared by:
Justin L. Bloom
Project Manager

For
Division of Isotopes Development
United States Atomic Energy Commission

Contract AT (30-1)-3062

April 15, 1963

ABSTRACT

The conversion of 225,000 curies of Strontium-90 to strontium titanate heat source pellets is described. Encapsulation of the fuel in 14 Hastelloy C containers and necessary leak testing, decontamination and calorimetry procedures are also covered.

Following completion of this first processing objective at the Quehanna Radioisotope Facility, loading of the SNAP 7B thermoelectric generator was accomplished on January 15, 1963.

CONTRIBUTORS

The work described in this report was performed by personnel of the Nuclear Chemistry Section under the technical direction of A. Schneider. The hot cell operations at Quehanna were managed by J. Cochran; analytical methods were developed by G. Samos, G. Pierson, J. Neace and J. Gray; remotely operated equipment was designed and built under the supervision of W. Ruehle, G. Torgeson, R. Rapp, W. McDonald and C. Young.

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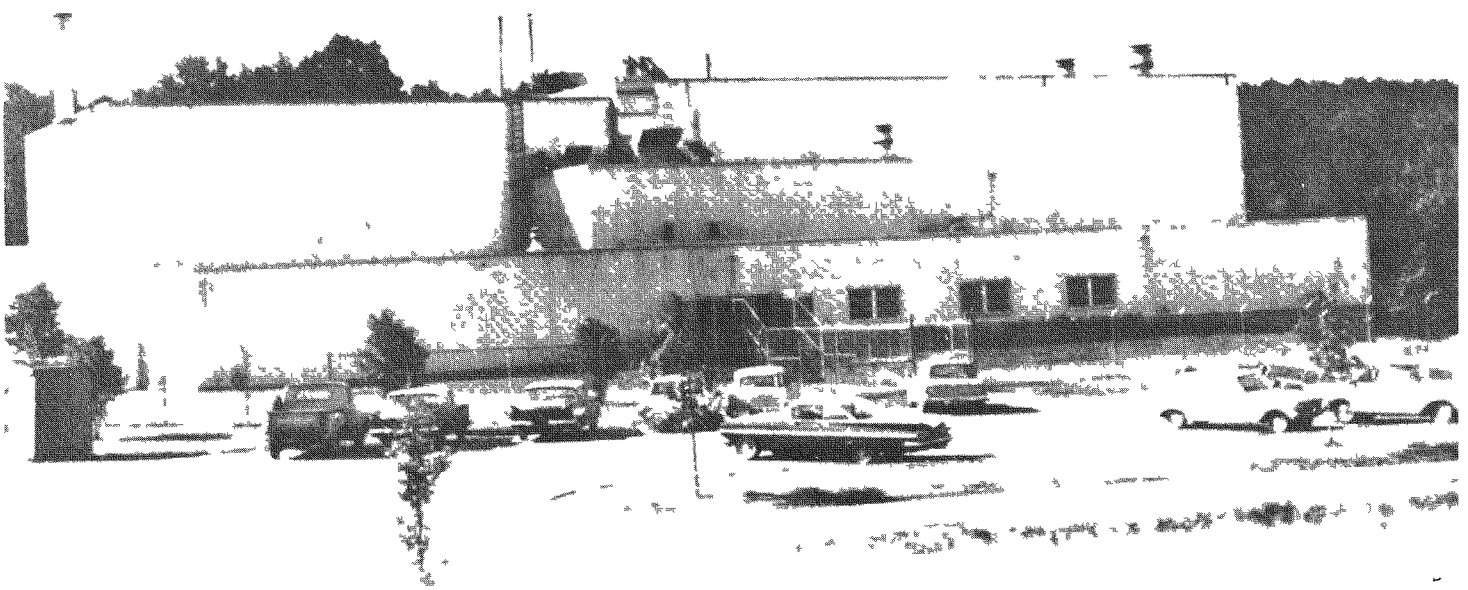

Quehanna Radioisotope Facility
Quehanna, Pennsylvania

I. INTRODUCTION

In October 1960, the Martin Company Nuclear Division began a program devoted to fabrication of four--later expanded to five--prototype thermoelectric generators which were to be used in various terrestrial applications. The generators, termed the SNAP 7 series, were to be fueled with Strontium-90 in the form of strontium titanate, and part of the program (sponsored by the Division of Reactor Development) consisted of establishing an industrial capability for the fabrication of the fuel. To meet this end, an existing, but unused, hot cell facility at Quehanna, Pennsylvania, was leased from the Pennsylvania State University. After decontamination of the cells and substantial modifications to the structure, installation of processing equipment began in September 1961, and was completed in June 1962.[1 to 8] During this interim period, the Fission Products Development Laboratory of Oak Ridge National Laboratory (ORNL) supplied the titanate fuel for generators which had been completed under the contract.[9]

A By-product Materials License,[10] authorizing the receipt, use, and storage of up to 500,000 curies of Strontium-90, was received from the Atomic Energy Commission's (AEC) Division of Licensing and Regulation in June 1962, and radioactive operations began in the following month under the sponsorship of the Division of Isotopes Development. All operations at the Quehanna facility which involve health and safety are inspected by the Division of Compliance. The facility is the first of its kind to be operated by private industry.

This report covers the processing of Strontium-90 from the beginning of hot cell operations to completion of the fuel for the SNAP 7B generator, and the subsequent loading of the generator on January 15, 1963. Future reports will describe the further conversion of Strontium-90 to pellets and powder for inventory purposes, pending requirements for loading additional generators.

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II. CRITERIA AND SPECIFICATIONS FOR FUEL FORM AND CAPSULE

A. FUEL FORM CRITERIA

There are several properties that must be considered in selecting the chemical form of a radioisotope to be employed as a massive heat source for terrestrial applications. These properties are:

(1) Low dissolution rate in sea water or fresh water. If, in the event of a catastrophic accident involving a system containing the radioactive heat source, the encapsulation barrier is ruptured, the rate of release of the radioisotope to the ecological environment will be significantly reduced by a relatively insoluble fuel form.

(2) High radioisotope concentration and material density. These two factors, when combined, determine the thermal power per unit volume of the source. Maximization of the so-called power density (expressed usually in watts/cm^3) tends to reduce the size and weight of the direct-conversion devices utilizing radioisotope heat sources.

(3) High melting point and good thermal conductivity. Typically, direct-conversion systems require heat sources which may reach internal temperatures in excess of 600° C. Problems of encapsulation and containment are magnified if the fuel compound is molten or partially molten at anticipated operating temperatures. Furthermore, the compound should be stable at elevated temperatures and in the intense radiation fields that it will experience.

(4) Ease of fabrication by remote techniques. The process by which the radioisotope is converted to the fuel form must be readily adaptable to hot cell operations and must afford relatively high yields and recoveries of the end product if the unit cost is to be kept within reasonable limits.

B. SELECTION OF STRONTIUM TITANATE AS FUEL FORM FOR STRONTIUM-90

A program to screen promising strontium fuel forms in terms of these criteria was carried out in the period 1958 to 1960.[11] In this program the following strontium compounds were evaluated:

Strontium aluminates--$SrO.Al_2O_3$ and $3SrO.Al_2O_3$

Strontium fluoride--SrF_2

Strontium oxide--SrO

Strontium silicates--$SrO.SiO_2$ and $2SrO.SiO_2$

Strontium sulfate--$SrSO_4$

Strontium sulfide--SrS

Strontium diorthophosphate--$SrHPO_4$

Strontium boride--SrB_6

Strontium zirconate--$SrO.ZrO_2$

Strontium titanate--$SrO.TiO_2$.

All except the last three were rejected as being completely inadequate in one or more respects. Considerable attention was then devoted to the boride, zirconate and titanate. The boride and zirconate were eliminated from consideration, since they were inferior to the titanate with respect to dissolution rate in water, potential power density and ease of fabrication. Strontium titanate became the form accepted by the USAEC.

C. PROPERTIES OF STRONTIUM TITANATE

The system $SrO-TiO_2$ was studied by Roy,[12] who compiled the first-phase diagram as shown in Fig. 1. The existence of the compounds Sr_2TiO_4 and $SrTiO_3$ has been confirmed. Of the two compounds, Sr_2TiO_4 would allow the achievement of greater power densities because of the greater strontium content; however, in preliminary tests $SrTiO_3$ appeared to be less soluble, and all subsequent work was restricted to this compound.

Strontium titanate is usually prepared by high temperature calcination of $SrCO_3$ and TiO_2, and the properties discussed below were determined for material obtained by this method.[11] The melting point of strontium titanate is 1910° C, and no phase transformations have been observed up to this temperature. The theoretical density is 5.11 gm/cm^3, which corresponds to a maximum strontium density

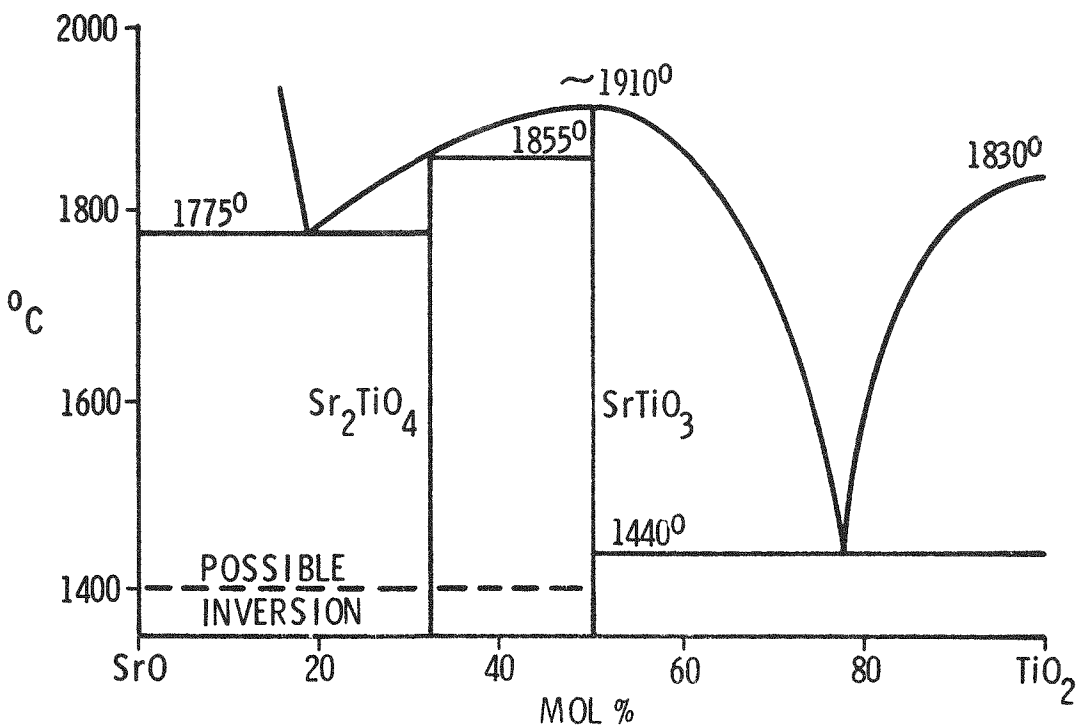

Fig. 1. $SrO\text{-}TiO_2$ Phase Diagram

of 2.44 gm/cm^3. The linear coefficient of thermal expansion varies from 9.4 x 10^{-6}/°C at 21° C to 11.2 x 10^{-6}/°C at 700° C. The thermal conductivity is dependent on the density of the specimens tested. A value of 0.0132 cal/(sec) (cm) (°C) was measured for material having a density 88.8% of theoretical, while a value of 0.0173 was obtained for a specimen with a density 94% of theoretical.

The rate of dissolution of strontium titanate in seawater over periods of time exceeding 100 days was studied by employing Strontium-90 as a tracer. Dissolution rates ranging from 0.71 to 1.28 micrograms of titanate per square centimeter of exposed surface per day of immersion were found.[13] More recently, comparable behavior was noted by Zigman with pellets containing Strontium-85 as the tracer material.[14] The dissolution rate of fully radioactive strontium titanate remains to be determined.

D. CRITERIA FOR SELECTING ENCAPSULATION MATERIAL; PROPERTIES OF HASTELLOY C

The most important criteria to be considered in the evaluation of potential metallic encapsulation materials for terrestrial applications are:

(1) Resistance to corrosive attack by air, fresh water and seawater.

(2) Suitably high melting point and good high-temperature mechanical properties.

(3) Chemical compatibility with the fuel form to be contained.

(4) Ease of fabrication.

(5) Reasonable cost and availability.

In an earlier materials evaluation program,[11] tungsten, molybdenum, and tantalum were considered and eliminated because they cannot be readily welded with a rod of the parent material. Nickel and Inconel likewise were considered and rejected because they showed a tendency to pit in seawater. Hastelloy C, on the other hand, met all requirements remarkably well. It finds extensive application in industry because of its excellent resistance to corrosion by chemical reagents and process fluids, and is essentially inert to attack by seawater. It is available in standard shapes and it can be fabricated by the usual techniques, including electrical welding by use of a parent

metal filler rod or by fusion. Its melting range of 1270° to 1305° C makes it compatible with present thermoelectric generator requirements. Extensive data on its mechanical properties as functions of temperature are available from the manufacturer, Union Carbide Stellite Company.

E. SPECIFICATIONS FOR SNAP 7B FUEL CAPSULES

From the point of view of optimum realization of electrical power over the useful life of the SNAP 7B thermoelectric generator, the following specifications were adopted for its fuel capsules:

(1) The radioisotope fuel was to provide a maximum of 1475 watts of thermal power at the time of generator loading.

(2) The minimum thermal power from the Strontium-90 isotope only was to be 1380 watts at generator loading.

(3) Capsule wall thickness and weld penetration were set according to the resistance to attack by seawater that was desired over a minimum 300-year period (accident condition only).

(4) Capsule exterior dimensions were established by specifying an internal volume sufficient to contain the desired thermal power at a minimum power density of 0.5 watt/cc, and by geometric considerations imposed by the thermoelectric generator (Fig. 2).

(5) The fuel was to be divided approximately equal among either 12 or 14 capsules, at the option of the fueling site. Permissible variation in power output from capsule to capsule was not to exceed ±10% of the average, except that if 14 capsules were utilized, the permissible variation applied to only 12 capsules and the residual power was to be distributed essentially equal between the remaining two.

