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(Category UC-80)
(Reactor Technology)
(Joint US-Euratom Program)

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SAXTON PLUTONIUM PROGRAM

MATERIALS DESIGN AND FABRICATION OF THE SAXTON PARTIAL PLUTONIUM CORE

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Prepared for the New York Operations Office
U. S. Atomic Energy Commission
Under AEC Contract AT(30-1)-3385

December 1965

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TOTAL	477

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ABSTRACT

The materials design and fuel fabrication portions of the Saxton Plutonium Project are described. The purpose of the Saxton Plutonium Project is to develop information concerning the utilization of plutonium-enriched fuel in pressurized water reactor systems, through design, fabrication and operation of a partial core of PuO_2-UO_2 fuel in the Saxton Reactor.

Materials design entailed selection of the cladding and fuel rod fabrication techniques employed for the project, development of fuel specifications, and providing materials information to other design groups for establishing design parameters and safety criteria. The fabrication techniques selected were vibrational compaction and pelletization of mechanically-mixed powder. Reasons for these selections are given. Also, the procedures used during manufacturing of the fuel rods and results of inspection and quality control are summarized.

The fuel rods are expected to operate at maximum linear rod powers of 16 Kw/ft and peak exposures greater than 25,000 MWD/Tonne (Pu+U). Fuel central temperatures as high as 2100°C are expected.

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INTRODUCTION

The potential of plutonium as a recycle fuel in thermal reactors has long been recognized by both industry and the AEC. As a result the AEC has supported extensive development programs at the National Laboratories since 1956. Cost analyses have indicated that if plutonium is not burned in thermal reactors following commencement of private ownership of fuel, fuel cycle costs will increase significantly. Consequently, in 1963, anticipation that private ownership would commence in 1971 resulted in extension of the National Laboratories' programs to the next logical step, bulk engineering tests in commercial type reactors.

Under Contract AT(30-1)-3385 administered by the USAEC New York Operations Office for the Joint US-Euratom R & D Board, nine complete fuel assemblies of plutonium enriched fuel are being tested in the Saxton Pressurized Water Reactor. The fuel assemblies were designed and built by Westinghouse and the individual rods were fabricated by Nuclear Materials and Equipment Corporation (NUMEC) and the Battelle Northwest Laboratories under sub-contract to Westinghouse.

The Saxton Reactor is operated by the Saxton Nuclear Experimental Corporation (SNEC) in technical cooperation with Westinghouse. This reactor is particularly suited for initiation of commercial bulk engineering tests of plutonium fuels because it is highly instrumented and performance can be closely observed and continuously evaluated.

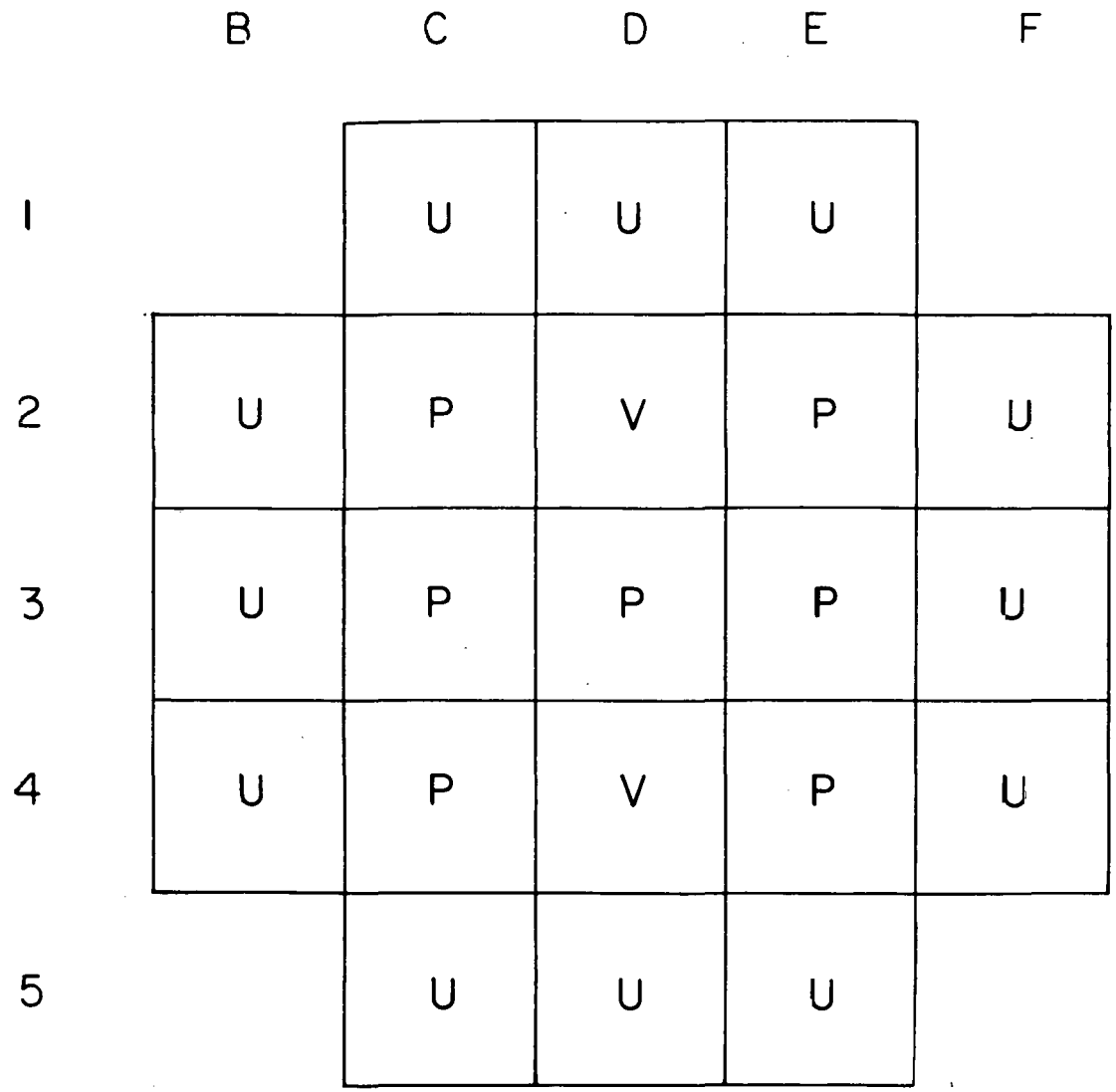
The major materials objectives of the program are to:

1. Perform pilot-scale tests of PuO_2-UO_2 fuel in a water reactor environment.
2. Provide statistically-valid performance comparison between two economically promising PuO_2-UO_2 fabrication techniques.
3. Provide a preliminary basis for plutonium fuel selection and design for large PWR.

This document describes the materials portion of the program required to design and manufacture the fuel. In particular, Part A describes the general materials program and the basis for materials design and specifications developed for the program. Part B summarizes the fuel fabrication phase of the program and includes description of the fuel rod manufacturing methods and results of inspection and quality control.

I. PROGRAM SUMMARY

To accomplish the objective of the program, nine fuel assemblies were inserted in the central region of the Saxton Core II in early October 1965, and will remain there for about two years. A schematic cross section of the core depicting the various fuel assembly locations is shown in Fig. 1. Seven assemblies contain pelletized fuel and two assemblies vibrationally-compacted (vipac) fuel. The central (9 x 9) assembly contains a removable 3 x 3 subassembly (Fig. 2). This entire subassembly or four of its eight rods can be removed for examination without removing the reactor vessel head. The subassembly, containing four vibrationally compacted and four pelletized plutonium bearing rods (as well as one centrally located flux thimble), was previously irradiated for two months in the periphery of the core and achieved burnups of 1,400 Mwd/tonne. The subassembly was transferred to the center of the core during the October loading. Zircaloy-4 cladding was used for the bulk of the plutonium-bearing fuel rods because it is expected to be generally employed in future cores; some Type 304 stainless steel cladding was included for comparison. Table I summarizes the materials selection for the program. All fuel is natural UO_2 enriched to 6.6 w/o PuO_2. The plutonium contained 8.6 w/o Pu-240. The reactor operating conditions for the program are summarized in Table II.



PLAN VIEW OF SAXTON CORE SHOWING FUEL ASSEMBLY LOCATIONS.

FIGURE 1

ENCLOSURE

TOP PLATE

TYPICAL REMOVABLE FUEL ROD

TYPICAL NON-REMOVABLE FUEL ROD

TYPICAL SAXTON REMOVABLE 3 x 3 ASSEMBLY

FIGURE 2

TABLE I

MATERIALS SELECTIONS

Clad	Form	Powder Prep. Method	Fuel Density % T.D.**	No. Rods Inserted In Reactor
Zr-4	Pellets	Mechanical Mixing	94±2	470
Zr-4	Vipac	Mech. Mix. - Nupac*	87±1	138
304 SS	Pellets	Mechanical Mixing	94±2	20
304 SS	Vipac	Mech. Mix. - Nupac*	87±1	10

*Battelle Northwest Laboratories high energy impaction process.

**Percentage Theoretical Density

Following irradiation, selected rods will be examined to evaluate fuel and clad performance. Examination will include:

1. Inspection of fuel assemblies for twist, bow, broken grid structures and fretting corrosion.
2. Determination of clad performance by stereomicroscopic and burst testing.
3. Determination of fuel performance by metallographic examination, fission gas release analyses, burnup analyses, and determination of the radial distribution of Cs_{137}, Sr_{90} and plutonium and uranium isotopes.

TABLE II

SAXTON REACTOR OPERATING CONDITIONS

MAXIMUM POWER LEVEL	23.5 MWt
NOMINAL POWER LEVEL	22.1 MWt
MAXIMUM LINEAR POWER DENSITY	16 KW/FT
MAXIMUM HEAT FLUX	531,400 BTU/HR-FT^2
AVERAGE COOLANT TEMPERATURE	277°C
NORMAL SYSTEM PRESSURE	2,000 PSIG
MAXIMUM CLAD SURFACE TEMPERATURE AT NORMAL PRESSURE	339°C
AVERAGE HOT SPOT CLAD TEMPERATURE (SS)	356°C
AVERAGE HOT SPOT CLAD TEMPERATURE (Zr-4)	367°C
MAXIMUM FUEL CENTRAL TEMPERATURES	2200°C
PEAK BURNUP	> 25,000 MWD/T (Pu + U)
CHEMICAL SHIM	2,000 PPM BORON (MAX.)

The program will provide a statistically valid overall comparison of fuel fabricated by two techniques. In addition, the detailed inpile behavior of PuO_2-UO_2 fuels will be compared with predicted behavior, and performance limitations of PuO_2-UO_2 fuel will be assessed. The program thus will provide a basis for fuel selection for a partial or full core loading of a large water reactor and provide preliminary design information.

II. FUEL SELECTION

A. General

Oxide fuel was chosen for the program because it offers the best compatibility with present water reactor fuel cycles. In selecting the fabrication processes, the following factors were considered:

1. The in-pile reliability of fuel fabricated by the method,
2. the projected economics of the process, and
3. the state of development of the process.

Evaluation of the available evidence led to selection of vibrational compaction and pelletization of mechanically blended fuel. Fuel fabricated by both methods already has been tested in various short-term experiments; testing of bulk quantities of vipac fuel in PRTR is continuing.

Other fabrication methods such as extrusion and swaging, were not considered sufficiently advanced for proof testing in commercial reactors. For example, current swaging techniques introduce residual stresses which may increase defect potential. Although attempts are being made to improve swaging techniques, swaging is not expected to be employed during early phases of plutonium utilization

B. Comparison of Pellet and Vipac Fuel

The available information was insufficient to determine unequivocally which of the two processes selected would be superior. The evidence suggested that vibrational compaction may be the cheaper manufacturing process,[1,2,3,4] but the cost differential cannot be predicted with precision. Also, the in-pile properties of pelletized fuel appeared to be better. Consequently it was decided to test both processes under the program.