(6) If the average power density of the fuel exceeded 0.5 watt/cc, steel spacers could be employed to fill the remaining voids in the capsules, provided that they were no thinner than 1/16 inch and were to be distributed as uniformly as possible among the fuel pellets.

(7) Upon loading a capsule, an axial gap no greater than 1/16 inch was to be left in the internal volume.

(8) The capsules were to be welded closed in a manner such that a minimum depth of penetration of 0.090-inch was obtained

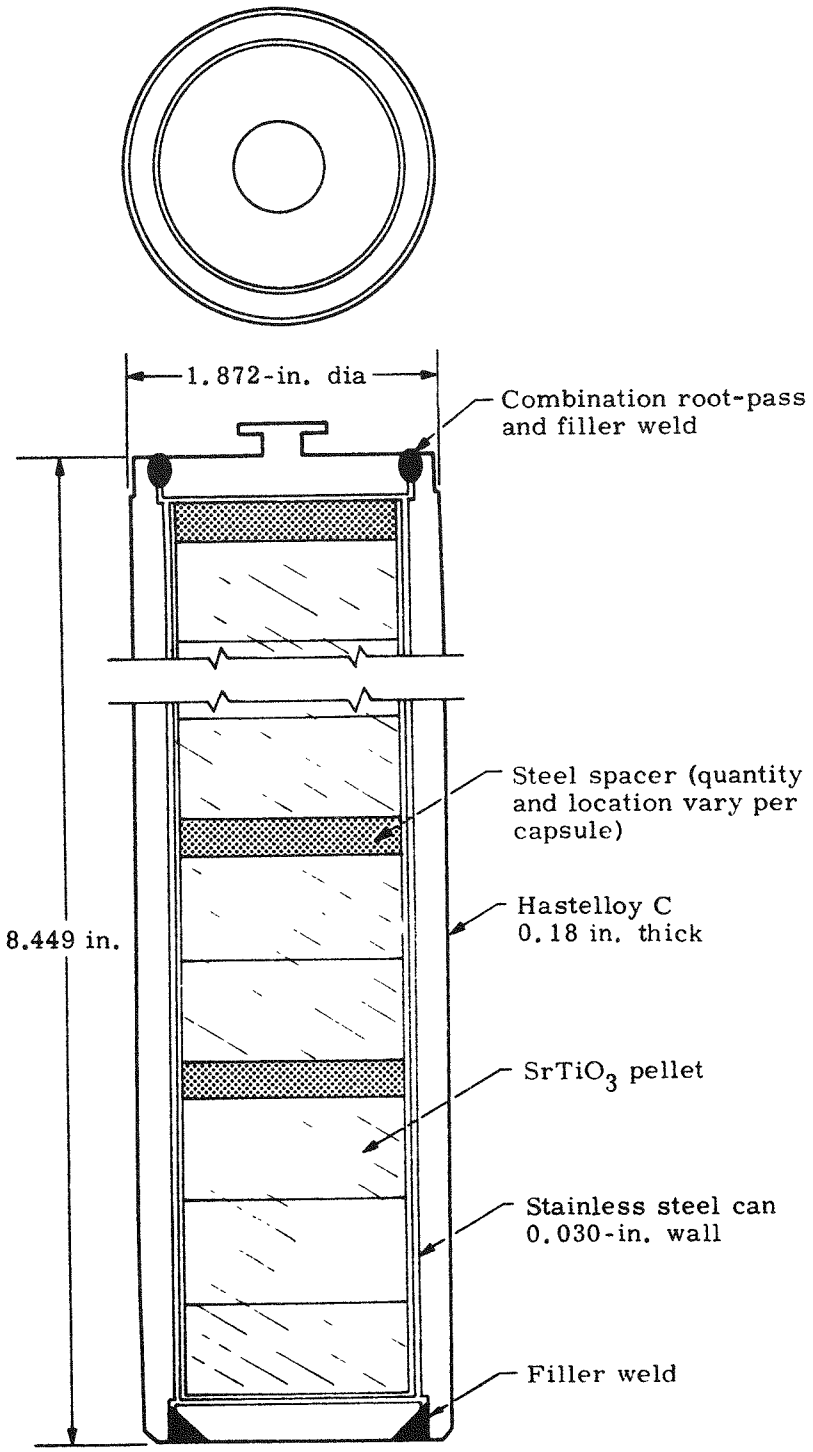

Fig. 2. SNAP 7B Fuel Capsule

and such that there would be no leakage of gas from the capsule as determined by testing equipment having a sensitivity of at least 10^{-6} cc/sec of helium (STP).

(9) Each welded capsule was to be decontaminated to less than 4000 dpm smearable, taken over the entire outer surface of the capsule.

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III. STRONTIUM TITANATE PROCESS DESCRIPTION

Purified Strontium-90 feed material is shipped to the Quehanna site from the Hanford Works in Richland, Washington, in special casks designed and fabricated for this purpose. Two casks (designated HAPO-II-1 and HAPO-II-2) are employed, each with a capacity to 170 kilocuries. The Strontium-90 is loaded into the casks at Hanford as a slurry of $SrCO_3$ in water, the solids being deposited on a screen within the cask (Fig. 3). Residual water is removed from the carbonate by evaporation. After decontamination and testing for leaks or internal pressure build-up, the cask is placed within a protective buffer (Fig. 4) and is transported on a flatbed rail car (Fig. 5) to Phillipsburg, Pennsylvania. Here the cask and buffer are transferred to a low-bed semitrailer truck for the remainder of the trip. Details of the cask design and safety evaluation may be found in reports issued by General Electric Company, Hanford Atomic Products Operation.[15, 16] Upon arrival at Quehanna, the nine-ton cask is transferred to a self-powered pallet truck and is moved into Cell 1 of the facility (Fig. 6). After a standard leak test is performed in accordance with Hanford specifications,[17] process lines are connected to the cask by quick-disconnect fittings. Manipulations are performed within a portable enclosure which is fitted to the top of the cask. Personnel then leave the cell, and subsequent processing is performed in general accordance with the flowsheet shown in Fig. 7. The carbonate is dissolved in dilute nitric acid, which is added by remote means. The CO_2 evolved is exhausted to the hot cell ventilation system after filtration to remove entrapped particulates. The solution is transferred by vacuum to a shielded and cooled storage tank located in Cell 1. When washing with dilute acid and water indicates that negligible activity is present in the cask, the cask is dried, leak-tested again, decontaminated manually and returned to Hanford.

The contents of the storage tank are sampled and the volume of the solution in the tank is measured by a bubbler-type liquid level indicator. Typically, a solution containing 2 to 3 curies/ml of Sr-90 in a total volume of 30 to 60 liters is obtained. Care is taken to minimize the volume of acid and water added, since this liquid ultimately becomes radioactive waste which must be removed from the site for disposal.

Increments of either 0.5 or 1.0 liter of solution are withdrawn from the storage tank by vacuum transfer to Cell 2, where all further chemical processing of Sr-90 is performed. The volume of each transfer is accurately controlled by use of a metering tank equipped with overflow weirs. When a volume of solution equivalent to

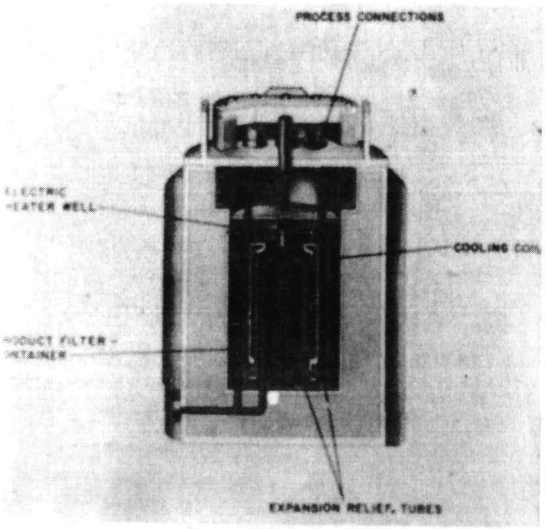

Fig. 3. HAPO II Shipping Cask

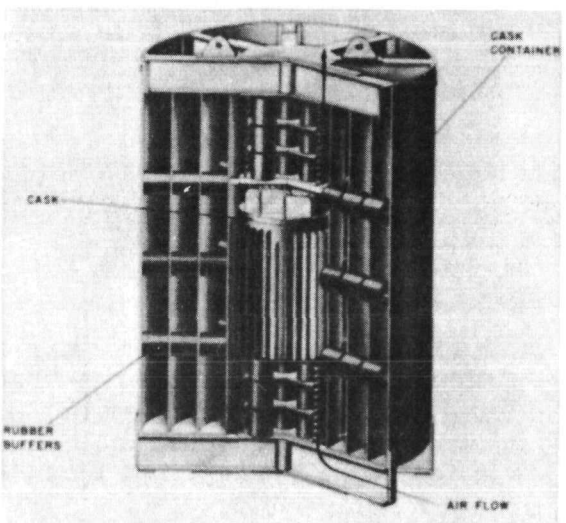

Fig. 4. Container for HAPO II Cask

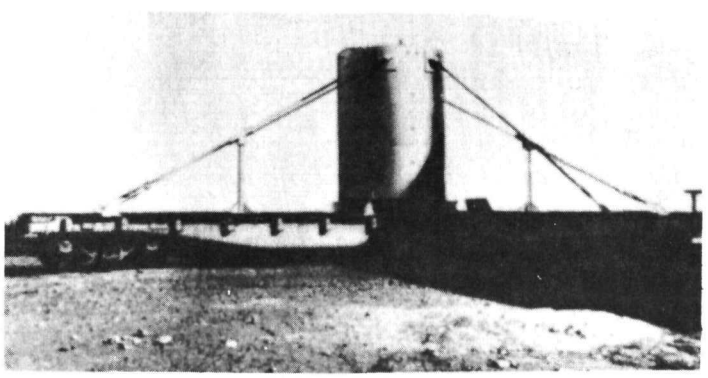

Fig. 5. Cask Assembly on Rail Car

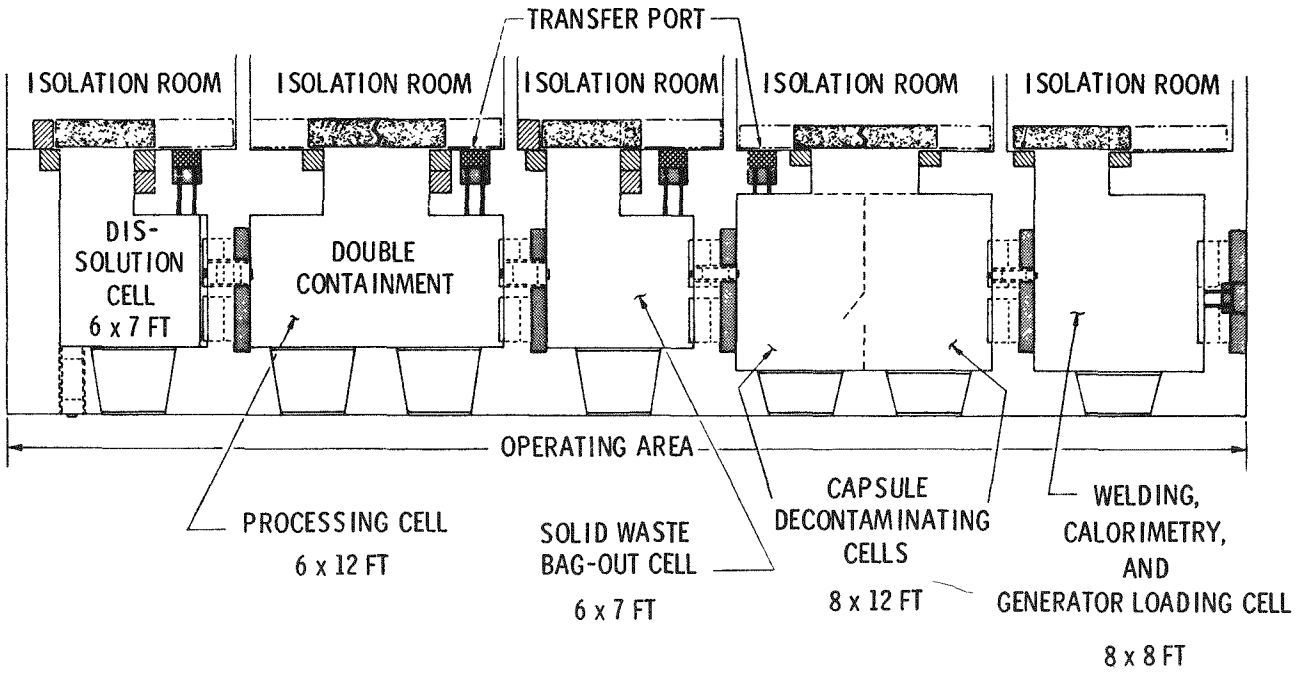

Fig. 6. Cell Layout--Quehanna

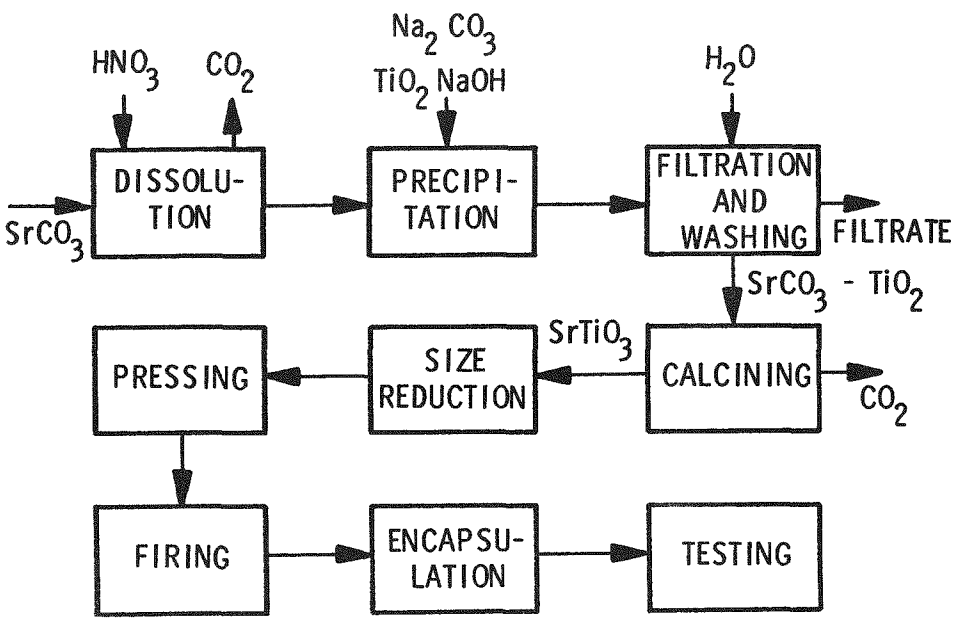

Fig. 7. Strontium Titanate Production Flowsheet

approximately 12 kilocuries has been transferred through the metering tank to a reaction vessel, the solution is neutralized with NaOH solution, and TiO_2 powder, in an amount equimolar to the quantity of alkaline earth cations, is added to the vessel by use of a manipulator. Air sparging is employed to mix reagents and to keep solids dispersed. Finally, an excess of Na_2CO_3 in dilute solution is added by a metering pump to precipitate the alkaline earth cations as carbonates. The resulting carbonate--TiO_2 slurry is thoroughly washed by decantation of the supernatant liquid and successive volumes of water, and the solids are removed from the remaining liquid by filtration through an alundum filter crucible. The crucible is heated in accordance with a prescribed temperature-time schedule in an electric furnace, and its contents are converted to the titanates of the alkaline earth elements present. After cooling to ambient temperature, the granules of titanate are reduced to powder in a modified Waring Blendor. Volumetric aliquots of the powder are transferred to the die of a hydraulically operated pellet press and are compacted into "green" pellets. On being subjected to a high temperature sintering cycle in the furnace, they are converted to the final fuel shape (Fig. 8).

Each pellet is weighed on a platform balance, and its diameter and height are measured in a fixture equipped with dial indicators. Its thermal power output is then determined to an accuracy of about 5% with a simple calorimeter. Cumulative weights and power outputs of the pellets from each process batch provide two different means for measuring recoveries and yields. All pellets which are structurally sound and within appropriate dimensional tolerances are stored in stainless steel tubes to await loading into capsules. The tubes are kept in a lead-walled safe within the processing enclosure to reduce the radiation dose to equipment. Off-specification or broken pellets are saved for ultimate reprocessing.

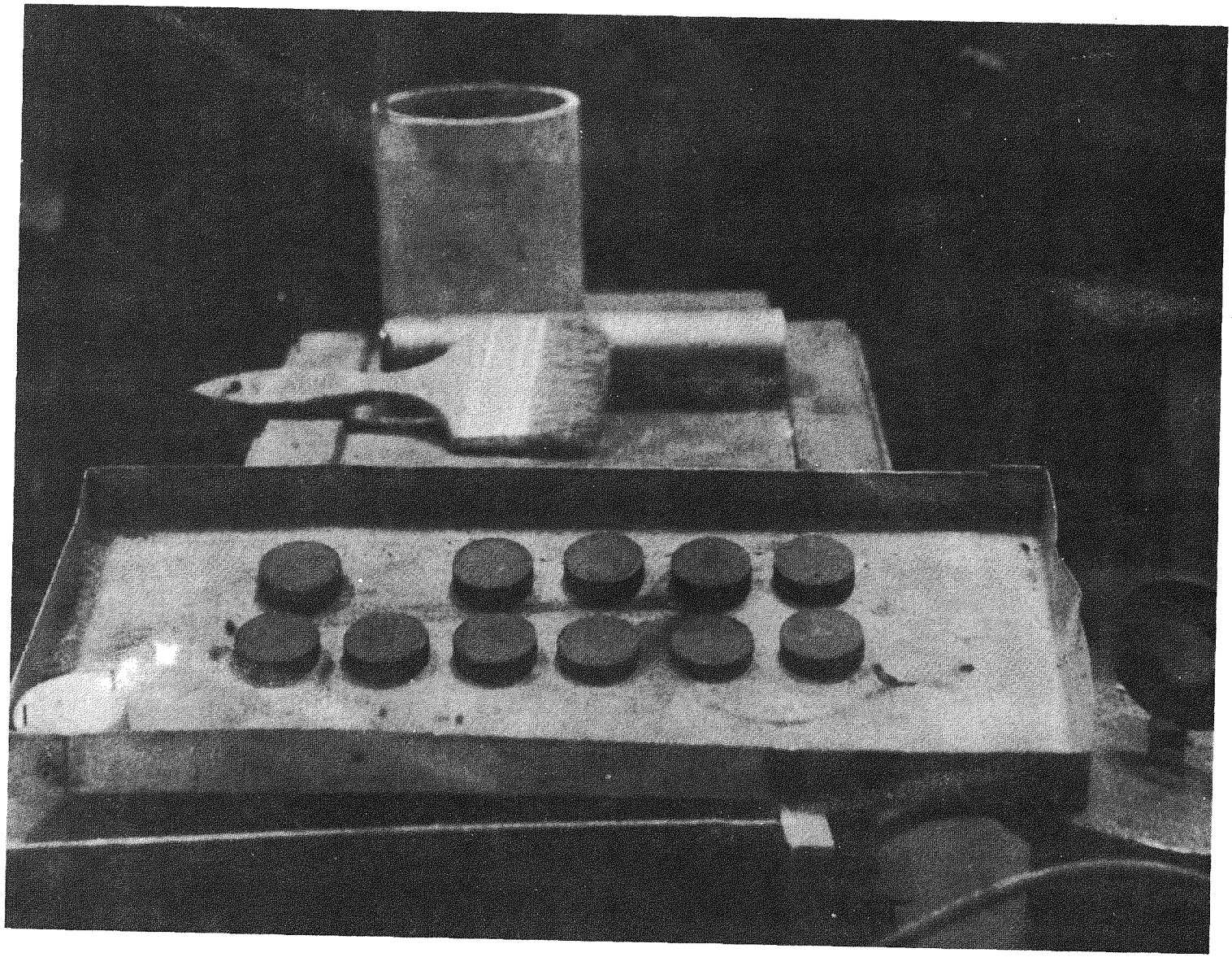

Fig. 8. $SrTiO_3$ Pellets

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IV. PROCESS OPERATIONAL EXPERIENCE

A. RECEIPT OF FEED MATERIAL

Three shipments of $SrCO_3$ were made from Hanford to provide sufficient feed for production of the SNAP 7B fuel. The analysis of each shipment, as reported by Hanford, is shown in Table 1[18, 19].

At Quehanna, the solutions resulting from dissolution of the contents of each cask were analyzed for Sr-90 concentration, Sr-89/Sr-90 ratio, total cations precipitated by the carbonate and free acid. From other measured or known factors, such as the volume of solution and the isotopic ratio of Sr-90 to total strontium, the number of curies received and the amounts of reagents to be added were computed.

Two alternative methods were employed to determine the Sr-89/Sr-90 ratio and Sr-90 concentration. In the first, strontium is separated from the bulk of the calcium and barium impurity by precipitation from concentrated nitric acid. Strontium nitrate is insoluble in concentrated nitric acid and leaves calcium and most of the barium in the supernatant solution. Barium chromate is insoluble in water solution and trace impurities of barium are removed by chromate precipitation after redissolution of the nitrate precipitate. Rare earths, present in trace amounts, are removed by an iron hydroxide scavenge from ammonium hydroxide solution. The purified strontium is precipitated as the oxalate.

An aluminum absorption curve is obtained, as soon as possible, for the beta radiation from the freshly separated precipitate. This curve is analyzed to resolve the Strontium-89 and Strontium-90 components.

In the second method, a carrier-free sample of radioactive strontium is prepared by passing the test solution through a bed of anion exchange resin in the hydroxyl form. Yttrium is retained as a hydroxide film on the resin beads, while strontium passes through the column. (Cesium and barium interfere, if present.)

The sample is radioassayed twice, once immediately after the separation and again after a period of about two days to allow the Yttrium-90 daughter of Strontium-90 to grow into the sample. Corrections are applied for Strontium-89 decay and for differences in counter efficiency for the beta particles from the nuclides. Strontium-89 and Strontium-90 activities are found by solving a pair of simultaneous equations, based on the radioassay data obtained from the sample as indicated.

TABLE 1

Strontium-90 Feed Analysis

Shipment No.	Curies Sr-90	Curie Ratio to Sr-90*				Sr-90 Isotopic Fraction	Weight Ratio to Total Strontium				
		Sr-89	Ce-144	Ru-106	Zr-95		Ca	Ba	Fe	Mn	Na**
1	170,000	0.07	2×10^{-3}	3×10^{-4}	3×10^{-4}	0.563	0.15	0.02	0.06	0.001	0.05
2	130,000	0.10	1×10^{-3}	6×10^{-4}	7×10^{-4}	0.563	0.19	0.005	0.005	0.05	0.10
3	94,000	0.005	3×10^{-3}	6×10^{-4}	9×10^{-4}	0.563	0.01	0.002	0.0032	0.018	--

*As of 5/1/62 for Shipments 1 and 2; as of 9/15/62 for Shipment 3

**Estimated

Measurement of total alkaline earths was made during the processing of the first batch from each cask. An accurately known amount of Na_2CO_3, considerably in excess of the amount anticipated to be required for precipitation of the cations, was added to a volume of solution that was equivalent to five or six kilocuries of Sr-90, after the solution had been neutralized with NaOH. The precipitate was filtered and washed in the conventional manner and the total filtrate was collected in a tank. A sample withdrawn from the filtrate was then analyzed by acid titration for carbonate concentration, and the content of alkaline earths was computed from the quantity of carbonate consumed. Since Sr-90 and total strontium were known from radiometric analysis, the difference obtained by the carbonate precipitation technique was assumed to be calcium--an accurate enough assumption for processing requirements.

Free acid in the feed solution was determined by microtitration of a 0.1-milliliter sample of the feed solution.

Analyses obtained for the three individual feed solutions are listed in Table 2[20,21,22].

Since a heel of solution is left in the storage tank from each preceding shipment, direct confirmation of the amount of Sr-90 received in each shipment cannot be made. However, calculations which take into account the volume and composition of the heel show good agreement, within limits of error of the analytical procedures, between the Quehanna and Hanford assays.

TABLE 2

Quehanna Feed Solution Analyses

Solution No.	Sr-90 (kc/liter)	Total Strontium (gm/liter)	Calcium (gm/liter)	Sr-89/Sr-90 Curie Ratio	Free Acid (N)
HR-1	2.02	25.4	7.72	0.016 (10/1/62)	0.85
HR-2	2.99	37.3	4.75	0 014 (10/1/62)	1.05
HR-3	3.02	37.7	2.96	0.00086 (1/15/63)	0.341

B. PROCESSING RESULTS

Typical chemical processing conditions and results for a representative batch of feed solution are depicted in Fig. 9. Inspection of actual conditions and results for the 30 batches processed (see Appendix A) will reveal that they varied markedly over the course of the program, but that progressive improvements in quality and yield of usable pellets were made. For convenience, a summary of pertinent information from the appendix is listed in Table 3.

The pellet quality in early batches suffered from two effects which were not apparent in dry runs and in tracer runs. First, the presence of residual sodium in the precipitate was found to affect adversely the characteristics of the calcination product, causing the formation of a hard, granular material which could not be easily reduced to powder in the blender. Increasing the number of water washes reduced the residual sodium content to a computed value of less than 1% and resulted in a calcination product that was easily comminuted to a free-flowing powder.

Second, it was determined that the highly radioactive precipitate in the filter crucible attained temperatures as much as 300° C higher than that indicated by the furnace thermocouples during the calcination step. A similar but smaller effect occurred during the sintering of pressed pellets. Reduction of the furnace temperatures accordingly improved the quality of both calcined and sintered products.

Recovery of usable pellets increased from 78% per batch in the processing of the first feed shipment to 93% per batch for the third shipment, due to improvements in manipulation and process conditions. It is not possible, under the restrictions of remote operation, to make individual Sr-90 materials balance calculations for each batch processed because of (1) deposition of material on walls of vessels and in process lines; (2) loss of small but significant amounts of titanate powder on equipment or supplies destined for waste burial; and (3) inability to make accurate measurements of the thermal power output of batches of titanate powder or broken pellets that are being reserved for future processing into usable pellets. However, a preliminary Sr-90 materials balance for the processing period from inception to January 15, 1963 is shown in Table 4. Simultaneously with the preparation of this report, more accurate figures are being determined and will be published in future reports on the progress of this program. Neglecting loss by decay, a maximum yield of Sr-90 in recoverable finished or intermediate products of 96% can be anticipated. A minimum yield of 91% will be expected if powder distributed through the equipment cannot be isolated and used.