In estimating the cost of fabrication by vibrational compaction, previous assumptions were re-examined. One common assumption is that tubing costs will be cheaper for the vibrational compaction process because of relaxed tolerances on the internal diameter. However, tubing for this process may require more stringent specifications on crack depth and length to compensate for possible effects of vibration on the fuel tubes during the vibrational compaction process. Some laboratories have assumed that incremental loading, i.e., vibrating fine PuO_2 particles into a rod containing vibrationally compacted UO_2, could be employed. This assumption should reduce fabrication cost estimates because the process does not require pre-blending the components and densifying the mixture. However, good control of fuel homogeneity may be difficult in this process[5] and its use may require a compensating increase in hot

channel factors. The cost penalties resulting from such an increase are expected to prevent general use of the method by industry.

Another assumption frequently made is that the vibrational compaction process easily yields densities of 89 to 90% theoretical on a production scale. While these densities have been achieved in some laboratories, they represent the maximum capability of the method, rather than values which can be achieved routinely in production. For fabrication of production quantities of fuel, compacted densities of 86-88% of theoretical are considered more realistic. The lower effective fuel density in vibrationally-compacted rods may have an adverse effect on fuel cycle economics.

Because of these assumptions, previous estimates have exaggerated the cost differentials between vibrationally compacted and pelletized fuel. Our analysis of these processes has indicated that vibrationally compacted PuO_2-UO_2 fuel may not be significantly cheaper than pelletized fuel. We estimated the cost of the compaction process to be potentially 5% less than the pellet process only if several optimistic assumptions were made. The two major assumptions were:

a. at least ten rods can be loaded and compacted at a time,

b. arc fused UO_2 is not required.

However, vibrational compaction has a decided advantage for fabrication of unique fuel rod geometries designed for high heat transfer. Furthermore, the perfection of alternate methods for preparing blended and densified PuO_2-UO_2 particles, such as the sol-gel process, may enhance the potential of the compaction process.

Difference in properties and in-pile behavior of the two fuel forms must also be considered in evaluating their relative merits. For example, pellets have a higher thermal conductivity; if fuel operation is limited by central temperature, higher linear power densities can be achieved through the use of pelletized fuel. Conversely, the continuous contact with the clad of vibrationally compacted fuel may partly compensate for the higher thermal conductivity of the pellet. However, good data are lacking for the contact conductance between loose powder and cladding.

The higher density of pelletized fuel results in reduced gas adsorption (e.g., water vapor) and reduced fission gas release

compared to vibrationally-compacted fuel. For thermal reactors of present design, the additional void volume in vibrationally-compacted fuels will accommodate the additional gas release. For high power-high burnup reactors, additional void volume is required. Moreover, in-pile behavior of pelletized fuel (thermal expansion, fuel swelling, and the resultant clad stresses) can be predicted more accurately than the in-pile behavior of vibrationally compacted fuel. Consequently, reactor designs employing pelletized fuel can be based on extrapolation of in-pile performance data at less risk than those employing vibrationally-compacted fuel.

C. Mechanically Mixed Versus Co-Precipitated Fuel

Mechanical blending of the individual PuO_2-UO_2 components was chosen as the powder preparation process because this method is expected to be significantly cheaper than co-precipitation. The lower cost of mechanical mixing accrues from the smaller equipment and less plutonium powder handling required at the wet chemical end of the process where criticality limitations are more severe. While co-precipitation yields a more homogeneous fuel mixture, the homogeneity obtainable by proper mechanical blending is considered ample for thermal reactor applications. Furthermore, there is some evidence that in-pile operation results in additional homogenization of the blended fuel.[6,7] No materials problems are anticipated as a result of using such fuels. Calculations

conducted for the EBWR PuO_2-UO_2 loading show also that the Doppler time delay resulting from the delay in heat transfer between PuO_2 particles and the surrounding UO_2 matrix does not pose a problem in thermal reactors.[8] Although the calculations were conducted for 1.5 w/o Pu enrichment, later calculations showed, as expected, that the time delay decreases as the Pu/U ratio is increased at constant particle size.[9]

D. In-Pile Performance

Pellet Fuel

Satisfactory in-pile performance of PuO_2-UO_2 pellets prepared from either mechanically mixed or co-precipitated powder had been established by irradiation of a number of test samples.[10,11,12,13,14] Pellets with enrichments in the thermal reactor range have been satisfactorily irradiated to exposures of approximately 11,000 MWD/T (U + Pu) at peak rod powers of 38 kw/ft and to approximately 27,000 MWD/T (U + Pu) at peak rod powers of 27 kw/ft.[10] Pellets with high enrichments in the fast reactor range have been satisfactorily irradiated to exposure of 77,400 MWD/T at maximum rod powers of approximately 22 kw/ft.[12] Fission gas release measurements, metallographic examination, and post-irradiation examination and evaluation, in general, indicated that the irradiation performance of PuO_2-UO_2 pellets is similar to that of UO_2.[10,11] The

reliability of pelletized fuel, of course, has been amply demonstrated by extensive irradiation in pressurized water reactors and need not be discussed in detail here. For example, over 100,000 fuel rods, containing over 100,000 kg of Westinghouse pelletized fuel, have been operated commercially without a failure.

Vibrationally Compacted Fuel

a. Evaluation of Defect Potential

Technical feasibility of the vibrational compaction process had been demonstrated by satisfactory in-pile performance of a number of test samples and by irradiation of bulk quantities of fuel rods in the PRTR.[2,6,7,15] Although a number of defects occurred during the early stages of these tests, the causes were identified in almost every case and have been eliminated in subsequent experiments. The net result has been increased confidence in the use of vibrationally compacted fuels; additional tests of vibrationally compacted fuel are being carried out in EBWR.

Thirty-four in-reactor failures occurred in 2,441 full-length UO_2-PuO_2 fuel rods irradiated in PRTR. Thirty-two of the thirty-four failures were attributed to fluoride contamination of the PuO_2, excess moisture content of the fuel, or to traces

of oil introduced by faulty powder attrition apparatus.[15,16,17] These cladding leaks occurred in both vibrationally compacted and swaged UO_2-PuO_2 fuel rods. One of the unexplained defects occurred in a swaged rod irradiated to 5170 MWD/ton; and the other in a vipac rod irradiated to ~5,000 MWD/T. Investigation of the latter defect is continuing.

Five-hundred and thirteen vibrationally compacted, full-length UO_2-PuO_2 fuel rods are currently being irradiated in the PRTR. The maximum exposure is ~10,000 MWD/ton (3/65). This exposure is considered significant since all failures of vibrationally compacted UO_2-PuO_2 rods, except one, that contained possibly contaminated fuel material occurred at less than 400 MWD/ton. The results of the PRTR program were considered in developing fuel specifications for the program.

Chloride, moisture, bad welds and poor spacer design (resulting in fretting) were the main causes of the five defects reported at Savannah River during the early stages of their program.[18,19] Two defects which occurred in swaged rods[20,21] have not been explained to date. Since corrective measures were taken, however, no defects attributable to the vibrational compaction process have been observed for thermal ratings ($\int k\,dT$) up to 40 w/cm.[18,22] The rods have been irradiated

to maximum exposures of 17,000 MWD/ton. While these rods contained only UO_2, there is no reason to suspect different behavior of PuO_2-UO_2 mixtures. Thinly-clad annular elements containing relatively low density fuel and operated at maximum thermal ratings of 50 to 68 w/cm have failed due to ridging of the outer sheath. The ridging apparently resulted from excess void volume in the tube. Such difficulties are not expected with fuel rod designs of contemporary and future thermal reactors.

b. Evaluation of Water Logging and Washout Potential

During the early stages of development of loose powder fuels, fuel washout and water logging in the event of a defect were considered as possible performance limitations. These conjectures were based on: 1) preliminary results of purposely defected fuel rods containing low density fuel (less than 85% TD) which was more susceptible to washout;[23,24] and 2) the reporting of a possible water logging failure of a swaged UO_2 fuel rod by Savannah River - details of which are classified.[25,26] Apprehensions were greatly relieved when the results of an unintentional defect in a swaged fuel rod containing UO_2 at 88% TD were reported.[27] Although the longitudinal split was 1.5 inches long and the reactor was

allowed to run at full power for 15 hours after the defect was detected, only a small amount of UO_2 (a maximum of 10% of the fuel in the area of the split) was eroded out of the rod. Additional out-of-pile tests at the General Electric Laboratories also indicated that vibrationally-compacted, swaged and rolled UO_2 fuels had sufficient erosion resistance to prevent substantial losses to the coolant.[28,29]

No significant fuel washout and no water logging failures were observed for the 34 UO_2-PuO_2 fuel rod cladding failures which occurred in PRTR during the last three years.[16,30] No severe reactor operating difficulties were reported. Reactor pressure and power cycles in several cases after the defects were detected, did not cause water logging failures.

The PRTR results were confirmed by the experience at Savannah River Laboratories. Erosion of UO_2 from vibratory compacted or swaged fuel rods has not been observed although several defects were experienced including the previously mentioned possible water logging failure which had a nine-inch crack.[18,20,21,25,26]

The erosion resistance of loose powder fuels results from high density packing coupled with in-pile sintering. There is some

evidence that in-pile sintering occurs at temperatures as low as 300°C.[31] Other evidence of enhanced sintering in a radiation field has also been reported.[32,33] These results may be explained by the following mechanisms: 1) localized high temperatures resulting in increased rates for all sintering mechanisms; 2) increased bulk and surface diffusion rates resulting from increased vacancy concentrations; and 3) enhancement of the vaporization-condensation process through recoil processes.

Two water logging - washout type failures were reported in 1962. However, both specimens were atypical of fuel elements now being manufactured and cannot be employed to evaluate failure probabilities in loose oxide fuel elements. The first case reported involved the failure of a swaged, MgO-PuO_2 fuel rod exposed for eight days of full power operation in the PRTR.[31] Cladding rupture during continued irradiation after failure resulted from interaction between the MgO and water that caused swelling and loosening of the fuel compact. No such reaction occurs in UO_2-PuO_2 fuels. The initial cladding defect apparently resulted from internal corrosion caused by fluoride contamination in the PuO_2, and release of adsorbed water from the MgO.

The second case reported concerned the failure of a swaged UO_2 fuel rod undergoing transient tests in SPERT.[34] The failure occurred during a 7.5 msec-period power excursion test in which fuel temperature rose by 300°C within 0.02 sec. It is certain that even a water-logged rod containing pellets would burst under these conditions. The initial defects apparently resulted from broken epoxy resin seals used to insert eleven thermocouples into the center regions of the rod. The rod underwent several power excursion tests and remained in the reactor water for two days prior to the last test. Fuel washout occurred because of the large opening, 12 inches wide, and because the fuel had not been irradiated long enough to sinter.

III. MATERIALS PROPERTIES

Previous satisfactory in-pile performance of PuO_2-UO_2 pelletized and vipac fuels had demonstrated the general feasibility of these types of fuel. For this project, however, it still was necessary to estimate the performance of the specific fuel rod design and the particular operating conditions of the Saxton reactor, and to provide other design and licensing groups with materials data required to evaluate design parameters and safety criteria. The information used to evaluate fuel rod performance is summarized below.

A. Melting Point

Although the melting point of the major constituent of a two component system in solid solution is normally expected to be depressed, independent experimenters have verified that an increase in UO_2 melting point occurs for PuO_2 additions up to 10 w/o.[35,36] At temperatures approaching the melting point, mechanically mixed oxide is expected to go into solid solution and hence an increase in melting point is also expected for this type of fuel. For 6.6 w/o PuO_2-UO_2 the reported data indicate an increase of 80°C; this increase was added to the base UO_2 value of 2800°C to obtain the melting point at the beginning of core life. Data obtained under another Westinghouse program showed that the UO_2 melting

point decreases with increasing burnup.[37] The data are shown in Fig. 3. Assuming a peak burnup of 30,000 MWD/T, the minimum melting point of the mixed oxide at the end of core life would be 2770°C. This value was used to evaluate safety margins.

B. Temperature Distribution

The temperature distribution across the fuel is, of course, a major factor in evaluating performance. The method of calculating temperature profiles in fuel elements has been described by Robertson.[38] The method allows for consideration of a variation in thermal conductivity of the fuel with temperature and the effect of neutron self-shielding. The temperature profile in a solid cylindrical rod is given by the relationship

$$\int_{T_s}^{T_o} k\,dT = \frac{q}{4\pi} \left\{ \frac{Io\,(Ka) - 1}{0.5\,(Ka)\,I_1\,(Ka)} \right\}$$

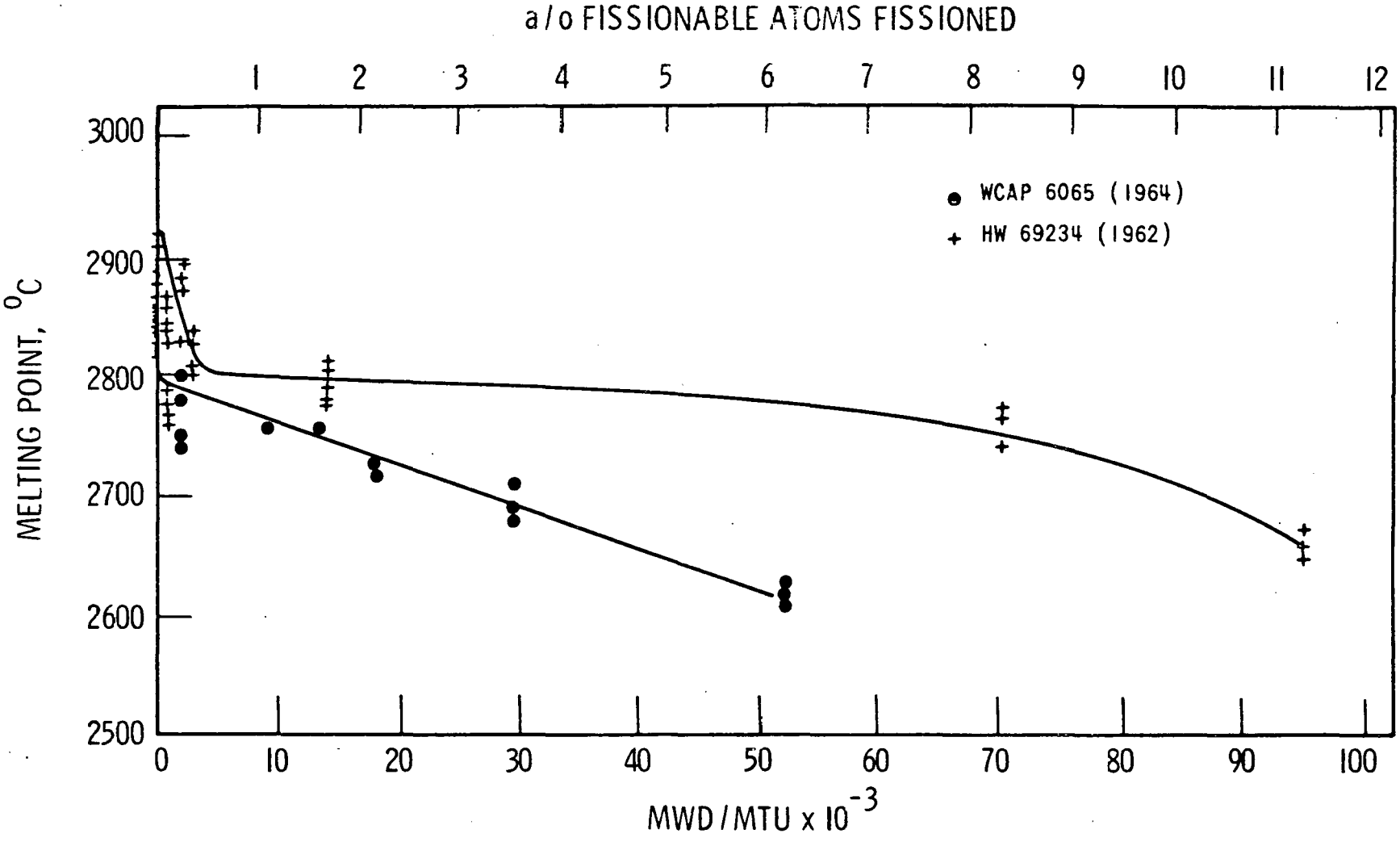
where

T_o and T_s are fuel central and fuel surface temperatures respectively

q is the linear heat rating watts/cm

k is the thermal conductivity watts/cm-°C

K is the inverse diffusion length for neutrons in the fuel, cm^{-1}



MELTING POINT OF IRRADIATED URANIUM DIOXIDE

FIGURE 3

I_o and I_1 are the modified Bessel functions of the zero and first order respectively

a is the radius of the fuel rod, cm

Flux Depression Factor

Values for the flux depression factor, $(I_o\ (Ka)-1)/0.5\ (Ka)I_1(Ka)$, given by Robertson are for U-235 enriched fuels in a specific reactor and could not be employed for this program. For the present program the quantity (Ka) was determined by the Wigner rational approximation:

$$(\bar{\phi}/\phi_s) = 1/(1 + a\Sigma_a) = 2I_o(Ka) \ / \ (Ka)\ I_o\ (Ka)$$

where $\bar{\phi}$ is the mean thermal neutron flux in the rod

ϕ_s is the thermal flux at the periphery of the rod

Σ is the macroscopic thermal neutron absorption cross section

From a knowledge of "a" and Σ_a, the equation was solved for (Ka) and hence K. Σ_a is dependent on the isotopic composition of the fissile oxide material.

Numerical values of Σ_a for the Saxton reactor calculated by the nuclear design group are given in Table III for 95% theoretically dense plutonium dioxide-natural uranium dioxide fuel.

TABLE III

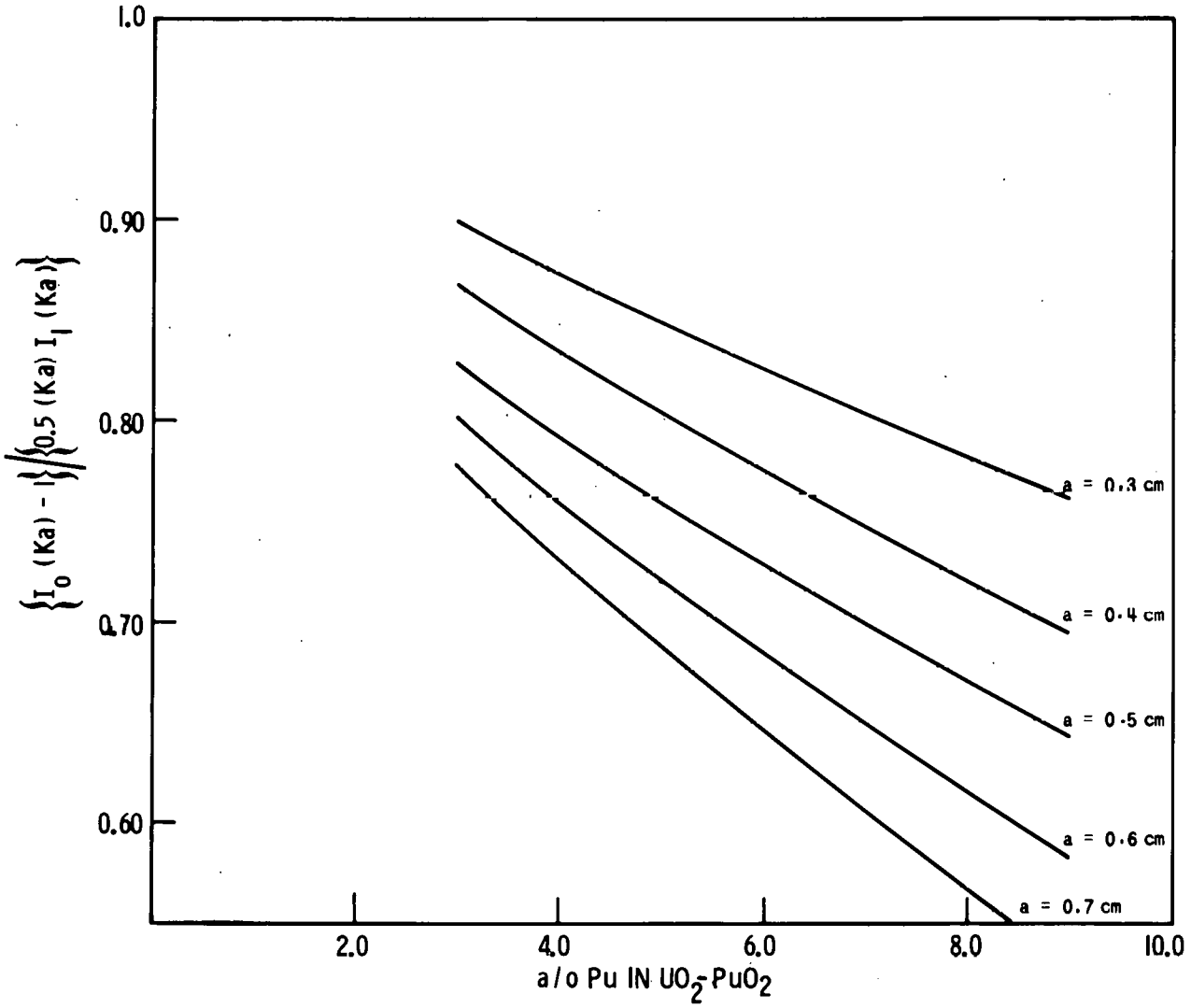
MACROSCOPIC THERMAL NEUTRON ABSORPTION CROSS SECTIONS

Plutonium (Atom - %)	Σ_a (cm^{-1})
3.98	0.9005
5.04	1.1036
5.97	1.2754
7.96	1.6292

Computed values of the flux depression factor are given in Fig. 4 as a function of the plutonium content of the mixed oxide fuel for a range of rod radii of 0.3 cm to 0.7 cm.