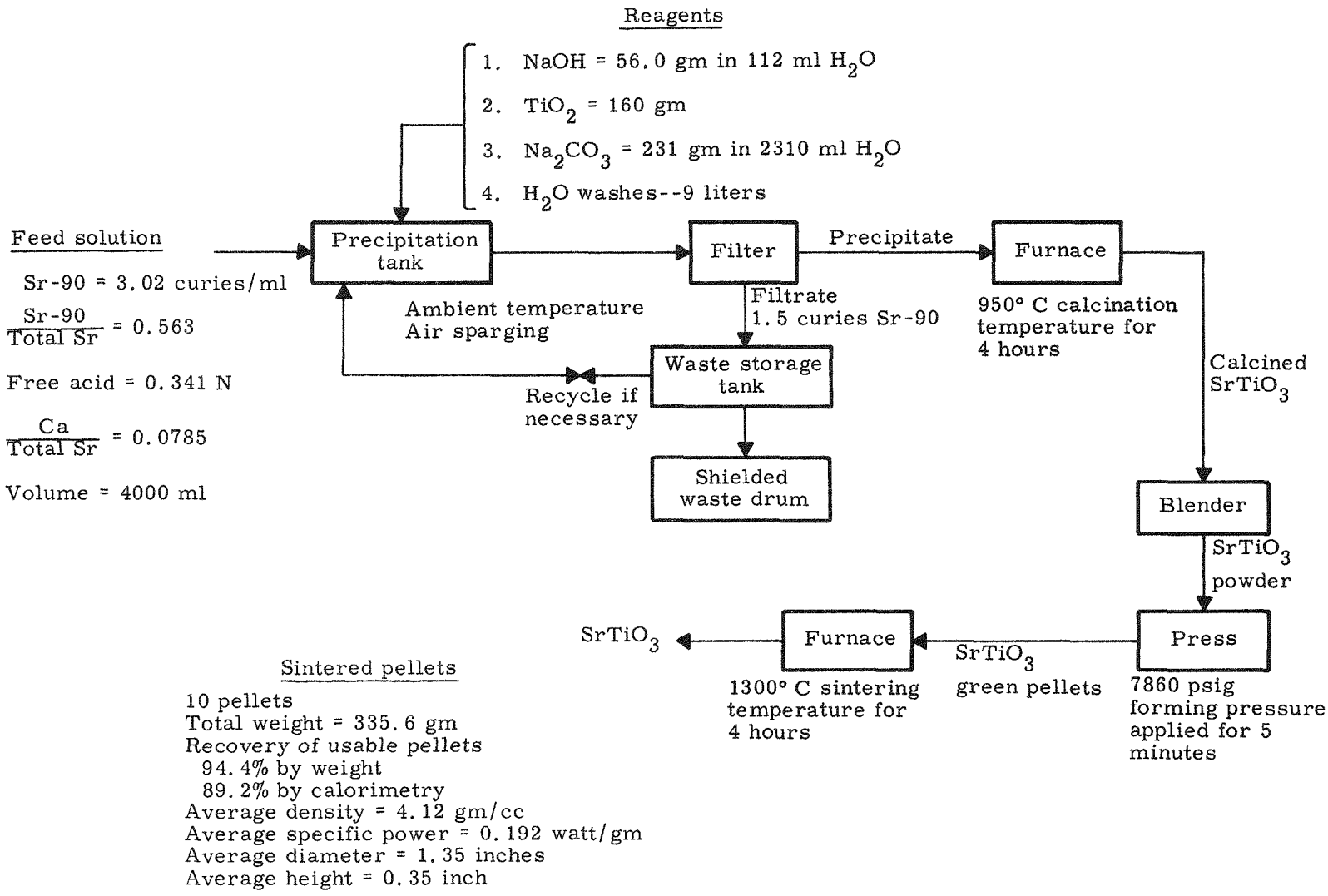


Fig. 9. Typical Chemical and Ceramic Processing Conditions in Cell 2

TABLE 3

Summary of Material Used in SNAP 7B

	Shipment 1 (HR-1)	Shipment 2 (HR-2)	Shipment 3 (HR-3)
Batches processed	14	12	4
Total pellets	93	110	36
Grams	3751.1	3756.4	1324.3
Watts	622.4	715.18	231.82
Average watts/gm	0.165	0.194	0.190
Watts/inch	11.41	17.31	16.86
Density	3.43	3.69	3.97
NOTES:	1 pellet lost from batch HR-1-6A*	2 pellets broken from batch HR-2-2B; scrapped	All pellets used
	2 pellets lost from batch HR-1-7B*	1 pellet too large to use from HR-2-3A; scrapped	
	1 pellet broken and scrapped from batch HR-1-7B	1 pellet lost from HR-2-3-B*	
	1 pellet recovered from batch HR-1-9A; remainder was spilled in the furnace when door was closed to start sintering cycle. After sintering, powder was swept up and put in scrap storage.	3 pellets from HR-2-6A broken; scrapped	
		2 pellets from HR-2-6B broken; scrapped	
	In run HR-1-6B, about 77% of powder contaminated with polyethylene. Stored for future recovery.		

*Four pellets recovered but individual identity not known; one pellet used in Capsule 13, one in Capsule 11, two stored for future use.

TABLE 4

Sr-90 Materials Balance as of January 15, 1963

(Preliminary)

Received:	394 kilocuries
Disposition:	
Loss by decay	5 kilocuries
Charged to SNAP 7B	225
Unused feed solution	57
Broken pellets	10
Good pellets not used in SNAP 7B	11
Calcined powder	40
Hold-up in precipitation tank*	10
Sent to waste**	20
Unaccounted for***	16
	394 kilocuries

*Conservative (low) estimate

**Estimate

***In process enclosure and in powder handling equipment

C. EQUIPMENT PERFORMANCE

1. Containment System

The spread of contamination from the multikilocurie operation is restricted by employing the philosophy of "double containment." That is, all process steps which involve the handling of exposed Strontium-90 compounds in any form are conducted within a primary stainless steel containment box located in Cell 2. The box occupies about nine feet of the lateral 12-foot dimension of the cell, the remaining space within the cell being equipped with stainless steel tanks, valves, and lines which permit transfers to the box to occur from Cell 1 or from the outside. The front and top of the box are equipped with double windows for viewing and external lighting, the inner windows being made of non-browning glass and the outer windows of 1-inch thick Plexiglas. The cell itself constitutes the second barrier against the release of Sr-90 to the manned area of the building. Air pressure in the box is maintained at 0.25-inch water less than the cell pressure, and the cell

pressure, in turn, is maintained independently at 0.50-inch water less than the ambient building pressure. Pressure balancing is accomplished dynamically by controlling air flow through a high capacity exhaust system. All air removed from the cells or from the box must pass through at least three high efficiency filters before being exhausted externally to the atmosphere.

This containment approach, while adding considerably to the safety of the operation, obviously complicates remote manipulation and the transfer of equipment and materials to and from the containment box.

To restrict uncontrolled air flow into the box and to reduce contamination, the master-slave manipulators (which penetrate the cell face and the front wall of the box) must be covered with plastic boots, the upper ends of the boots being sealed to the box wall by clamps operated from the manned area. Deposition of airborne radioactivity on the surfaces of the boots within the box causes such rapid deterioration that their usefulness is limited to approximately one week. Degraded boots are dropped into the containment box during the changing process and must be removed as highly contaminated dry waste. The volume of waste generated because of this circumstance was unexpectedly high and contributed to the early failure of the overhead transfer box.

The original concept of maintaining containment included two modes of entry to and egress from the box. The first, intended only for occasional use to replace large items of equipment, consisted of an arrangement whereby a separate steel overhead transfer box could be remotely mated to the top of the containment box after removal of the top shield plugs of the cell. A complex mechanism then sealed a door in the bottom of the transfer box to a door in the top of the containment box. Both doors were retracted into the interior of the transfer box. After introduction of materials to the transfer box by means of a small hoist, the door opening operation was reversed, and the transfer box was removed to another location for controlled discharge. After some 30 such operations during a three-month period, principally to remove manipulator boots, the door mechanism failed beyond repair. A stationary transfer system was promptly designed and built. This system permits controlled transfers of waste from Cell 2 to Cell 3 through an overhead tunnel. The tunnel was prefabricated in sections, aluminum being the principal structural material. This achieved a reduction in weight, simplified installation problems and reduced the intensity of penetrating bremsstrahlung generated by contamination on its inner surfaces. A horizontal bridge crane with fixed hoist in the lateral branch of the tunnel enables buckets containing waste to be raised vertically in Cell 2, moved horizontally to a position over Cell 3, and lowered directly into shielded waste drums in that cell. This system has operated without incident since its installation (Figs. 10 and 11).

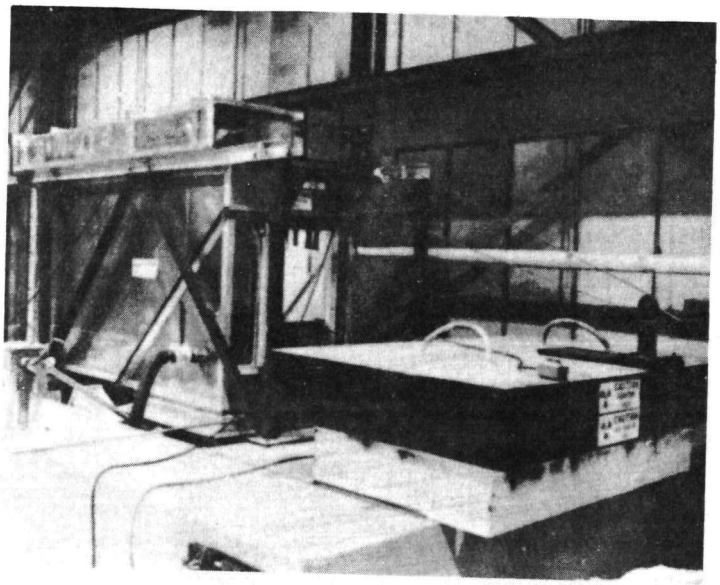
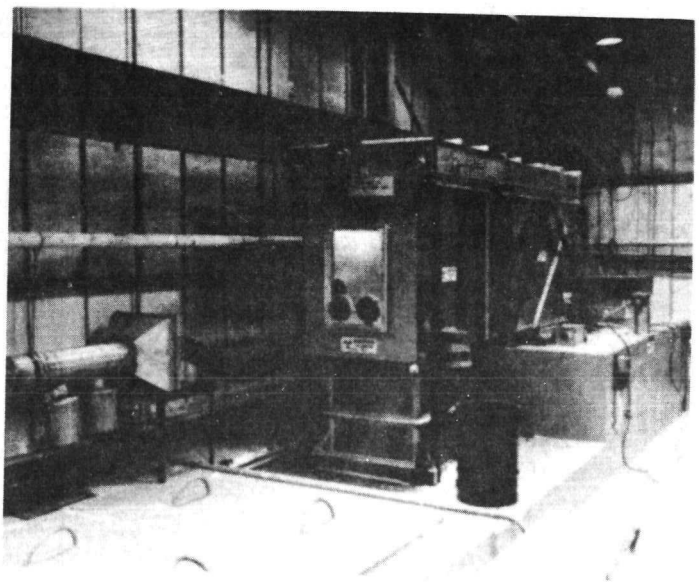


Fig. 10. Stationary Overhead Transfer System

Fig. 11. Stationary Overhead Transfer System



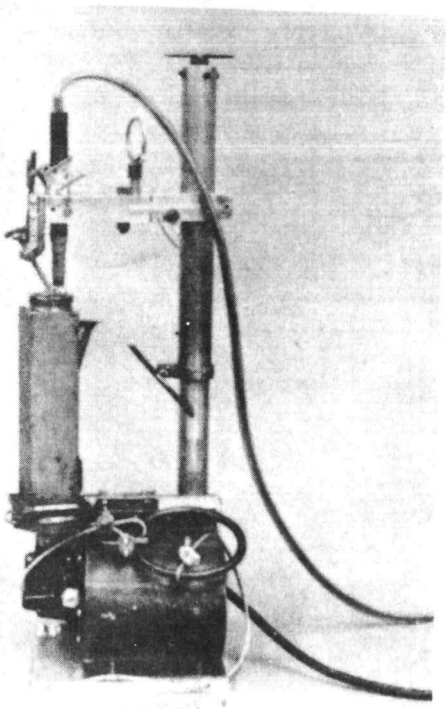


Fig. 12. Capsule Welder

The second mode of egress and entry was patterned after the Los Alamos "alpha" transfer system, in which double doors are also used to prevent escape of radioactivity. It was intended to provide a means by which loaded capsules could be moved in sealed cans from Cell 2 to Cell 4 and thence to Cell 5. Again, failures in the complex door mechanism have made necessary repeated repairs by use of the manipulators. Improvements have been made in the method of handling the heavy lead shield required for the capsules, but the operation is still cumbersome, and will be replaced ultimately by a more effective transfer device.

2. Process Equipment

Aside from the anticipated complement of valve failures, inoperable liquid level indicators, and radiation damaged plastic tubing (necessary, for example, to connect the precipitation tank with the movable tops of the filter vessels), most of the process equipment has performed within expectations, with the exception of the remotely operated capsule welder. This device, of the same type as employed by ORNL in the fabrication of previous $SrTiO_3$ heat sources, consisted of a steel pressure-vacuum chamber equipped with a capsule rotating device and welding electrode. All welding qualification tests were performed in an identical apparatus at the Baltimore site and produced fusion closure welds meeting all specifications. The Quehanna welder performed equally well in dry runs. Welds were performed under 30 psig of helium pressure in the chamber. Because of the high welding amperage employed, provisions for water coolant circulation around bearings on rotating shafts were made. The welder was in the hot cell environment for three months before its operational use became necessary, and the first attempt to weld a capsule was unsuccessful because of excessive water leakage. Remote examination revealed that radiation damage to elastomeric seals within the welder had caused the leakage, although it had been postulated that the mass of the welder would inhibit such damage. The seals could not be replaced remotely, and a new and simplified welder and welding technique were developed and qualified (see Section V-A).

V. ENCAPSULATION, LEAK TESTING, DECONTAMINATION AND CALORIMETRY

A. ENCAPSULATION

As pellets were produced and their individual thermal outputs measured by calorimetry, they were assigned to specific fuel capsules in such a manner that their stacked height would not exceed the height limitation within the capsule and so that the combined thermal output of the pellets assigned to a capsule would be within specifications. Stainless steel liners, fabricated from tubing with 0.030-inch wall thickness and open at one end, were employed to hold the pellet complement for each capsule. The loaded liners were stored in a shielded box in Cell 2. Empty Hastelloy C capsules were transferred into Cell 2, and a remotely operated Heliarc welder (Fig. 12) was installed.

The liner containing the pellets was inserted into the capsule as carefully as possible to minimize contamination of the capsule lip in the region where welding was to be performed. The lid was put in place and the capsule was placed in a vacuum chamber. After being evacuated through the gap around the lid and back-filled with helium, the capsule was then transferred to the rotation block of the welder. The welding tip was adjusted so that it was in the center of the U-shaped groove between lid and body and at a height that would give an 0.030-inch arc. Three tack welds were then made to restrain the lid, using a current of 110 amperes for two seconds. These welds were spaced 90 degrees apart at three of the four quadrants of a circle. A full fusion welding pass was then made, starting at the fourth quadrant. It required 29 seconds. Welding time was controlled by an automatic timer and was established by the preset rotational speed of the capsule. The purpose of this weld was to give a minimum penetration of 0.055 inch and to seal the capsule for leak testing purposes.

After each capsule had been decontaminated and leak tested, it was transferred to Cell 5 (maintained in essentially uncontaminated condition), where an identical Heliarc welder was installed. A ring of Hastelloy C wire was dropped into the welding groove, tack welded in place and fused to the capsule in the same manner as outlined above. Total weld depth from the combination fusion and filler welds exceeded 0.090 inch. Figures 13 and 14 show a typical capsule after completion of each of the two welding steps.