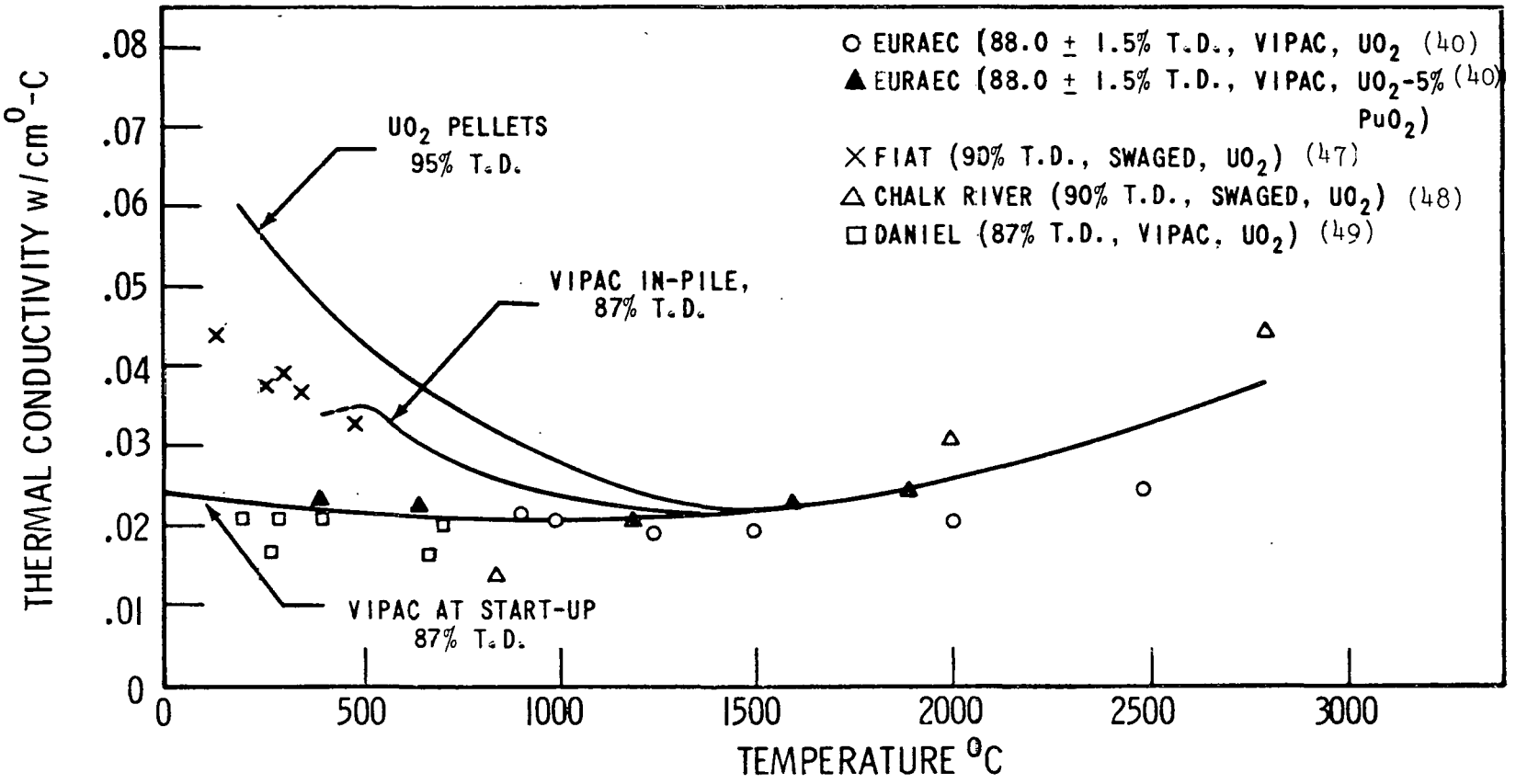
Thermal Conductivity

At the time the materials design was being developed, no thermal conductivity data for PuO_2-UO_2 pellets were available. The thermal conductivity temperature curve for UO_2 fuel, shown in Fig. 5 therefore was used to estimate the temperature distribution. Adequate safety margins were included in the design in the event a significant reduction of the thermal conductivity resulted from addition of PuO_2. A significant reduction was not expected,



VARIATION OF FLUX DEPRESSION FACTOR WITH ROD RADIUS AND ENRICHMENT, 95% THEORETICALLY DENSE MATERIAL

FIGURE 4



THERMAL CONDUCTIVITY CURVES FOR PELLETIZED AND VIBRATIONALLY COMPACTED FUEL

FIGURE 5

however. At the lower temperatures, the discreet PuO_2 particles do not significantly diffuse into the UO_2. Some diffusion results from sintering during fabrication but PuO_2 particle domains can be identified by autoradiography. Hence, for thermal conductivity considerations, the mixture can be assumed to consist of a UO_2 matrix containing dispersed PuO_2 particles. The thermal conductivity of such a system (with a dilute second phase) approximates that of the matrix as indicated by the Rayleigh-Maxwell equation:[39]

$$k_m = k_c \frac{1 + 2V \frac{1 - k_c/k_d}{2\, k_c/k_d + 1}}{1 - V \frac{1 - k_c/k_d}{2\, k_c/k_d + 1}}$$

where k_m, k_c and k_d are the thermal conductivities respectively of the mixture, the continuous matrix phase (UO_2), and the discontinuous phase (PuO_2), and V is the volume fraction of the discontinuous phase. For $k_c >> k_d$ the equation reduces to

$$k_m = k_c \frac{1 - V}{1 + V/2}$$

and for $k_d >> k_c$, it reduces to

$$k_m = k_c \frac{1 + 2V}{1 - V}$$

For 6.6 w/o PuO_2 in UO_2, the limits of k_m are 0.91 k_c to 1.32 k_c. Also, data developed at the Belgo-Nucleaire Laboratories for UO_2 and for mechanically-mixed 5 w/o PuO_2-UO_2 vipac fuels suggest that

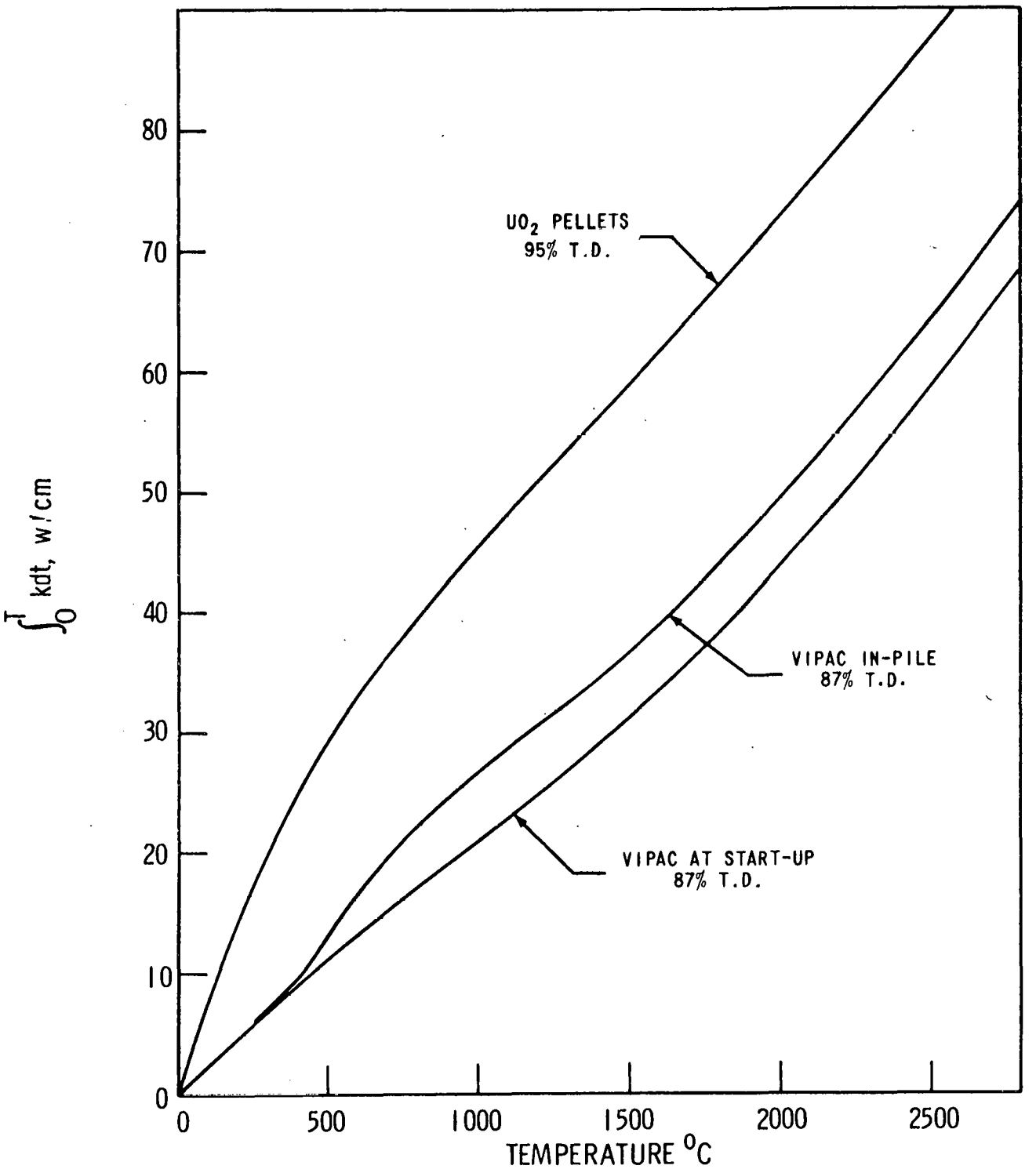
below 1000°C the thermal conductivities are essentially equal.[40] At high in-pile temperatures, significant diffusion of PuO_2 into the UO_2 matrix probably occurs. At elevated temperatures, however, the effect on thermal conductivity of solid solution formation is normally small. Hence no significant reduction in thermal conductivity was anticipated. In fact the Belgo-Nucleaire experiments cited above indicate that mixed oxide has a higher thermal conductivity than UO_2 at high temperatures (above 1250°C). The increase may have been due to loss of oxygen from PuO_2 resulting in substoichiometric fuel. The hotter region of fuel in-pile may also lose small amounts of oxygen to the cooler fuel regions resulting in increased thermal conductivities for the central portions of the fuel.

In the case of vipac fuel very little data existed even for UO_2 fuel. However, a thermal conductivity-temperature curve (Fig. 5) was established from the available data and the expected behavior of vipac fuel. Above 1500°C the curve was assumed to coincide with the pellet design curve on the basis that the sintering and densification rates are rapid enough that vipac fuel will behave as a pellet of approximately 95% T.D. Although the available data in this region are consistent with the curve, additional verification is required. Two curves are shown for the lower temperatures,

one for start-up and one for in-pile operation. Improved thermal conductivity for the latter case was assumed to result from in-pile sintering. Evidence of enhanced in-pile sintering and improved thermal conductivity has been reported in the literature.[31,32,33] However, sintering at low temperatures results in bridging of the particles to form a continuous network, but does not result in significant shrinkage. Consequently, vipac fuel below 1000°C was assumed to behave as a pellet of 88% T.D. The effective thermal conductivity of high density pellets has been correlated to the 100% T.D. value by a porosity factor of (1-P),[41] while for low densities a factor of (1-2P)[42] has been employed (where P is the volume fraction of porosity). To retain conservatism in the design, the in-pile curve between 500 and 1000°C was based on a (1-2P) porosity correction factor applied to the current thermal conductivity curve for pellets. Integrated thermal conductivity curves for both pelleted and vipac fuel are shown in Fig. 6.

Contact Conductance

The remaining parameters required to estimate fuel temperature distribution are the thermal contact and gap conductances. A thorough study of these parameters for pelletized UO_2 fuels had been conducted previously by Westinghouse. Results of this study were assumed applicable to PuO_2-UO_2 pellets. No data, however, were available for vipac fuel and no reliable calculational methods



HEAT RATING CURVES FOR VIPAC AND PELLETIZED FUEL

FIGURE 6

existed. A rough approximation can be obtained by assuming that vipac fuel contact conductance is (1-2P) times that of pellet fuel for equal contact pressures. This approximation gives a value of 1,000 BTU/hr/ft/°F if the pellet value at slight contact pressure is used. This value was used for design purposes. In-pile data on UO_2 vipac fuel obtained from another Westinghouse program[43] were used to estimate that this value was reasonable.

The data were used to calculate the contact conductance from the equation:

$$h = \frac{Q}{T_s - T_i}$$

where h is the contact conductance in BTU/hr/ft^2/°F, Q is the surface heat flux in BTU/hr/ft^2, and T_s and T_i are the fuel surface and clad I.D. temperatures respectively in °F. T_i was calculated from the known clad O.D. temperature, the thermal conductivity of the stainless steel cladding and the surface heat flux obtained from burnup data. T_s was calculated from the equation:

$$\int_{T_r}^{T_s} k\,dT = \frac{q}{4\pi} \left\{ \frac{I_o(Ka) - I_o(Kr)}{0.5\ Ka\ I_1(Ka)} \right\}$$

where T_r is the fuel temperature at radius r, and the remaining symbols are as previously defined.

T_r was determined from pore migration phenomena, q from burnup data, K from the method described previously using GETR cross sections, and the $\int k dT$ from the previously established heat rating curves. The density of the fuel employed in the particular experiment evaluated was 86.7% T.D. Three cross sections of the capsule were examined. The 1850°C isotherm radius was used for all calculations. The results are summarized in Table IV.

Although the variation in results is rather large, this analysis indicates that the design value of 1,000 BTU/hr/ft^2/°F, when used with the established heat rating curves, is conservative.

TABLE IV

CONTACT CONDUCTANCE FOR VIBRATIONALLY COMPACTED FUEL

Q, BTU/hr/ft^2	$T_s - T_i$, °F	h, BTU/hr/ft^2/°F
4.87×10^5	241	2020
4.68	223	2100
4.42	385	1145
	Average	1755 ± 23%

C. Clad Hydriding

The hydrogen pickup by the Zircaloy clad and the thickness of the ZrO_2 coating formed in-pile were calculated for linear rod powers of 16 Kw/ft and assuming 40% down time for the reactor. A computer code previously developed at Westinghouse was used for the calculations.[44] The hydrogen level at the end of life was calculated to be 71 ppm. All hydrogen in the fuel (from water and other sources) was assumed to be available for clad hydriding when establishing fuel specifications. The level was specified such that the amount available from the fuel added to 71 ppm was less than 275 ppm H_2 in the clad at the end of life. This conservative limit was based on initial evaluation of hydriding problems which were in progress at Westinghouse when the Saxton specifications were determined. More recent evaluations indicate that hydrogen contents significantly above this level can be tolerated. The temperature drop across the ZrO_2 film was calculated to be 12°F using 0.93 BTU/hr/ft/°F for the film conductivity.

D. Plutonium Migration

The question of possible operating difficulties resulting from plutonium migration was considered. Based on a review of the available evidence, no difficulties with migration were anticipated for the Saxton reactor operating conditions. Bailey and Chikalla irradiated to burnups ranging from 352 to 19,600 MWD/T mechanically

mixed oxide pellets with Pu concentrations ranging from 0.0259 to 7.45 Mol % and densities from 63 to 93% T.D.[10] Although they observed significant migration of Cs-137 and Ru-106, essentially no migration of Pu was observed even at the highest rod power (38 Kw/ft).

Radiation tests on EBWR prototype capsules (vipac fuel enriched with 1.5 wt % PuO_2 and 2.5 wt % PuO_2) illustrated rod power effects.[7] At a power level of approximately 10 Kw/ft, little change in the autoradiograph of the specimens was observed. At slightly higher levels, approximately 11 Kw/ft, grain growth and homogenization of the fuel were noted at the center of the rod. At approximately 13 Kw/ft particles believed to be a combination of U, Pu and fission products increased the density of the autoradiograph at the grain growth regions of the specimens. At above 30 Kw/ft these particles agglomerated and formed an annular ring within the grain growth regions. In all cases these concentrations of fission products and unidentified particles were near the center of the fuel. Autoradiographs of UO_2 pellets with similar irradiation histories show similar effects. Some evidence of plutonium migration in U-235 enriched fuel has been reported.[45] In no case, however, has particle agglomeration in either Pu or U-235 enriched fuels been significant enough to cause operating difficulties.

E. Fuel-Clad-Compatibility

Another question investigated was the possibility of a Zr-fuel reaction. No difficulties were anticipated.

Reaction of PuO_2-UO_2 fuel with zirconium clad has never been observed in any of the PRTR fuel rods or in capsules operating as high as 30 Kw/ft. The only case where reaction of PuO_2-UO_2 fuel with Zircaloy was observed was in a capsule operated at a surface heat flux of 1,000,000 BTU/hr/ft^2. Out-of-pile tests have shown that PuO_2 will react with Zircaloy-2 at 1093°C.[46] There is no evidence, however, that the reaction will occur at the Saxton clad temperatures (391°C maximum).

IV. FUEL SPECIFICATIONS

Fuel specifications developed for the program were based on normal Westinghouse UO_2 specifications, with adjustments and additions made where necessary to reflect the presence of plutonium and to accommodate differences in fabrication methods between U-235-enriched and plutonium-enriched fuel. With perhaps one exception (vipac total gas release) the specifications readily could be met by an experienced UO_2 fabricator. The results of the PRTR program were considered in developing both the pellet and vipac fuel specifications. In the case of vipac fuel, published specifications for the EBWR program were used as a guide to evaluate and to adjust for differences between the normal Westinghouse pelletizing process and what could be achieved by Hanford's "Nupac" process.

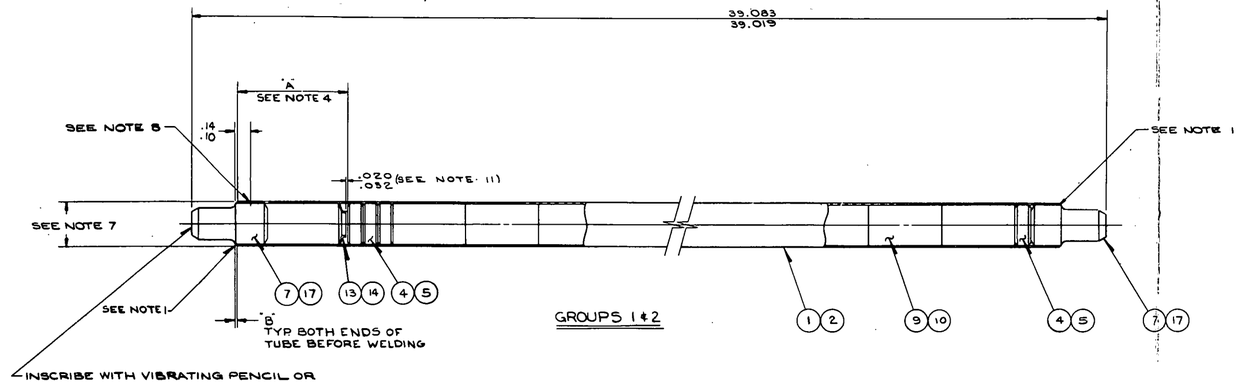
The first set of specifications developed were reviewed in detail with the fabricators chosen. (NUMEC for pelletized fuel and Hanford for vipac fuel) Both fabricators requested numerous changes. Most changes were accepted because they could be accommodated by adjustments in fuel rod designs which were not firm at the time of initial discussions. The specifications which were finally set by Westinghouse, approved by the AEC and agreed to by the fabricators are included at the end of this section as SAX-P001, SAX-P002, SAX-P003, and SAX-P004. Complementary

design specifications required to fabricate reliably the fuel rods are included on the drawings shown in Figs. 7A to 7D.

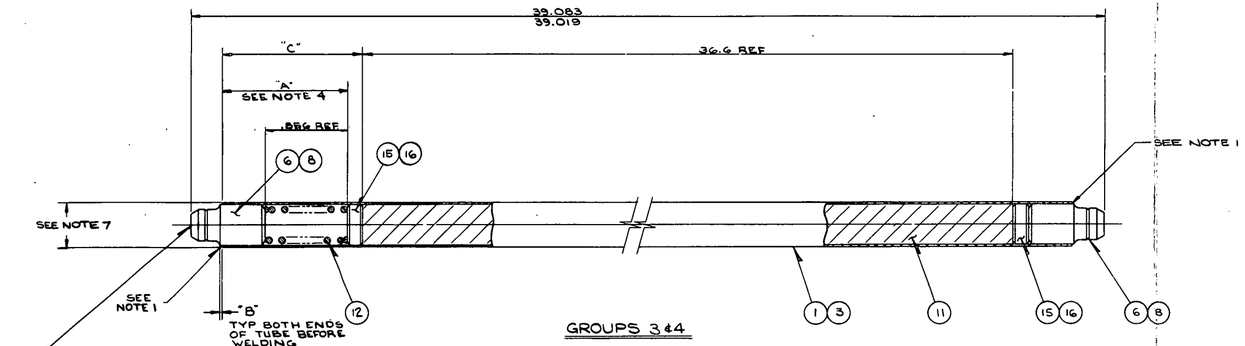
Discussion of the major differences between these specifications and those normally employed for pelletized UO_2 follows:

a. The nitrogen level was increased from 30 ppm normally used for UO_2 pellets to 75 ppm. This change was made because the sintering atmosphere used for PuO_2-UO_2 pellets is a non-explosive 8% H_2-N_2 mixture compared to 100% H_2 used for UO_2 and thus additional nitrogen pickup was anticipated. Increased N_2 impurity was also assumed for arc-fused UO_2 used in the vipac process because the material is prepared under a N_2 atmosphere. For vipac fuel the limit was increased to 100 ppm at the request of the Hanford Laboratories.

b. The limits of oxygen-to-metal ratio for pelletized fuel were changed from 2 $\pm$ 0.02 to 1.97 to 2.02 at the request of Numec. The broader limits were requested because partial reduction of the PuO_2 often occurs during sintering, although the factors controlling the degree of reduction are not well understood. The change was accepted because a shift towards substoichiometric fuel results in improved thermal conductivity and no deleterious effects were anticipated.



INSCRIBE WITH VIBRATING PENCIL OR ELECTRO-ETCH IDENTIFICATION NUMBER ON TOP END PLUG WITH CONSECUTIVE NO'S. SEE NOTE 2.



INSCRIBE WITH VIBRATING PENCIL OR ELECTRO-ETCH IDENTIFICATION NO. ON TOP END OF PLUG WITH CONSECUTIVE NO'S. SEE NOTE 2

GROUP	DIM. A	DIM. B	DIM. C
1	1.112 / .982	.014 / .020	—
2	1.237 / 1.107	.020 / .026	—
3	1.179 / 1.040	.014 / .020	1.483 / 1.170
4	1.295 / 1.165	.020 / .026	1.608 / 1.295

BILL OF MATERIAL

NOTE	ITEM	TITLE	DRAWING & GR. OR IT.	MATERIAL SPECIFICATION	EQUIVALENT SPECIFICATIONS FOR ⓦ USE ONLY	NO. REQ. GR. 1	GR. 2	GR. 3	GR. 4	GR. 5
	1	FUEL TUBE	4998772 IT. 4			1	—	1	—	
	2	FUEL TUBE	4998772 IT. 6			—	1	—	—	
	3	FUEL TUBE	674C863 IT. 1			—	—	—	1	
	4	FILLER	4988981 IT. 1			AS REQ.	—	—	—	
	5	FILLER	4988981 IT. 2			—	AS REQ.	—	—	
	6	END PLUG	674C886 IT. 2			—	—	2	—	
	7	END PLUG	674C886 IT. 3			—	2	—	—	
	8	END PLUG	674C886 IT. 1			—	—	—	2	
Y	9	PELLET STACK	5008071 GR. 2			1	—	—	—	
Y	10	PELLET STACK	5008071 GR. 3			—	1	—	—	
X/	11	FUEL COLUMN				—	—	AS REQ.	AS REQ.	
	12	SPRING	5008086 - IT. 1			—	1	1	1	
	13	SPRING	5008157 IT. 1			1	—	—	—	
	14	SPRING	5008157 IT. 2			—	1	—	—	
	15	FILLER	5008158 IT. 1			—	—	AS REQ.	—	
	16	FILLER	5008158 IT. 2			—	—	—	AS REQ.	
	17	END PLUG	674C886 IT. 4			2	—	—	—	

'X' - FUEL COLUMN TO CONSIST OF A MIXTURE OF URANIUM DIOXIDE & PLUTONIUM DIOXIDE POWDER VIBRATORY COMPACTED IN ACCORDANCE WITH WAPD APPROVED PROCEDURE TO A DENSITY OF 87 ± 1% OF THEORETICAL. POWDER TO BE PREPARED FOR COMPACTION BY DYNAPAK OR EQUIVALENT PROCESS. ENRICHMENT OF UO_2, OXIDE COMPOSITION, PuO_2 CONTENT, AND PARTICLE SIZE & DENSITY FOR POWDER TO BE SPECIFIED ON P.O.