Completed capsules were stored in a shielded cask in Cell 5 to await final calorimetry and generator loading. Final assignment of pellets to each capsule and their location within the capsule are given in Appendix 2 for reference purposes.

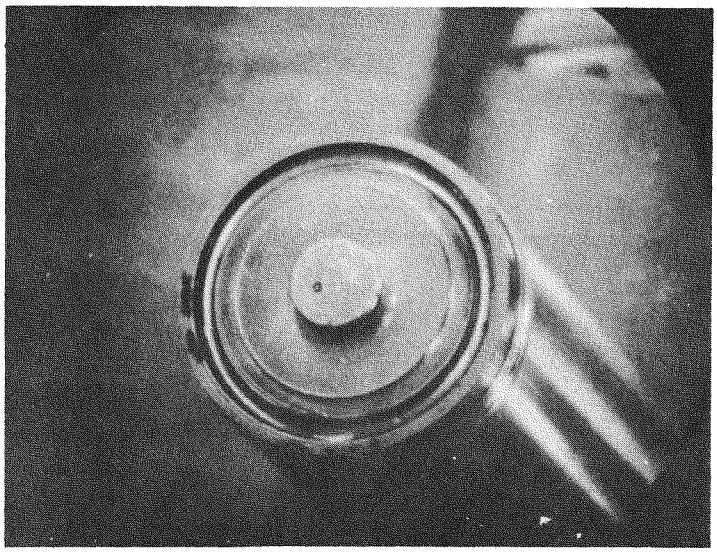


Fig. 13. Capsule With Root Weld Made

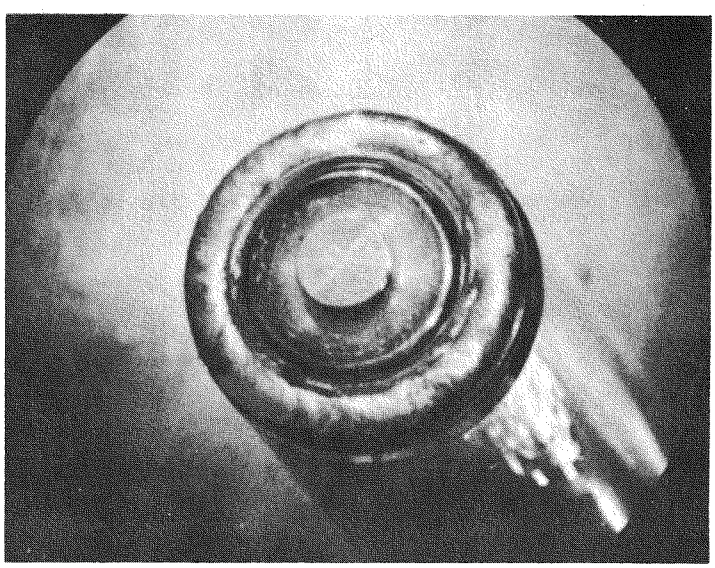


Fig. 14. Capsule With Filler Weld Made

B. LEAK TESTING

Before the welded Hastelloy C capsules were removed from the Cell 2 containment box, a determination was made of the helium leak rate from each capsule. Specifications required that the helium leak rate for each capsule not exceed 1×10^{-6} cc(STP)/sec. In the event this value were exceeded, it would then be necessary to reweld the capsule and subject it to another leak test. Leak rates from the 14 capsules prepared for fueling the SNAP 7B generator averaged 3×10^{-7} cc(STP)/sec and none exceeded the specification.

Equipment used for these tests consisted of a Veeco Leak Detector capable of sensing a helium leak as small as 3×10^{-3} cc(STP)/yr, a Duo-seal vacuum pump, a gas-fill chamber, a leak test chamber, and helium and argon supply. A schematic diagram of the equipment is shown in Fig. 15.

To ensure accuracy, the Veeco unit was operationally checked with a calibrated leak source at the start of each run. The test was then started by inserting the capsule into the gas-fill chamber. With all other equipment isolated by valving, the fill chamber was evacuated for 30 minutes using the Duo-seal vacuum pump, after which helium was purged into the fill chamber for 30 minutes. The capsule was transferred to the leak test chamber and the fill chamber system was purged with argon for approximately five minutes.

With the other equipment isolated by valving, the Veeco test manifold is evacuated to 150 to 200 microns. A helium scan is then made to the closed valve (F) on the leak test chamber. If excessive helium is present, the system is flushed with argon. This is repeated until a reasonably low helium background is established. The capsule is first checked for a large leak by closing the Veeco line valve (G) and opening the leak test chamber valve (F) for 30 seconds. If the helium scan indicates a large leak, the system is again purged with argon to the closed valve (F) on the leak test chamber and the test repeated. A sustained high concentration of helium requires rewelding of the capsule. However, if the scan indicates the helium to be present at concentrations only three to five times higher than background, the test is continued. The Veeco line valve (G) and the test chamber valve (F) are opened and the system is evacuated to 150 to 200 microns. The test is completed when a steady-state condition is indicated by the leak detector.

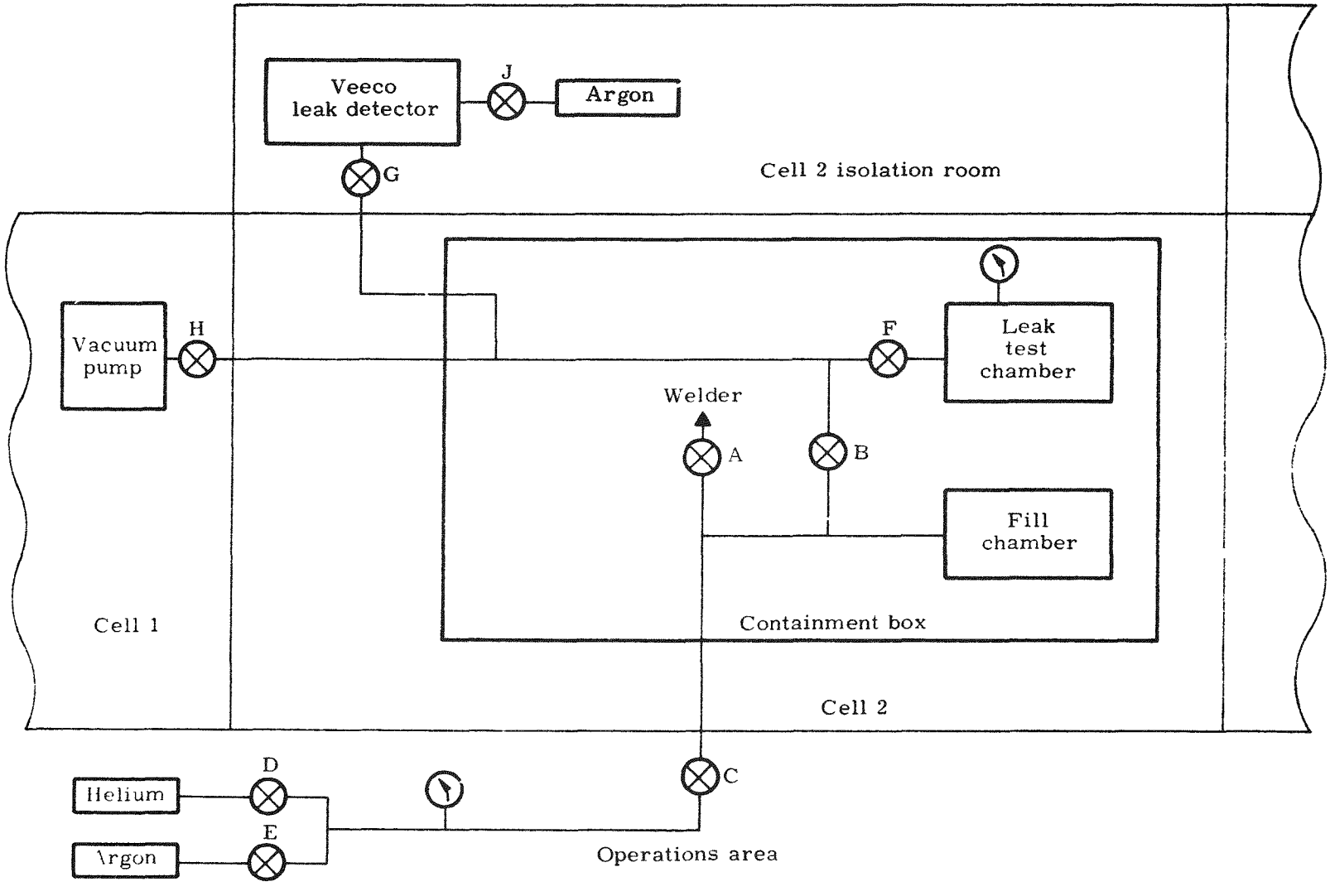


Fig. 15. Capsule Leak Detection System

C. CAPSULE DECONTAMINATION

The first phase of the general program for decontaminating the fuel capsules was accomplished in Cell 2, where gross contaminants were removed by submerging the capsules in 0.1 M HNO_3. At this time, only the first fusion weld had been performed on the top closures. The capsules were then transferred to Cell 4, which was divided into two parts by a temporary partition so that separate contamination levels could be maintained. In the more highly contaminated section, the capsules were received and monitored for contamination by smears. The walls of this part of the cell were covered with plastic sheeting and the top of the working table with aluminum foil to reduce overall contamination as the work progressed. Initial smearable contamination levels were as high as 200 mr/hr, due principally to material adhering to the rough metal surface on the lid that was caused by oxidation during welding. Each capsule in turn was decontaminated to about 10,000 dpm by scrubbing with soap solutions and cleansers, dilute HNO_3 and finally with NaOH solution. Disposable brushes handled by the master-slave manipulators were employed. After washing each capsule with clean water and drying it with absorbent cellulose pads, smears were taken again from top, side and bottom surfaces. The capsule was then placed in a disposable metal can and transferred through a port to the cleaner area of the cell where the process employed earlier was repeated until smear levels over the entire capsule surface were less than 1000 dpm. Figure 16 shows a capsule in the process of decontamination.

D. CALORIMETRY

Calorimetry was performed on the SNAP 7B fuel at two separate stages in the process: the thermal output of each individual pellet was measured prior to loading into the pellet liners and a determination was made for each completed capsule prior to insertion in the generator.

1. Pellet Calorimeter

Physical construction of the pellet calorimeter followed closely a design employed by Oak Ridge. The calorimeter proper consisted of a heat sink, from which extended a vertical copper tube terminated by a pellet holder. Two iron-constantan thermocouples were used; one was embedded in the copper tube immediately under the pellet cup while the other was embedded in the tube near the heat sink. In operation, water was run through the heat sink base at a constant inlet temperature and velocity. A pellet was placed in the cup and the assembly was then covered with a dewar flask to provide thermal insulation. The rate of heat flow through the copper tube and therefore the temperature difference between the two thermocouples was proportional to the thermal power of the pellet. There were two serious shortcomings in the original design: the heater used for the original

Fig. 16. SNAP 7B Capsule

calibration could not be placed back in the calorimeter for periodic checks, and the thermocouple leads were exposed, which resulted in radiation damage to the insulation. A new calorimeter, shown in Fig. 17, was designed and fabricated which eliminated these deficiencies.

2. Capsule Calorimeter

The capsule calorimeter, illustrated in Fig. 18, consists of a large insulated water container of known capacity, a stirrer and appropriate thermocouples. A heat exchanger is provided for water temperature control. The water temperature is lowered to approximately 60° F and a capsule (or an electrical calibration heater in the shape of a capsule) is placed in the water. Cooling of the water is continued until the system reaches thermal equilibrium. At this point, external cooling is discontinued and the temperature rise of the water is recorded for a period of two hours. The heat capacity of the calorimeter was obtained during a series of calibration runs, in the course of which the power input to the heater was fed through a stabilized transformer and measured with a calibrated wattmeter. Details of the calorimeter calibration, computation of the fueled capsule power, and estimate of the probable error in the generator fuel load are given in Appendix C.

E. SUMMARY

A final tabulation of data on leak rates, contamination levels and thermal outputs for each of the 14 capsules is given in Table 5.

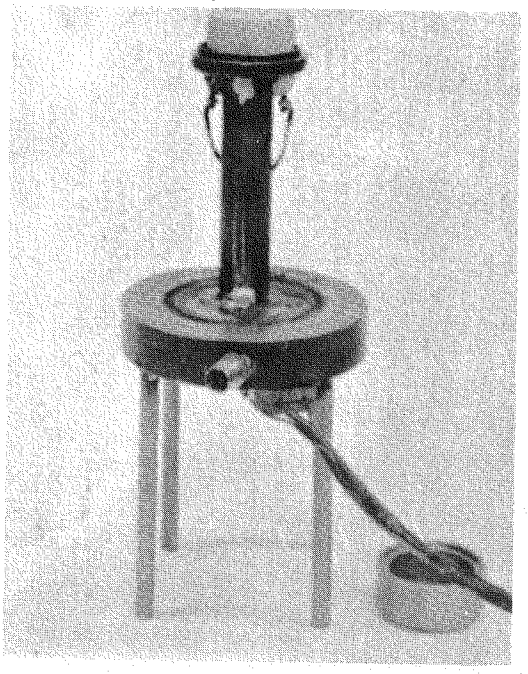


Fig. 17. Pellet Calorimeter

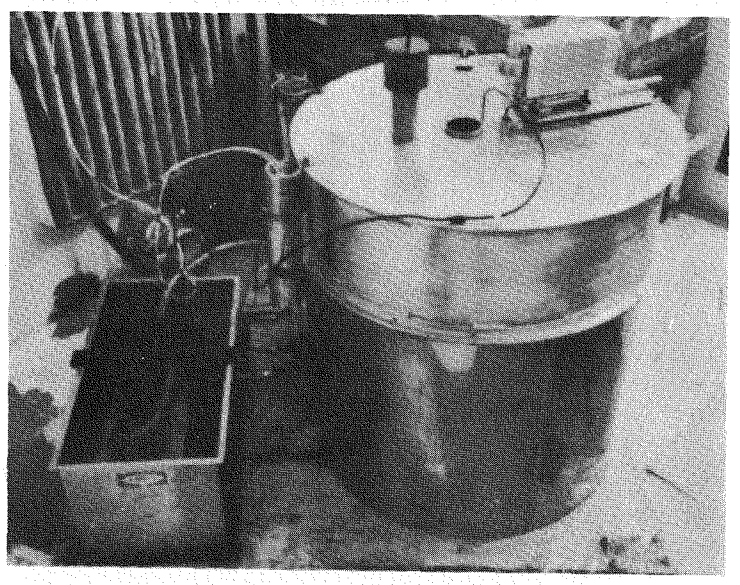


Fig. 18. Capsule Calorimeter

TABLE 5

SNAP 7B Capsule Data

Capsule No.	Total Thermal Watts	Thermal Watts Sr-90 Only	Helium Leak Test Results (cc/sec)	Smear Test Results*	Sr-90 (kilocuries)	Sr-89 (kilocuries)
1	95.1	94.8	3.34×10^{-7}	276	15.1	0.09
2	98.4	98.1	2.68	564	15.6	0.09
3	101.6	101.3	8.36	720	16.1	0.10
4	100.5	100.2	3.35	180	16.0	0.10
5	98.8	98.5	6.7	138	15.7	0.09
6	96.6	96.3	2.01	786	15.3	0.09
7	97.9	97.6	1.26	492	15.5	0.09
8	107.8	107.5	1.34	918	17.1	0.10
9	111.6	111.3	1.68	600	17.7	0.11
10	110.4	110.1	2.35	684	17.5	0.11
11	122.4	122.0	2.01	860	19.4	0.12
12	86.5	86.2	6.7	176	13.7	0.08
13	96.8	96.5	1.68	318	15.4	0.09
14	82.6	82.4	3.83	168	13.1	0.08
Total	1407.0	1402.8		6830	223.2	1.34

*dpm smearable per capsule

Blank

VI. GENERATOR LOADING

The SNAP 7B thermoelectric generator, shown schematically in Fig. 19, was fueled with 14 SR-90 capsules on January 15, 1963. The operation was performed without incident and required approximately one hour.

Prior to the loading operation, Cell 5 was equipped with special handling tools, tables, vacuum pump and a cooling tank. Argon and helium supply lines and thermocouple leads were inserted through plugs in the face of the cell. A radiation monitoring probe was placed approximately one meter from the generator.

The generator was lowered into the cooling tank with an overhead crane. The generator cover plate, uranium shield block, thermal insulation and the capsule holddown plate were removed manually. This equipment was placed in a predetermined location on the work tables to simplify subsequent remote handling after the generator was loaded.

The generator was checked for cleanliness, cooling water was added to the tank and the water recirculating pump was checked for operability. It was necessary that the cooling system be capable of dissipating up to 5000 Btu/hr. The generator output terminals were short-circuited, and the thermocouple leads were connected to a potentiometer in the operations area. Personnel then left the cell.

Remote operations consisted of inserting the 14 capsules according to the plan shown in Fig. 20, followed by the capsule holddown plate, thermal insulation, and uranium shield block. Throughout this operation, a stream of argon flowed through the interior of the generator to protect the thermoelectric couples from oxidation. The recirculated cooling water temperature was maintained at 55° to 60° F and the internal temperature of the generator was continuously monitored (Fig. 21).

Health physics personnel then entered the cell and collected an air sample, smeared the work tables and made a cursory radiation survey of the general area. A more comprehensive smear and radiation survey of the generator was made later. The air sample and smears taken in Cell 5 showed no significant contamination.

Operating personnel entered the cell, installed the cover plate and connected a helium fill line to the generator. The generator was evacuated to less than 100 microns, back-filled with helium and leak checked with the Veeco Leak Detector. No leaks were detected. The temperature in the generator was then allowed to reach 800° F and it was again evacuated and back-filled with helium.

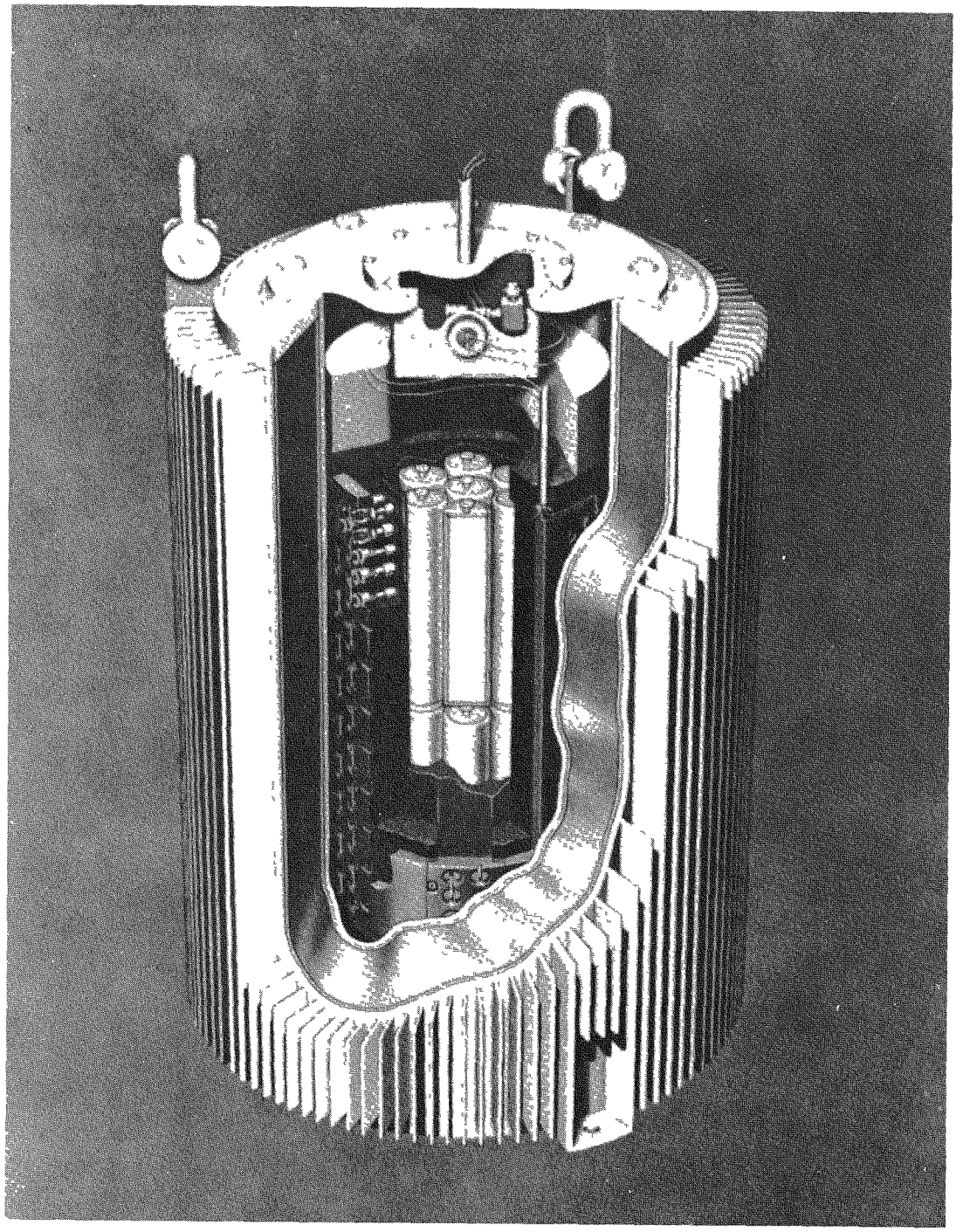


Fig. 19. SNAP 7B Generator (artist's concept)

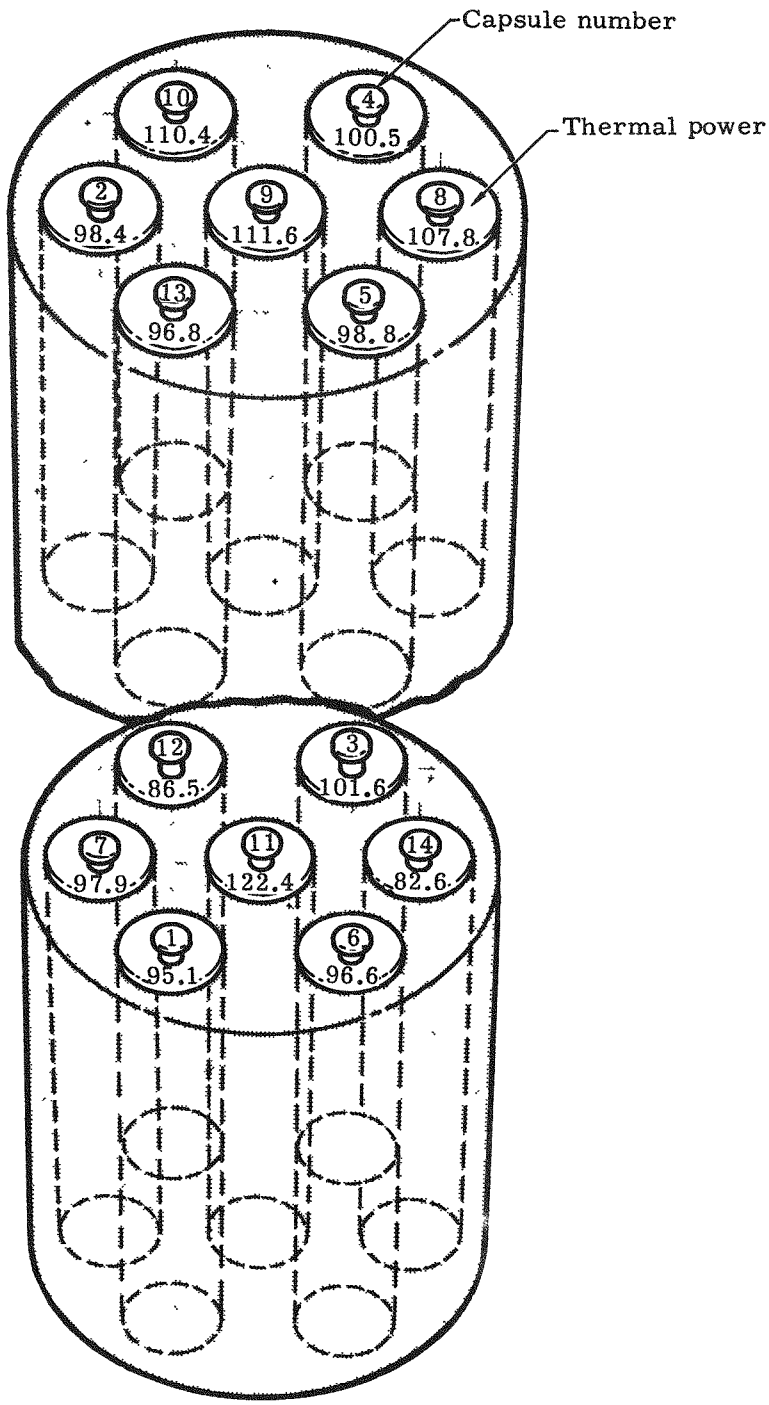


Fig. 20. Locations of Capsules in Generator

Completed SNAP 7B generator

Fuel capsules being loaded into SNAP 7B

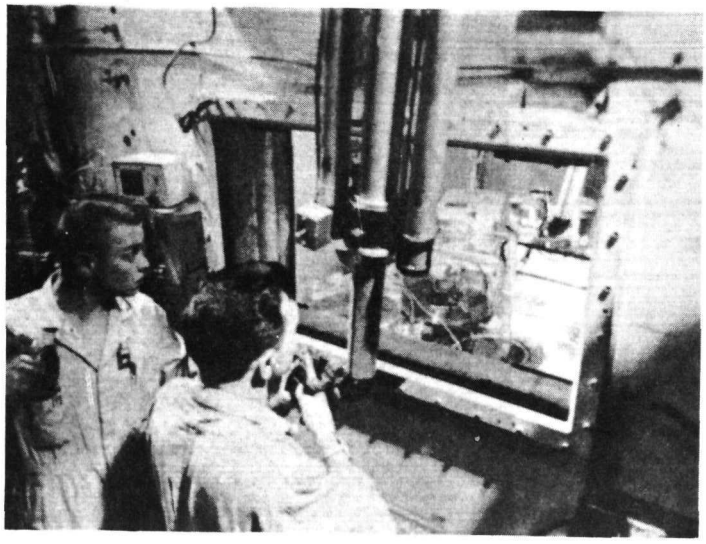


Fig. 21. Fueling of SNAP 7B Generator

The water temperature in the cooling tank was increased to 80° F and the generator temperature was allowed to stabilize. Next, a check was made on the short-circuit current and open-circuit voltage. Internal resistance was then computed to confirm that no damage had occurred to the system and the generator was returned to the short-circuited condition.

The SNAP 7B generator was removed from the cell, its cover was tack welded in place, and final smears and radiation levels were determined. These results are summarized in Table 6. The generator was returned by truck to Baltimore to await acceptance by the AEC.

TABLE 6

Generator Radiation and Survey Results

Smear test--general exterior < 168 dpm from 29 smears.

Radiation at shield plug, before cover was in place:

At contact < 50 mr/hr

At cover height < 30 mr/hr

General radiation level:

		mr/hr
At contact	Bottom	18
	Top	12
	Sides	6
At one meter	Bottom	< 0.8
	Top	< 0.5
	Sides	< 0.7

Blank

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APPENDIX A

BATCH PROCESS CONDITIONS AND INDIVIDUAL PELLET DATA

In the pages that follow, the nominal process conditions for each hot run are given, and the pertinent data on each pellet produced are tabulated. In a few instances, measurements of diameter or height could not be ascribed to a given pellet because of the difficulty of maintaining identification within the hot cell. Consequently, computation of density or linear power could not be made for such pellets.

The term "linear power," in units of watts per inch of axial length of pellet, was coined as an aid in assigning pellets to various capsules, since the number of pellets which could be loaded into a capsule was obviously limited by the available height within the capsule. As the linear power increased with operating experience, it became necessary to employ steel spacers to fill the void volume left in a capsule after a number of pellets equivalent to approximately 100 thermal watts had been assigned to that capsule. The steel spacers were distributed as uniformly as possible among the pellets.