'Y' - GAS & VAPOR CONTENT OF FUEL TO BE LIMITED TO FOLLOWING:

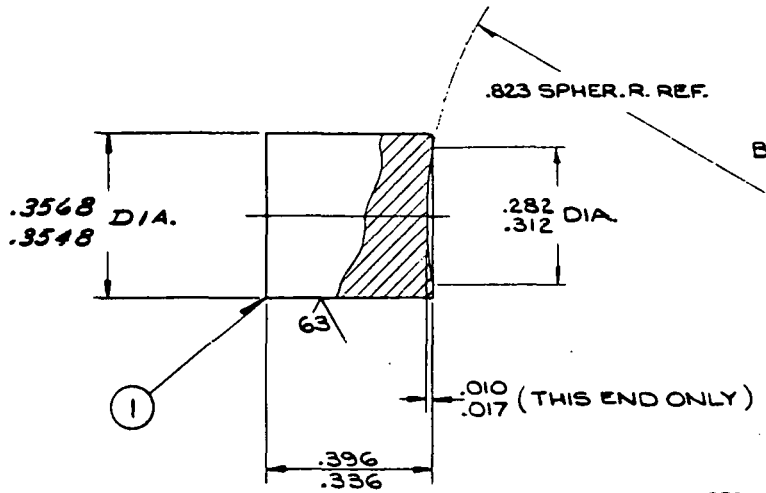
GROUPS 1 & 2 — H_2O - 30 PPM
N_2 - 75 PPM
H_2 - 15 PPM
TOTAL GAS - .08 cc/gm (EXCLUSIVE OF H_2O)

GROUPS 3 & 4 — H_2O - 100 PPM
N_2 - 100 PPM
H_2 - 20 PPM (Si-H & C-H BONDS)
TOTAL GAS - .06 cc/gm (EXCLUSIVE OF H_2O)

NOTES:

1. WELD PROCEDURE & INSPECTION TO BE APPROVED BY WAPD.
2. RECORD IDENT. NO., FUEL WT. & METAL WT.
3. MOISTURE CONTENT OF FUELS PRIOR TO WELDING TO BE AS SPECIFIED IN NOTE 'Y'. TUBE MUST BE DRY.
4. USE ONE FILLER AT BOTTOM OF FUEL TUBE AND ADD FILLERS TO TOP END AS NECESSARY (MIN. OF ONE ADDITIONAL AT TOP END TO OBTAIN THIS DIMENSION.
5. ROD ASS'Y MUST BE STRAIGHT WITHIN .010 PER FT. BETWEEN END PLUG WELDS WHEN LYING ON A SURFACE PLATTE.
6. PRIOR TO ASS'Y, WIPE INSIDE & OUTSIDE SURFACES OF TUBE, SPACER, END PLUGS, & SPRING (USE ALCOHOL ONLY AS A SOLVENT) WITH SWABS TO REMOVE ALL FOREIGN MATTER. WIPE WITH DRY SWAB AFTER CLEANING.
7. MAX. DIA. PERMITTED AFTER WELDING AS FOLLOWS: GROUPS 1 & 3 - .395 DIA. GROUPS 2 & 4 - .399 DIA (BEFORE PICKLING) ALL SURFACES IN WELD AREA TO HAVE SMOOTH TRANSITION. CAUTION ! NO GRINDING OF TUBE WALL PERMITTED. ROLLING OF WELDS PERMITTED PROVIDED THE OPERATION DOES NOT EXTEND OVER THE UNSUPPORTED CLAD AREA. THE ROLLING PROCEDURE IS TO BE APPROVED BY W APD ENGINEERING.
8. PRICK PUNCH END PLUGS OF GROUPS 1 & 2 AT 3 EQUALLY SPACED LOCATIONS TO OBTAIN .001/.003 INTERFERENCE FIT WITH TUBE. CAUTION ! REMOVE ALL SHARP EDGES IN RAISED METAL CAUSED BY PRICK PUNCHING SO AS NOT TO SCORE I.D. OF TUBE. (TYP BOTH ENDS)
9. FUEL ROD ASS'YS (GRS. 2 & 4) TO BE CORROSION TESTED AFTER WELDING IN ACCORDANCE WITH W APD APPROVED PROCEDURE. MAX. TUBE & WELD DIA. AFTER PICKLING TO BE .397
10. THIS DIMENSION TO BE ESTABLISHED BY SPRING INSERTION TOOL & IS NOT AN INSPECTION REQUIREMENT.

FIGURE 7A - Non-Removable Saxton Plutonium Fuel Rods



BILL OF MATERIAL						NO. REQ.			
NOTE	ITEM	TITLE	DRAWING & GR. OR IT.	MATERIAL SPECIFICATION	EQUIVALENT SPECIFICATION FOR (T) USE ONLY	GR. 1	GR. 2	GR. 3	
A/B	1	PELLET				1			

NOTES:

A. TO BE SINTERED BY WAPD APPROVED PROCESS FROM URANIUM DIOXIDE & PLUTONIUM DIOXIDE POWDER. PLUTONIUM DIOXIDE CONTENT OF POWDER AND ENRICHMENT OF URANIUM DIOXIDE TO BE AS SPECIFIED ON P.O. FINAL DENSITY OF PELLET TO BE 94 ± 2% OF THEORETICAL DENSITY.

B. POWDER TO BE PREPARED BY MECHANICAL MIXING AS SPECIFIED ON P.O.

FULL SIZE OUTLINE

250/ ALL OVER UNLESS OTHERWISE SPEC.

SEE PROCESS SPECIFICATION NO CAP535128-1 FOR SUPPLEMENTARY MANUFACTURING INFORMATION

UNLESS OTHERWISE SPECIFIED THE FOLLOWING TOLERANCES APPLY

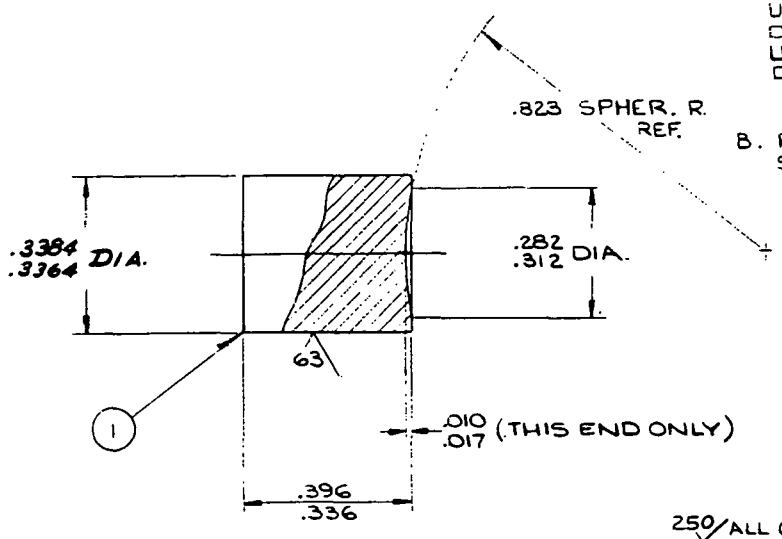
STRAIGHTNESS, FLATNESS, SQUARENESS, ROUNDNESS, PARALLELISM, AND ANGULARITY VARIATIONS ARE PERMITTED WITHIN THE PROFILE ESTABLISHED BY THE LIMITS OF SIZE.

CONCENTRICITY MUST BE WITHIN THE SUM OF THE TOLERANCES (TIR) OF THE DIAMETERS BEING COMPARED — SURFACE ROUGHNESS IN MICRO-INCHES: 250 OR BETTER.

ALL EDGES OR CORNERS .005 - .020 (APPROXIMATE RADIUS OR CHAMFER). — ALL DIMENSIONS CORRECTED TO 70°F ± 2°F.

SCREW THREADS PER ASA B1.1. — PIPE THREADS PER ASA B2.1. — WELD DIMENSIONS ARE MINIMUM

FIGURE 7B - Saxton Plutonium Pellet Drawing for Zr-4 Cladding



BILL OF MATERIAL						NO. REQ.			
NOTE	ITEM	TITLE	DRAWING & GR. OR IT.	MATERIAL SPECIFICATION	EQUIVALENT SPECIFICATION FOR Ⓢ USE ONLY	GR. 1	GR. 2	GR. 3	
A, B	1	PELLET				1			

NOTES:

A. TO BE SINTERED BY WAPD APPROVED PROCESS FROM URANIUM DIOXIDE & PLUTONIUM DIOXIDE POWDER. PLUTONIUM DIOXIDE CONTENT OF POWDER AND ENRICHMENT OF URANIUM DIOXIDE TO BE AS SPECIFIED ON P.O. FINAL DENSITY OF PELLET TO 94 ± 2% OF THEORETICAL DENSITY.

B. POWDER TO BE PREPARED BY MECHANICAL MIXING AS SPECIFIED ON P.O.

FULL SCALE OUTLINE

250/ ALL OVER UNLESS OTHERWISE SPECIFIED

SEE PROCESS SPECIFICATION NO. CAP595128-1 FOR SUPPLEMENTARY MANUFACTURING INFORMATION

UNLESS OTHERWISE SPECIFIED THE FOLLOWING TOLERANCES APPLY

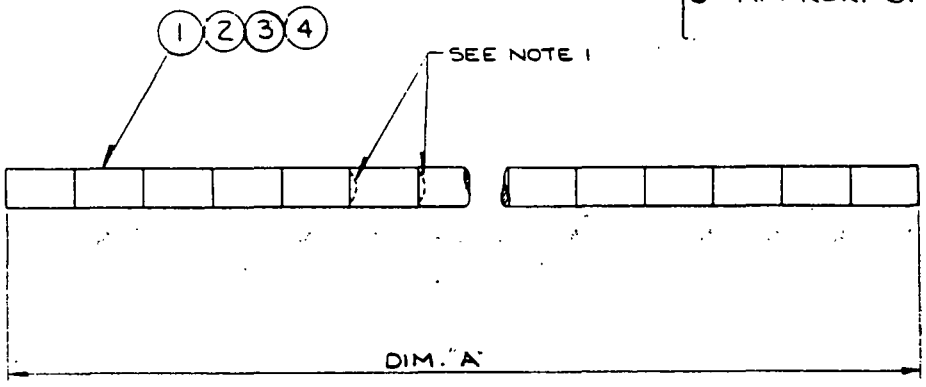
STRAIGHTNESS, FLATNESS, SQUARENESS, ROUNDNESS, PARALLELISM, AND ANGULARITY VARIATIONS ARE PERMITTED WITHIN THE PROFILE ESTABLISHED BY THE LIMITS OF SIZE.

CONCENTRICITY MUST BE WITHIN THE SUM OF THE TOLERANCES (TIR) OF THE DIAMETERS BEING COMPARED. — SURFACE ROUGHNESS ON HOLES: 250/ OR BETTER.

ALL EDGES OR CORNERS .005 - .020 (APPROXIMATE RADIUS OR CHAMFER). — ALL DIMENSIONS CORRECTED TO 70° F ± 2° F.

SCREW THREADS PER ASA B1.1. — PIPE THREADS PER ASA B2.1. - HELD DIMENSIONS ARE MINIMUM

FIGURE 7C - Saxton Plutonium Pellet Drawing for 304 SS Cladding



BILL OF MATERIAL

NOTE	ITEM	TITLE	DRAWING & GR. OR IT.	GR.1	GR.2	GR.3	GR.4	GR.5	GR.6	GR.7	GR.8	GR.9
C	1	FUEL PELLET	500 B 069 IT. 1	AS REQ	-	-	-					
D	2	FUEL PELLET	500 B 077 IT. 1	-	AS REQ	-	-					
D	3	FUEL PELLET	500 B 078 IT. 1	-	-	AS REQ	-					
D	4	FUEL PELLET	500 B 078 IT. 1	-	-	-	AS REQ					

D- APPROX. 100 PELLETS REQUIRED.
C- APPROX. 61 PELLETS REQUIRED.

NOTE:
1. PELLETS IN GROUPS 2,3,&4 MUST BE STACKED WITH DISHED ENDS ALL ORIENTED IN SAME DIRECTION.

DIM "A"	GR. NO.
36.90 36.30	1
36.783 36.417	2
36.783 36.417	3 & 4

SEE PROCESS SPECIFICATION NO. CAP5935129-1 FOR SUPPLEMENTARY MANUFACTURING INFORMATION.