RUN HR 1-1

Batch Volume	2.5 liters
Sr-90 Content	5000 curies
Calcining Cycle	1100° C for 3/4 hour
Forming Pressure	7450 psi (die diameter = 1.556 inches)
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.227	0.354	24.5	3.58	0.153	10.6	3.75	1
1.258	0.675	47.75	3.48	0.145	10.2	6.90	1
1.248	0.571	38.6	3.38	0.149	10.1	5.75	1
1.234	0.533	38.0	3.64	0.150	10.7	5.70	1
1.221	0.475	32.2	3.54	0.165	11.2	5.30	1

RUN HR 1-2

Batch Volume	3.0 liters
Sr-90 Content	6000 curies
Calcining Cycle	1100° C for 3/4 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.227	0.703	49.5	3.64	0.15	10.57	7.425	2
1.198	0.487	33.5	3.73	0.16	11.0	5.35	2
1.195	0.465	31.6	3.70	0.163	11.1	5.15	2
1.220	0.483	34.6	3.74	0.16	11.5	5.55	2
1.180	0.420	30.0	3.98	0.162	11.6	4.85	2
1.200	0.457	32.5	3.84	0.159	11.3	5.15	2

RUN HR 1-3A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1100° C for 3/4 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.225	0.492	35.3	3.71	0.176	12.6	6.20	2
1.248	0.649	42.1	3.26	0.169	11.0	7.125	2
1.262	0.687	41.7	3.00	0.173	10.5	7.195	2
1.265	0.653	41.5	3.10	0.17	10.8	7.075	3
1.259	0.638	41.5	3.19	0.168	10.9	6.950	3
		62.9		0.175		10.97	13
1.285	0.745	45.7	2.90	0.136	8.33	6.20	3
1.275	0.662	39.6	2.84	0.154	9.22	6.10	3

RUN HR 1-3B

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1100° C for 3/4 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.250	0.590	36.6	3.09	0.17	10.6	6.225	3
1.275	0.551	35.5	3.08	0.17	11.0	6.05	3
1.275	0.567	38.1	3.22	0.167	11.2	6.35	4
1.281	0.657	41.5	2.99	0.166	10.5	6.90	4
1.265	0.651	41.4	3.09	0.167	10.6	6.90	4
1.273	0.584	39.2	3.21	0.167	11.2	6.55	4
1.273	0.649	41.0	3.03	0.161	10.2	6.60	4
		54.5		0.163		8.88	13

RUN HR 1-4A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1100° C for 3/4 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.250	0.668	42.8	3.18	0.167	10.7	7.125	5
1.219	0.466	29.5	3.33	0.178	11.3	5.25	13
1.240	0.739	46.6	3.18	0.165	10.4	7.68	5
1.238	0.550	36.0	3.32	0.175	11.4	6.28	5
1.243	0.737	46.4	3.17	0.161	10.1	7.47	5
1.277	0.793	56.75	3.42	0.162	11.6	9.17	5

RUN HR 1-5A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1025° C for 1 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.298	0.457	37.0	3.75	0.165	13.4	6.10	6
1.294	0.529	40.0	3.50	0.173	13.1	6.90	6
1.292	0.490	34.8	3.30	0.167	11.9	5.82	6
1.285	0.444	34.8	3.68	0.172	13.5	5.97	6
1.294	0.793	67.2	3.93	0.156	13.2	10.45	6
1.296	0.353	28.0	3.68	0.183	14.5	5.12	6
1.299	0.497	37.6	3.50	0.168	12.7	6.30	6

RUN HR 1-5B

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1025° C for 1 hour
Forming Pressure	7450 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.298	0.618	46.5	3.48	0.167	12.5	7.75	6
1.304	0.682	51.1	3.44	0.163	12.2	8.30	6
1.304	0.492	34.2	3.19	0.173	12.0	5.90	6
1.289	0.508	35.8	3.30	0.172	12.1	6.15	7
1.294	0.475	33.0	3.22	0.173	12.0	5.70	7
1.304	0.740	55.1	3.41	0.161	12.0	8.88	7
1.312	0.547	38.4	3.17	0.162	11.4	6.24	7
1.324	0.600	39.7	2.93	0.17	11.2	6.73	7
1.312	0.565	37.55	3.00	0.171	11.4	6.44	7
1.309	0.565	37.5	2.98	0.172	11.4	6.45	7
1.312	0.380	23.3	2.77	0.129	7.9	3.00	7

RUN HR 1-6A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1000° C for 2.5 hours
Forming Pressure	6750 psi (die diameter = 1.636 inches)
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.341	0.490	34.5	3.04	0.170	11.9	5.85	7
1.345	0.527	34.2	2.77	0.169	10.9	5.76	7
1.344	0.569	36.7	2.80	0.17	11.0	6.25	8
1.348	0.655	37.8	3.20	0.163	9.4	6.16	8
1.329	0.491	32.5	2.85	0.186	12.3	6.05	8
1.344	0.595	39.1	2.82	0.168	11.0	6.55	8
1.331	0.412	23.7	2.50	0.185	10.6	4.38	8
1.351	0.623	37.1	2.52	0.178	10.6	6.58	

RUN HR 1-6B

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1000° C for 2.5 hours
Forming Pressure	7750 psi (die diameter = 1.671 inches)
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.363	0.635	43.05	2.77	0.165	11.2	7.1	10
1.401	0.550	50.1	3.50	0.159	14.5	7.97	11

RUN HR 1-7A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1025° C for 2.5 hours
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.364	0.471	38.85	3.45	0.157	13.0	6.10	10
1.364	0.486	39.95	3.43	0.166	13.7	6.64	10
1.356	0.450	39.45	3.70	0.167	14.6	6.56	10
1.365	0.519	37.65	3.02	0.167	12.2	6.30	10
1.370	0.448	37.40	3.44	0.167	13.9	6.24	10
1.365	0.712	52.85	3.09	0.160	11.8	8.42	10
1.380	0.638	53.20	3.40	0.158	13.2	8.42	10
1.360	0.406	34.10	3.54	0.166	14.0	5.66	10

RUN HR 1-7B

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1000° C for 2.5 hours
Forming Pressure	8060 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.317	0.728	61.50	4.02	0.156	13.1	9.56	9
1.318	0.449	29.00	2.90	0.177	11.4	5.14	9
1.320	0.519	42.75	3.76	0.168	13.9	7.20	9
1.320	0.554	43.75	3.53	0.169	13.4	7.40	
	0.455	33.50		0.179	13.2	6.00	13
1.300	0.329	26.95	3.63	0.186	15.2	5.00	9
1.314	0.597	42.75	3.22	0.166	11.9	7.10	9
1.314	0.559	44.10	3.62	0.168	13.2	7.40	
1.312	0.319	25.40	3.60	0.193	15.4	4.90	

RUN HR 1-8A

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	8060 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.295	0.463	44.0	4.40	0.166	15.8	7.30	8
1.298	0.442	42.2	4.405	0.171	16.3	7.20	8
1.310	0.455	44.4	4.44	0.166	16.2	7.38	8
1.293	0.489	46.2	4.40	0.169	16.0	7.80	8
1.302	0.448	42.8	4.38	0.173	16.6	7.41	8
1.292	0.445	42.8	4.47	0.173	16.6	7.39	8
1.301	0.493	47.7	4.44	0.166	16.1	7.93	8
1.297	0.430	41.7	4.48	0.170	16.5	7.10	8
1.302	0.395	38.2	4.43	0.173	16.7	6.60	10

RUN HR 1-8B

Batch Volume	5.0 liters
Sr-90 Content	10,000 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	8060 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.340	0.432	33.2	3.60	0.171	13.1	5.66	9
1.340	0.478	38.2	3.35	0.166	13.2	6.33	9
1.336	0.501	36.8	3.19	0.170	12.5	6.26	9
1.325	0.466	38.0	3.60	0.168	13.7	6.36	9
1.376	0.677	52.0	3.14	0.158	12.1	8.22	11
1.346	0.504	40.8	3.48	0.175	14.2	7.15	13
1.308	0.369	29.8	3.68	0.178	14.4	5.30	9

RUN HR 1-9A

Batch Volume	4.765 liters
Sr-90 Content	9530 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	8060 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Pellet tray spilled in furnace when the door was closed. The entire run, with the exception of No. 1 pellet, was scrapped.

RUN HR 2-1

Batch Volume	2.0 liters
Sr-90 Content	2000 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3478	0.5185	46.5	3.84	0.178	15.97	8.28	1
1.3338	0.4905	36.3	3.23	0.191	14.15	6.94	1
1.3368	0.4755	35.2	3.22	0.187	13.80	6.56	1
1.3408	0.4345	30.6	3.05	0.173	12.13	5.27	1
1.3588	0.4035	37.1	3.86	0.203	18.64	7.52	1
1.3538	0.4905	43.7	3.78	0.172	15.30	7.50	1
1.3318	0.4955	45.0	3.98	0.177	16.10	7.98	1
1.3408	0.4755	39.6	3.61	0.180	15.05	7.14	1

RUN HR 2-2A

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	1040° C for 3/4 hour
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.451	0.3685	34.0	3.39	0.1829	16.9	6.22	11
1.440	0.396	33.7	3.19	0.186	15.9	6.28	11
1.466	0.60	53.4	3.23	0.177	15.7	9.44	11

RUN HR 2-2B

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3868	0.3535	28.8	3.31	0.1847	15.05	5.32	1
1.3938	0.3511	32.5	3.71	0.182	16.91	5.94	
1.3798	0.3495	29.2	3.44	0.189	15.82	5.53	
1.3828	0.3325	28.0	3.42	0.184	15.49	5.15	1
1.3788	0.330	27.8	3.45	0.188	15.88	5.24	1
1.3828	0.3465	27.5	3.23	0.188	14.95	5.18	2
1.380	0.343	29.0	3.45	0.187	15.80	5.42	2
1.376	0.328	27.1	3.41	0.193	16.00	5.25	2
1.369	0.292	23.8	3.39	0.197	16.10	4.70	2

RUN HR 2-3A

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	1040° C for 3/4 hour
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.391	0.499	37.6	3.03	0.171	12.83	6.41	13
		80.2					14
1.502	0.656	58.3	3.06				
1.424	0.542	44.5	3.14	0.183	14.90	8.18	13
1.468	0.781	70.0	3.23	1.172	15.40	12.0	11

RUN HR 2-3B

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	1050° C for 3/4 hour
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.388	0.396	42.2	4.30	0.215	20.1	9.1	2
1.467	0.640	49.1	2.77	0.187	15.3	9.2	
1.395	0.515	45.0	3.49	0.220	21.46	9.93	11
1.387	0.312	32.0	4.13	0.227	21.54	7.26	2
1.388	0.386	40.0	4.18	0.214	20.60	8.59	2
1.404	0.468	50.0	4.21	0.214	22.8	10.74	11
1.396	0.367	39.7	4.32	0.216	23.4	8.60	11

RUN HR 2-3B

(Precipitate Recovered from Back-up Filter)

Calcining Cycle	935° C for 3 hours
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.325	0.635	59.5	4.16	0.187	18.1	11.16	3
1.322	0.312	33.4	4.77	0.194	20.8	6.50	2
1.340	0.377	32.5	3.74	0.201	17.3	6.55	3
1.338	0.370	34.0	4.00	0.203	18.6	6.88	3
1.332	0.330	29.4	3.91	0.185	16.5	5.44	3
1.335	0.395	36.1	3.99	0.182	16.6	6.56	3
1.315	0.340	29.7	3.93	0.200	17.4	5.94	3
1.342	0.380	35.2	4.00	0.189	17.5	6.68	3
1.335	0.322	28.9	3.92	0.194	17.4	5.60	3

RUN HR 2-4A

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	7750 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.308	0.347	32.2	4.21	0.179	16.60	5.76	3
1.310	0.351	32.1	4.14	0.185	16.95	5.95	3
1.325	0.380	34.7	4.04	0.180	16.42	6.24	4
1.304	0.343	30.6	4.08	0.183	16.33	5.60	4
1.325	0.353	31.6	3.96	0.187	16.77	5.92	4
1.322	0.364	33.2	4.05	0.182	16.57	6.03	4
1.310	0.372	34.2	4.16	0.179	16.42	6.11	4
1.312	0.330	29.6	4.05	0.181	16.27	5.37	4
1.310	0.375	31.9	3.85	0.182	15.47	5.80	4

RUN HR 2-4B

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	8390 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.311	0.328	30.3	4.17	0.191	17.68	5.8	4
1.315	0.312	29.2	4.20	0.192	17.95	5.6	4
1.325	0.378	32.2	3.77	0.188	16.03	6.06	4
1.344	0.296	28.8	4.19	0.1902	18.51	5.48	4
1.320	0.302	28.0	4.14	0.188	17.38	5.25	4
1.318	0.342	28.9	3.78	0.180	15.20	5.20	5
1.323	0.328	31.2	4.22	0.189	17.99	5.90	5
1.334	0.307	25.9	3.68	0.194	16.35	5.02	5
1.327	0.219	20.8	4.19	0.212	20.14	4.41	5
1.323	0.254	21.9	3.83	0.202	17.00	4.42	5
1.321	0.259	23.7	4.07	0.208	19.07	4.94	5

RUN HR 2-5A

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	8390 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.350	0.342	31.0	3.865	0.193	17.49	5.98	5
1.343	0.439	34.8	3.415	0.190	15.03	6.60	5
1.350	0.434	34.8	3.418	0.192	15.39	6.68	5
1.340	0.456	40.0	3.795	0.181	15.83	7.22	5
1.313	0.426	32.5	3.441	0.213	16.27	6.93	5
1.295	0.356	34.2	4.44	0.196	18.88	6.72	6
1.322	0.495	42.7	3.833	0.184	15.88	7.86	5
1.340	0.345	30.3	3.80	0.196	17.28	5.96	6

RUN HR 2-5A (continued)

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.296	0.351	30.9	4.07	0.197	17.37	6.10	6
1.318	0.320	29.0	4.06	0.200	18.12	5.80	6
1.317	0.366	33.2	4.06	0.187	16.93	6.20	6
1.298	0.315	27.3	4.00	0.208	18.09	5.70	6
1.299	0.337	30.0	4.10	0.204	18.21	6.14	7
1.325	0.337	30.0	3.94	0.210	18.72	6.31	7
1.331	0.367	32.9	3.93	0.209	18.80	6.90	7
1.335	0.341	30.5	3.90	0.219	19.65	6.70	7
1.326	0.327	29.8	4.03	0.194	17.68	5.78	1