UNLESS OTHERWISE SPECIFIED THE FOLLOWING TOLERANCES APPLY

STRAIGHTNESS, FLATNESS, SQUARENESS, ROUNDNESS, PARALLELISM, AND ANGULARITY VARIATIONS ARE PERMITTED WITHIN THE PROFILE ESTABLISHED BY THE LIMITS OF SIZE. CONCENTRICITY MUST BE WITHIN THE SUM OF THE TOLERANCES (T.I.R.) OF THE DIAMETERS BEING COMPARED. — SURFACE ROUGHNESS OF HOLES: 250 OR BETTER. ALL EDGES OR CORNERS .005 - .020 (APPROXIMATE RADIUS OR CHAMFER). — ALL DIMENSIONS CORRECTED TO 70° F = 21° F SCREW THREADS PER ASA B1. 1. — PIPE THREADS PER ASA B2. 1. - WELD DIMENSIONS ARE MINIMUM

FIGURE 7D - Saxton Plutonium Pellet Stack Drawing

c. The limit for moisture content in vipac fuel was increased from 30 ppm normally employed for pellets to 100 ppm. This increase was necessary because control of moisture content is more difficult for vipac fuel than for pelletized fuel. It should be noted, however, that the total hydrogen content (as water and other forms) specified for both fuels used for the program is essentially the same. In the case of vipac fuel the specification for H_2 contained in oil as C-H or Si-H groups (SAX-P002 - 4.1.5) is equivalent to approximately 5 ppm of H_2. This value added to the hydrogen content of 100 ppm of water yields 16 ppm. Although significant amounts of hydrogen from other sources in the vipac fuel was not expected, it was indirectly controlled by the total gas release specification (SAX-P002 - 4.1.8). If all the gas released at 1000°C were hydrogen (definitely not the case) this would be equivalent to approximately 5 ppm of H_2 in the fuel. In the case of pelletized fuel, Numec employed hot extraction techniques to analyze hydrogen content from all sources except water. A limit of 15 ppm was set for the hot extraction test which when added to the H_2 content of 30 ppm of water (SAX-P001 - 5.1.6) yields approximately 18 ppm.

d. Particle size limitations were specified for the PuO_2 and UO_2 powders employed in preparing PuO_2-UO_2 feed for either process

(SAX-P001 - 6.2 and SAX-P002 - 5.1). Such limitations, not normally required for UO_2 fuel, are necessary when using the mechanical mixing technique to aid in assuring satisfactory plutonium distribution. The limitations were based on Doppler time delay calculations conducted for the EBWR program, and on examination of autoradiographs of a series of PuO_2-UO_2 blends prepared with various size fractions. Blends prepared from minus 325 mesh PuO_2 and minus 65 mesh UO_2 (or smaller particle size) were found satisfactory.

e. Requirements for autoradiographs of samples from each batch of fuel prepared were added to the normal UO_2 specifications to aid in evaluating whether a satisfactory degree of plutonium homogeneity had been achieved.

f. Normal welding specifications for UO_2 fuel rods were significantly changed because the PuO_2-UO_2 fuel rods (particularly the vipac rods) had to be welded in the vertical position to avoid plutonium alloying and resultant contamination of the weld zone. The normal Westinghouse butt weld is not applicable to vertical rod welding and a fillet type weld suggested by Hanford and agreed to by Numec was used. Because this type of weld cannot be examined properly by x-ray techniques, destructive examination of dummy rods welded in-box with each lot of rods was required to assure quality control.

g. Finished fuel rod contamination requirements were added to the UO_2 specification because of the potential plutonium health hazard (SAX-P003 - VII B and SAX-P004 - VII B).

h. The total gas release specification was raised from 0.@5 to 0.06 cc/gm. in the case of vipac fuel (SAX-P002 - 4.1.8). This specification was difficult to achieve and probably should be further relieved for future programs unless improved techniques are developed. Increased plenum volume may be needed in each fuel rod to compensate for the additional gas release.

WESTINGHOUSE SPECIFICATION SAX-P001

PLUTONIUM DIOXIDE-URANIUM DIOXIDE PELLETS

1.0 This specification applies to solid cylindrical plutonium dioxide-uranium dioxide fuel pellets for nuclear power reactors.

2.0 No change shall be made in the quality of successive shipments of material furnished under this specification without first obtaining the approval of the purchaser.

MANUFACTURE

3.0 Manufacture

The pellets shall be manufactured by cold pressing and sintering. No materials shall be added to the PuO_2-UO_2 except small quantities of organic binders and/or an organic lubricant needed for pelletization.

4.0 Financial Responsibility

The manufacturer shall be financially responsible for all losses and contamination occurring in his pelletizing operation, including repurification, reconversion into a form acceptable to AEC and unrecoverable losses of uranium and plutonium, all related shipping charges, and any use charges, unless otherwise specified on the Purchase Order.

CHEMICAL PROPERTIES AND TESTS

5.0 Chemical Composition: The pellets shall conform to the following chemical composition:

5.1 Group I Requirements:

5.1.1 Elements

Element	ppm (Max)	Macroscopic Cross Section (2200 m/sec) Imparted by This Level of Impurity $cm^2/cm^3 \times 10^{-5}$
Al	300.0	1.5
B	1.5	63.7
Bi	2.0	0.0002
Ca	100.0	0.66
Cd	1.0	28.0
Co	6.0	2.3
Cr	500.0	18.3
Cu	50.0	1.75

For additional elements see next page.

Element	ppm (Max)	Macroscopic Cross-Section (2200 m/sec) Imparted by This Level of Impurity $cm^2/cm^3 \times 10^{-5}$
Fe	500.0	13.6
In	3.0	3.0
Mg	50.0	0.08
Mn	10.0	1.5
Mo	150.0	2.4
Ni	300.0	14.4
Pb	20.0	0.010
Si	500.0	1.4
Sn	5.0	0.015
Ti	40.0	3.1
V	1.0	0.059
W	50.0	3.0
Zn	20.0	0.21
C	100.0	0.016
F	10.0	0.0007
N	75.0	6.2
Cl	10.0	

5.1.2 The ratio of oxygen to metal in the plutonium-uranium pellet shall be between 1.97 and 2.02. Vendor shall submit details of their test procedure for approval.

5.1.3 The hydrogen content (exclusive of any amount contributed by water) shall not exceed 15 ppm. Vendor shall submit details of their test procedure for approval.

5.1.4 Plutonium-Uranium Ratio - The ratio of plutonium to uranium in any pellet sample shall be 0.071 ± 0.001.

5.1.5 **The total rare earth composition (Gd, Sm, Eu and Dy) shall not exceed 0.6 ppm. For calculation of the total thermal neutron absorption cross-section, the macroscopic cross-section absorption imparted by 0.6 ppm of these rare earths is 91.44×10^{-5} cm^2/cm^3.**

5.1.6 **The total moisture content shall not exceed 30 ppm. Moisture desorption temperatures employed in test shall exceed 700°C. Details of test procedure shall be submitted by vendor for approval.**

5.1.7. The total plutonium plus uranium content shall be 87.8% by weight minimum.

5.1.8 The total gas release exclusive of H_2O shall not exceed 0.05 cc/gm of PuO_2-UO_2 fuel at S.T.P. Gas release shall be measured by out-gassing for at least 30 min. at temperatures of at least 1000°C and a pressure of 1×10^{-6} mm Hg.

5.1.9 Isotopic. The isotopic composition of UO_2 and PuO_2 shall be the same as that of the material received.

5.1.10 The total thermal neutron absorption cross-section imparted by all impurities listed in Group I, Section 5.1 and, in Group II, Section 5.2, shall not exceed 100×10^{-5} cm^2/cm^3.

The impurity level of the rare earth elements shall be included in the calculation of the total macroscopic cross-section absorption when analyzed.

PHYSICAL PROPERTIES AND TESTS

6.0 Weight Per Unit Length: The pellets shall be inspected for weight per unit length with the limits calculated as follows:

$$\text{Maximum grams per inch} = K(\text{Max Diameter})^2 (\text{Max Density})$$
$$\text{Minimum grams per inch} = K(\text{Min Diameter})^2 (\text{Min Density})$$

Where diameter is in inches, specified on the drawing, density is in % T.D., specified on the drawing. Theoretical density shall be calculated by linear interpolation between the theoretical densities of UO_2 and PuO_2 (10.96 gm/cc and 11.46 gm/cc respectively).

$$K = \frac{\pi (2.54)^3 (\text{T.D.})}{4}$$

Allowance shall be made for the average weight of fuel removed by the "dished" ends according to $(1/6)\pi h (3r^2 + h^2) 16.387 \times D$ where h is the average dish height in inches, r is average dish radius in inches and D is the nominal density in gms/cc.

6.1 The vendor shall submit for approval a sampling plan, procedural details, and standards for a test method such as autoradiography to demonstrate that the pelletized PuO_2-UO_2 fuel blend is sufficiently homogeneous.

6.2 (Mechanically mixed fuel only) All PuO_2 powder employed in preparing the initial PuO_2-UO_2 fuel blend shall pass through a 325 mesh U.S. Standard Sieve. All UO_2 powder employed in preparing the initial PuO_2-UO_2 fuel blend shall pass through a 200 mesh U. S. Standard Sieve.

DIMENSIONS

7.0 Dimensions: The dimensions and tolerances shall conform to those specified on the pellet drawing.

8.0 Squareness of Ends: The plane of each end shall not deviate from a plane perpendicular to the pellet axis, taken through the extreme edge of the pellet, by more than 0.010 inch across the diameter of the pellet.

9.0 Chips and Fissures: Chips and fissures shall be inspected per mutually agreeable visual standards. Standards shall meet the following requirements:

9.1 The chipped pellets shall not have lost more than 10 per cent of the area at either end of the pellets.

9.2 The sum of the circumferential length along the periphery of the pellet and the radial depth of each imperfection on the pellet cylindrical surface shall not exceed one-tenth inch. The maximum axial length of any one chip shall not exceed 1/8 inch. The sum of the circumferential lengths of all chips, and pock marks in any one plane perpendicular to the pellet cylindrical axis shall not exceed 1/8 inch except as specified in Section 9.1. In cases of doubt of acceptability, fissures and chips are acceptable provided they meet the weight per unit length specification and withstand shipping, handling, and tube loading without further chipping.

SAMPLING

10.0 Dimensional Samples

10.1 Pellets shall be inspected 100% visually for chips, fissures, etc.

10.2 A 95x97 attribute sampling plan will apply to the diameter and density. Based on a 30 kg batch size, containing approximately 6000 pellets, a random sample of 125 pellets will be drawn. With zero defective parts the lot will be accepted; with two defective parts the lot will be rejected; and with one defective part an additional random sample of 125 pellets will be drawn and it must contain zero defectives for lot to be accepted.

10.3 For dish and squareness of ends, a random sample of pellets equivalent to 1/8 the number of pellets drawn on the basis of 95x97 percent sampling plan will be drawn from the original sample. If there are no rejects the lot will be accepted and if there is one or more rejects, the lot will rejected.

11.0 Chemical Samples

11.1 Seller will randomly select three (3) pellets from each batch, approximately 30 kg per batch, and upon completion of the last batch will make a composite sample for rare earth, isotopic and thermal neutron cross section analysis.

11.2 One analysis is to be performed per batch to determine the chemical composition and impurities listed under Section 5.0 of this specification. The samples for these analyses shall consist of a minimum of six randomly selected pellets from each batch.

11.3 Gas release will be measured from chips of pellets selected at random from the composite sample of each batch.

11.4 Three analyses per batch are to be performed for Pu/U ratio. Pellets for these analyses are to be drawn from the beginning, middle and end of each pellet batch.

11.5 Autoradiography will be performed on one pellet from each batch.

TEST REPORTS

12.0 Test Reports:

12.1 Three (3) copies of certified analyses for total U, U-235, Pu, Pu isotopic concentrations and the impurities specified in Section 5, shall be submitted to the purchaser when each pellet batch is released for fabrication into fuel elements. The vendor shall submit the batch size for purchaser's approval.

12.2 The vendor shall provide three (3) copies of all inspection and test reports as soon as they are generated.

PACKING AND MARKING

13.0 Packing: The packaging shall conform to pertinent ICC and AEC regulations, regarding nuclear materials, and shall be approved by the purchaser.

14.0 Marking: Each container shall be individually and consecutively numbered and shall be plainly marked as follows: Purchase Order Number, (Plutonium Dioxide-Uranium Dioxide Pellets) W Spec. SAX P001, Gross, Tare and Net Weight; PuO_2-UO_2) Lot number from which the pellets were made; Name of Manufacturer; total gms U-235, total gms of Pu, Pu isotopic concentrations.

INSPECTION

15.0 Inspection:

15.1 Test and inspection shall be made at the place of manufacture in the presence of purchaser representative.

15.2 The manufacturer shall afford the purchaser's representatives, free of cost, all reasonable facilities to satisfy themselves that the material furnished is in accordance with this specification.