RUN HR 2-5B

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	Start at 7750 psi. Increase 645 psi for each pellet up to 10,960 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.402	0.180	17.7	3.89	0.218	21.44	3.86	11
1.398	0.300	20.0	2.65	0.238	15.87	4.76	11
1.430	0.276	21.5	2.96	0.228	17.75	4.90	11
1.420	0.435	33.5	2.97	0.219	16.92	7.36	11
1.430	0.335	24.4	2.77	0.226	16.48	5.52	11
1.426	0.382	31.3	3.13	0.212	17.40	6.65	11
1.372	0.378	31.4	3.43	0.218	18.07	6.83	7
1.402	0.378	30.8	3.22	0.221	18.02	6.81	11
1.378	0.331	28.5	3.52	0.214	18.43	6.10	7
1.340	0.300	33.3	4.80	0.213	23.67	7.10	7
1.372	0.558	51.9	4.15	0.205	19.07	10.64	8
1.[illegible]5	0.560	52.1	3.88	0.206	19.21	10.76	8

RUN HR 2-6A

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	8390 psi for 5 minutes
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.337	0.346	31.3	3.94	0.205	18.55	6.41	9
1.325	0.378	35.8	4.19	0.205	19.45	7.35	9
1.446	0.357	27.5	2.86	0.220	16.90	6.04	
1.407	0.392	35.3	3.54	0.213	19.20	7.52	
1.388	0.501	45.0	3.63	0.206	18.50	9.28	10
1.392	0.287	27.0	3.78	0.218	20.04	5.88	
1.387	0.286	26.6	3.76	0.217	20.01	5.78	9
1.383	0.304	27.4	3.66	0.216	19.41	5.90	9
1.325	0.313	28.0	3.96	0.219	19.5	6.10	9
1.327	0.280	26.8	4.24	0.216	20.07	5.78	10

RUN HR 2-6B

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	935° C for 4 hours
Forming Pressure	8390 psi
Sintering Cycle	1400° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.400	0.452	46.0	4.03	0.204	20.75	9.38	
1.378	0.354	30.5	3.54	0.212	18.30	6.47	10
1.390	0.359	31.3	3.50	0.212	18.40	6.62	
1.384	0.322	28.9	3.64	0.216	19.35	6.23	4
1.300	0.409	38.2	4.30	0.203	18.94	7.75	10
1.350	0.253	20.6	3.48	0.229	18.66	4.72	13
1.306	0.335	31.4	4.28	0.206	19.40	6.50	10
1.355	0.255	21.4	3.56	0.227	19.00	4.85	10
1.332	0.270	24.2	3.93	0.218	19.60	5.28	9
1.312	0.589	55.8	4.28	0.205	19.40	11.43	9

RUN HR 3-1

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	954° C for 4 hours
Forming Pressure	7750 psi
Sintering Cycle	1450° C for 2 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3628	0.4685	43.0	4.14	0.186	17.12	8.0	13
1.3708	0.3735	34.4	4.01	0.191	16.75	6.58	13
1.3518	0.3565	31.1	3.83	0.196	16.6	6.1	13
1.343	0.3630	32.1	4.28	0.178	14.2	5.7	13
1.3608	0.4185	35.1	3.52	0.190	15.4	6.66	13
1.3368	0.3405	30.0	3.90	0.193	16.75	5.80	13
1.3538	0.3575	21.8		0.217	12.85	4.72	13
	0.4835	39.2		0.160	12.2	6.28	13
	0.453	33.6		0.181	13.63	5.4	13

RUN HR 3-2

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	980° C for 12 minutes, 954° C for 3 hours
Forming Pressure	8060 psi
Sintering Cycle	1400° C for 3 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3648	0.394	34.1	3.69	0.192	16.63	6.56	12
1.3538	0.559	49.6	3.85	0.182	16.05	8.99	14
1.3478	0.298	23.1	3.79	0.214	16.63	4.96	12
1.325	0.396	30.2	3.89	0.183	13.99	5.54	14
1.321		37.5		0.188	16.04	6.90	14
1.323		24.1		0.204	15.10	4.92	14
		25.6				4.87	12

RUN HR 3-3

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	950° C for 4 hours
Forming Pressure	8060 psi
Sintering Cycle	1320° C for 3 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3408	0.3510	32.7	4.02	0.190	17.5	6.2	14
1.361	0.4010	39.3	4.11	0.182	17.75	7.16	14
1.3408	0.3684	36.1	4.26	0.188	18.35	6.78	14
1.4428	0.406	40.0	3.67	0.183	17.77	7.30	14
1.3448	0.375	34.9	4.0	0.193	17.82	6.74	14
1.3598	0.381	36.6	4.04	0.190	18.25	6.96	14
1.3688	0.420	41.2	4.06	0.187	18.30	7.68	14
1.3558	0.4415	42.5	4.07	0.184	17.66	7.80	14
1.3568	0.3475	33.6	4.1	0.193	18.60	6.47	12
1.3558	0.293	27.3	3.94	0.197	18.40	5.38	12

RUN HR 3-4

Batch Volume	4.0 liters
Sr-90 Content	12,000 curies
Calcining Cycle	954° C for 4 hours
Forming Pressure	8060 psi
Sintering Cycle	1300° C for 4 hours

PELLET DATA

Diameter (in.)	Height (in.)	Weight (gm)	Density (gm/cc)	Specific Power (watts/gm)	Linear Power (watts/in.)	Power (watts)	Fuel Capsule No.
1.3498	0.3770	37.0	4.19	0.181	18.05	7.16	12
1.3448	0.3395	32.5	4.11	0.188	18.0	6.44	12
1.3508	0.2935	28.4	4.12	0.199	19.29	5.78	12
1.3388	0.3390	32.6	4.17	0.190	18.38	6.2	12
1.3508	0.3325	32.2	4.12	0.199	19.25	6.42	12
1.3538	0.3810	37.4	4.16	0.192	18.75	7.20	12
1.3658	0.4220	41.9	4.14	0.188	18.75	7.92	12
1.3495	0.3405	32.6	4.08	0.196	18.95	6.47	12
1.3358	0.3425	32.2	4.09	0.194	18.25	6.26	12
1.3448	0.3075	28.8	4.09	0.195	18.68	5.62	12

APPENDIX B

PELLET ASSIGNMENTS AND CAPSULE LOADING PLAN

Identification of pellets in the following tabulations is as follows: 2-1-1 means "Shipment or Hot Run No. 2; Batch No. 1; Pellet No. 1."

Capsule 1		Capsule 2		Capsule 3		Capsule 4	
Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.
1	2-1-1	1	2-2B-6	1	2-3BF-1	1	2-4A-3
2	2-1-2	2	2-2B-7	2	1-3A-4	2	1-3B-3
3	1-1-1	3	1-2-1	3	2-3BF-3	3	2-4A-4
4	2-1-3	4	2-2B-8	4	1-3A-5	4	1-3B-4
5	2-1-4	5	1-2-2	5	2-3BF-4	5	2-4A-5
6	2-1-5	6	2-2B-9	6	2-3BF-5	6	2-4A-6
7	2-1-6	7	1-2-3	7	2-3BF-6	7	1-3B-5
8	1-1-2	8	2-3B-1	8	1-3A-7	8	2-4A-7
9	2-1-7	9	1-2-4	9	2-3BF-7	9	1-3B-6
10	2-1-8	10	1-2-5	10	2-3BF-8	10	2-4A-8
11	1-1-3	11	1-2-6	11	2-3BF-9	11	2-4A-9
12	2-2B-1	12	2-3B-4	12	1-3A-8	12	1-3B-7
13	2-5A-17	13	1-3A-1	13	1-4A-1	13	2-4B-1
14	1-1-4	14	1-3A-2	14	2 4A-2	14	2-4B-2
15	2-2B-4	15	2-3B-5	15	1-3B-1	15	2-4B-3
16	1-1-5	16	1-3A-3	16	1-3B-2	16	2-4B-4
17	2-2B-5	17	2-3BF-2	Spacer between 2 and 3; 14 and 15		17	2-6B-4
						18	2-4B-5

Capsule 5		Capsule 6		Capsule 7		Capsule 8	
Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.
1	2-4B-6	1	1-5A-1	1	2-5A-14	1	2-5B-11
2	2-4B-7	2	1-5A-2	2	1-5B-4	2	1-6A-3
3	1-4A-1	3	2-5A-6	3	2-5A-15	3	1-6A-4
4	2-4B-8	4	1-5A-3	4	1-5B-5	4	2-5B-12
5	2-4B-9	5	1-5A-4	5	1-5B-6	5	1-6A-5
6	1-4A-3	6	1-5A-5	6	2-5A-16	6	1-8A-1
7	2-4B-10	7	1-5A-6	7	1-5B-7	7	1-8A-2
8	2-4B-11	8	1-5A-7	8	2-5A-13	8	1-8A-3
9	2-5A-1	9	1-5B-1	9	1-5B-8	9	1-6A-6
10	1-4A-4	10	1-5B-2	10	2-5B-7	10	1-8A-4
11	2-5A-2	11	2-5A-8	11	1-5B-9	11	1-8A-5
12	2-5A-3	12	2-5A-9	12	1-5B-10	12	1-8A-6
13	2-5A-4	13	2-5A-10	13	2-5B-9	13	1-6A-7
14	1-4A-5	14	1-5B-3	14	2-5B-10	14	1-8A-7
15	2-5A-5	15	2-5A-11	15	1-5B-11	15	1-8A-8
16	1-4A-6	16	2-5A-12	16	1-6A-1		
17	2-5A-7			17	1-6A-2		

Spacer between 3 and 4; 15 and 16

Capsule 9		Capsule 10		Capsule 11		Capsule 12	
Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.	Pellet Location	Pellet No.
1	1-7B-1	1	1-7A-1	1	1-6B-2	1	3-4-4
2	1-7B-6	2	1-7A-2	2	2-3B-3	2	3-4-5
3	1-7B-3	3	1-7A-3	3	2-3B-6	3	3-4-6
4	2-6A-1	4	1-7A-4	4	2-3B-7	4	3-4-8
5	1-7B-2	5	1-7A-5	5	2-5B-1	5	3-4-9
6	2-6A-2	6	1-7A-6	6	2-5B-2	6	3-4-10
7	1-7B-7	7	1-7A-7	7	2-5B-3	7	3-2-3
8	1-8B-1	8	1-7A-8	8	2-5B-5	8	3-4-1
9	1-8B-2	9	2-6A-5	9	2-5B-6	9	3-4-2
10	1-8B-3	10	2-6B-7	10	Pellet X	10	3-4-3
11	1-8B-4	11	2-6A-10	11	2-5B-8	11	3-4-7
12	2-6B-10	12	2-6B-2	12	2-5B-4	12	3-2-1
13	2-6B-9	13	1-6B-1	13	2-2A-1	13	3-3-9
14	1-8B-7	14	1-8A-9	14	2-2A-2	14	3-3-10
15	2-6A-7	15	2-6B-5	15	2-2A-3	15	3-2-7
16	2-6A-8	16	2-6B-8	16	2-3A-5	Spacers between 1 and 2; 2 and 3; 3 and 4; 4 and 5; 5 and 6; 6 and 7; 7 and 8; 8 and 9; 9 and 10; 12 and 13	
17	2-6A-9	2 spacers between 9 and 10		17	1-8B-5		
				2 spacers between 1 and 2; 3 spacers on top			

Capsule 13	
Pellet Location	Pellet No.
1	3-1-1
2	3-1-2
3	3-1-3
4	3-1-4
5	3-1-5
6	3-1-6
7	3-1-7
8	1-7B-5
9	1-8B-6
10	2-3A-1
11	2-3A-4
12	1-4A-2
13	1-3A-6
14	1-3B-8
15	3-1-8
16	3-1-9
17	2-6B-6
18	Unidentified pellet

Capsule 14	
Pellet Location	Pellet No.
1	3-2-2
2	3-2-4
3	3-3-1
4	3-3-2
5	3-3-3
6	3-3-4
7	3-3-5
8	3-3-6
9	3-3-7
10	3-3-8
11	2-3A-2
12	3-2-6
13	3-2-5

Spacer between 1 and 2; 2 and 3; 3 and 4; 4 and 5; 5 and 6; 11 and 12; 12 and 13

0.25 inch spacer

APPENDIX C

CAPSULE CALORIMETER CALIBRATION

Calibration runs were made with a special electrical heater of the same overall dimensions as the SNAP 7B fuel capsule. Power input to the heater was fed through a stabilized transformer and measured with a calibrated wattmeter. From these calibration runs, made over the entire range of power anticipated from capsules, a calorimeter constant, Q, was determined. Fueled capsule power was then computed as the product of Q times the measured rate of temperature rise from the capsule run.

A mathematical description of the determination of Q, computation of fueled capsule power and estimate of probable error in the generator fuel load follows:

A. DEFINITIONS

ΔT = the temperature rise (° F) between successive observations, spaced 10 minutes apart

$y = \sqrt{\frac{\Sigma(\Delta T)^2}{M}}$, the least squared average temperature rise for 10 minutes from a series of M + 1 temperature readings in a run. Units of y are ° F per 10 minutes.

x = computed power output, in watts, from the heater or fueled capsule.

$\overline{x}$ = measured input power to the calibration heater in watts.

Q, the calorimeter constant, was computed from n calibration runs by:

$$Q = \sqrt{\frac{\Sigma\left(\frac{\overline{x}^2}{y^2}\right)}{n}}, \text{ watts per } ^\circ F \text{ per 10 minutes.}$$

Finally, from each fueled capsule run the computed power output, x, was given by:

$$x = Qy.$$

B. ESTIMATE OF ERRORS

From n calibration runs the standard deviation, σ, is given by:

$$\sigma = \sqrt{\frac{\Sigma (x - \bar{x})^2}{n}}$$

The standard error per run = $\pm \sigma t$ in watts, where t is a statistical constant dependent upon the level of confidence desired and the "degrees of freedom." For the SNAP 7B generator loading, 19 calibration tests were made. The degrees of freedom were 19 -2 = 17. The confidence level was taken at 95% for which t = 2.11.

The full generator load included 14 capsules, and 2 runs were made on each capsule. The probable error, E, is given by:

$$E = \pm t \sigma \frac{\sqrt{14}}{\sqrt{2}}$$

C. CALORIMETRY RESULTS

The calorimeter constant, Q = 25.307 watts/°F/10 minutes. For the generator loading Σx = 1407.0 watts. Probable error for the full generator loading is E = $\pm$ 10.0 watts.