15.3 Material accepted by the purchaser's inspector at the place of manufacture which subsequently reveals imperfections not detected at the place of manufacture, or which subsequent tests or analysis show not to be in accordance with this specification, is subject to rejection.

COMPLIANCE WITH REGULATIONS

16.0 Compliance with Regulations: The manufacturer shall have appropriate licenses and clearances indicating that he is aware of and responsible for complying with all applicable regulations of Federal, State and local regulatory bodies with respect to receiving, accounting for, processing, storing and shipping of PuO_2-UO_2 powder and pellets.

WESTINGHOUSE SPECIFICATION SAX-P002

LOOSE POWDER FOR VIBRATIONALLY COMPACTED
PLUTONIUM DIOXIDE-URANIUM DIOXIDE FUEL

1.0 This specification applies to loose powder plutonium dioxide-uranium dioxide fuel to be used in manufacturing fuel elements by the vibrational compaction process.

2.0 No change shall be made in the quality of successive shipments of material furnished under this specification without first obtaining the approval of the purchaser.

3.0 The manufacturer shall be financially responsible for all losses and contamination occurring in his manufacturing operation, including repurification, reconversion into a form acceptable to AEC, and unrecoverable losses of uranium and plutonium, all related shipping charges, and any use charges, unless otherwise specified on the Purchase Order.

CHEMICAL PROPERTIES AND TESTS

4.0 CHEMICAL COMPOSITION: The powder shall conform to the following chemical composition:

4.1 Group I Requirements:

4.1.1 Elements

Element	ppm (Max)	Macroscopic Cross Section (2200 m/sec) Imparted by This Level of Impurity $cm^2/cm^3 \times 10^{-5}$
Al	500.0	2.5
B	1.5	63.7
Bi	2.0	0.0002
Ca	100.0	0.66
Cd	1.0	28.0
Co	6.0	2.0
Cr	500.0	18.3
Cu	50.0	1.75
Fe	1000.0	27.2
In	3.0	3.0
Mg	50.0	0.08
Mn	10.0	1.5

For additional elements see next page.

Element	ppm (Max)	Macroscopic Cross Section (2200 m/sec) Imparted by This Level of Impurity $cm^2/cm^3 \times 10^{-5}$
Mo	150.0	2.4
Ni	300.0	14.4
Pb	20.0	0.010
Si	500.0	1.4
Sn	5.0	0.015
V	1.0	0.059
Zn	20.0	0.21
C	150.0	0.024
F	10.0	0.0007
N	100.0	8.3
Cl	20.0	

4.1.2 The ratio of oxygen to uranium in the uranium-dioxide shall be 2.0 ± 0.02.

4.1.3 The ratio of oxygen to plutonium in the plutonium-dioxide shall be 2.0 ± 0.10.

4.1.4 The ratio of plutonium to uranium in any dry powder sample shall be 0.071 ± 0.002.

4.1.5 H_2 Content: - Employ a carbon tetrachloride Soxhlet extraction followed by infrared examination of the stretching frequency of the C-H bond and the Si-H bond to show that these groups are not present to greater than 20 ppm.

4.1.6 The total moisture content shall not exceed 100 ppm. Moisture desorption temperatures employed in test shall exceed $700^{\circ}C$.

4.1.7 The total plutonium plus uranium content of any powder sample as determined by routine analysis shall be 87.0% by weight minimum. A special analysis on a composite sample must prove that plutonium plus uranium content is actually 87.7% by weight minimum.

4.1.8 The total gas release exclusive of H_2O shall not exceed 0.06 cc/gm of PuO_2-UO_2 fuel at S.T.P. Fuel which passes through a 200 mesh U.S. Standard sieve must be out-gassed for at least 30 minutes at temperatures of at least $1000^{\circ}C$ and a pressure of 1×10^{-6} mm Hg during test.

4.1.9 The isotopic composition of UO_2 and PuO_2 shall be the same as the material received.

4.1.10 The total thermal neutron (2200 m/sec) absorption cross-section imparted by all impurities listed in Group I, Section 4.1 and the rare earths shall not exceed a boron equivalent of five (5).

The total rare earth content will not be routinely determined. The effect of the absorption cross-section of these elements will be included in the EBC calculations. A sample of UO_2 powder will be sent to Westinghouse Analytical Laboratories for rare earth analysis.

PHYSICAL PROPERTIES

5.0 Particles, crystals, and inclusions of any material other than UO_2 or PuO_2 and porous particles of PuO_2 or UO_2 shall not exceed one percent by weight of the batch size.

5.1 Particle Size:

5.1.1 All PuO_2 powder employed in preparing the initial PuO_2-UO_2 fuel blend shall pass through a 325 mesh U. S. Standard sieve.

5.1.2 All UO_2 powder employed in preparing the initial PuO_2-UO_2 fuel blend shall pass through a 200 mesh U. S. Standard sieve.

5.1.3 All the densified PuO_2-UO_2 fuel employed in fabricating the fuel elements shall pass a 6 mesh U. S. Standard sieve.

5.2 The particle density of the PuO_2-UO_2 fuel blend shall be greater than 98.7% of theoretical density. Details of and a sampling plan for a vacuum-mercury displacement test shall be submitted by vendor for purchaser's approval. Theoretical density shall be calculated by linear interpolation between the theoretical densities of UO_2 and PuO_2 (10.96 gms/cc and 11.46 gms/cc respectively).

5.3 The vendor shall submit for purchaser's approval a sampling plan, procedural details, and standards for a test method such as autoradiography to demonstrate that the densified PuO_2-UO_2 fuel blend is sufficiently homogeneous.

CHEMICAL SAMPLES AND TESTS

6.0 Chemical Samples and Tests

6.1 The vendor shall submit for purchaser's approval sampling plans for and details of all tests they will employ to control the chemical composition and impurities listed under Section 4.

6.2 The vendor shall submit for approval a sampling plan and details of a test method to demonstrate that the fuel which has been processed, stored and shipped has the same U^{235} enrichment and Pu isotopic ratios as the received fuel.

TEST REPORTS

7.0 Test Reports

7.1 A complete test report will be submitted with finished fuel rods. Report will include three (3) copies of certified analyses for total U, U^{235}, Pu, Pu isotopic concentrations, and the impurities specified in Section 4 for each fuel batch. The vendor shall submit the batch size for the purchaser's approval.

7.2 On site purchaser's inspectors will review inspection and test reports prior to release of fuel batches for manufacture into fuel elements.

PACKING AND MARKING

8.0 Packing

The packaging shall conform to the pertinent ICC and AEC regulations regarding nuclear materials, and shall be approved by the purchaser.

9.0 Marking

Each container shall be individually and consecutively numbered and shall be plainly marked as follows: Purchase Order Number, (Plutonium Dioxide-Uranium Dioxide Loose Oxide Powder), W. Spec SAX. P002, Gross, Tare, and Net Weight; (PuO_2-UO_2) Lot Number from which the powder was made, Name of Manufacturer, Total gms U^{235}; Total gms Pu; Pu Isotopic Concentrations.

INSPECTION

10.0 Inspection

10.1 Test and inspection shall be made at the place of manufacture in the presence of purchaser's representative.

10.2 The manufacturer shall afford the purchaser's representatives, free of cost, all reasonable facilities to satisfy themselves that the material furnished is in accordance with this specification.

10.3 Material accepted by the purchaser's inspector at the place of manufacture which subsequently reveals imperfections not detected at the place of manufacture, or which subsequent tests or analysis show not to be in accordance with this specification, is subject to rejection.

COMPLIANCE WITH REGULATIONS

11.0 Compliance with Regulations

The manufacturer shall have appropriate licenses and clearances indicating that he is aware of and responsible for complying with all applicable regulations of Federal, State and local regulatory bodies with respect to receiving, accounting for, processing, storing and shipping of PuO_2-UO_2 powder.

WESTINGHOUSE SPECIFICATION SAX-P003

FUEL ROD INSPECTION AND LOADING REQUIREMENTS FOR PELLETIZED PuO_2-UO_2 FUEL

I. The purchaser shall supply all clad material, end plugs, springs, and Al_2O_3 spacers as specified on drawing.

II. The clad and end plugs shall be inspected by purchaser before shipment. Vendor shall inspect clad for cleanliness before loading.

III. Shipment to Vendor

A. Each rod shall be individually bagged and shipped to vendor for loading. Identification of materials and sizes, and inspection certification shall be included.

IV. Hardware itemized in Section I shall be inspected for shipping damages at Vendor's plant, in presence of purchaser's representative.

V. Identification - Each rod shall be individually identified according to Westinghouse specifications.

VI. Rods shall be filled as per Westinghouse specification.

A. Each rod shall be weighed before and after filling and those weights recorded on rod identification form.

B. Each rod shall be measured for length as per drawing and that length recorded on rod identification form.

C. Plutonium Loading

(1) The weight of plutonium in each rod shall be controlled to $\pm$ 1.5% of the specified weight. (Weights will be provided at later date.)

(2) The weight of plutonium in any random 100 rods shall be controlled to $\pm$ 0.15% of the specified weight. (Weight will be provided at later date.)

D. Samples from each lot shall be retained for reference. Sample identification shall include, Lot Number, Fuel Rod Numbers, Purchase Order Number, Name of Manufacturer, Name of Purchaser, Gross, Tare and Net Weight, Total gms U-235, Total gms Pu, and Pu Isotopic Concentrations.

VII. Completed Rod Inspection and Procedures

A. Weld

(1) Weld and inspect - as per (W) Process Spec. 292712 (stainless steel clad) or CAP 292717-1 (Zircaloy clad).

a. The welds shall be made vertically using a modified Hanford method.
b. Vendor will prick punch end plug in accordance with the drawings.
c. X-ray of welds is not required.
d. Ten preproduction samples (short length tubing) of welded Zircaloy rods and ten of stainless rods shall be submitted to the purchaser to qualify the welding procedure and to establish weld parameters.
e. During production runs, the vendor will make one dummy rod for test purposes in each production lot. The dummy rod shall be inserted at random in any position in the weld box indexing head, except that it shall not be the first or last rod welded. The lot size shall not exceed 33 rods including the dummy.

(i) The dummy rods shall be cross-sectioned in two planes perpendicular to each other and perpendicular to the circumferential plane of each end plug weld. The first cross-section cut shall be made at a point in the weld periphery located between the points where the weld overlap begins and ends.

(ii) Photomicrographs are required on the polished cross-sections. Sections are to be etched to show the weld puddle clearly at the four 90° intervals.

(iii) If either of the dummy rod welds are rejected, repeat (i) and (ii) for welds from the production rods welded immediately prior to and immediately following the dummy rod. If both of these rods are found acceptable, the entire lot is acceptable. If either one is not acceptable, the entire lot will be rejected.

(2) Weld diameter check - as per Drawings No. 540F555 and 882D154.

(3) Each weld shall be dye penetrant tested as per specification 80165-3. Penetrant required is ZL-22 or ZL-1.

(4) Vendor shall submit for purchaser's approval details of inspection procedures for Item VII-A-2.

(5) The gap between the spacer and end plug shall be controlled as follows:

(a) Distance from top of tube to top of spacer shall be gauged by a go-no go gauge.
(b) Distance from top of end plug to top of tube shall be gauged by an insertion fixture.

(6) The end of the completed rod with variable number of spacers shall be X-rayed in the horizontal position after holding the rod in vertical position with the variable spacer end at the top to determine that the proper number of spacers have been added.

(7) Seller shall submit a procedure for helium check for purchaser's approval. Procedure must include the following:

(a) Equipment shall be capable of detecting leak rate of 10^{-6} cc He per second at 45 psi pressure differential.
(b) Rods shall be leak tested within 24 hours of completion or stored in helium atmosphere.
(c) If condition b is not met, rods must be pressurized in helium at a minimum of 150 psig for a minimum of 15 minutes and tested within 24 hours.
(d) Procedure applies for both zircaloy and stainless steel rods.

B. Contamination

(1) Each assembled fuel rod shall be wipe tested and the wipe shall be counted in a gas proportional counter with 50% geometry and less than three counts per minute background; and if the counts obtained per minute of time do not exceed ten, then the rods shall be considered free of alpha contamination. If the counts exceed ten, then the rod shall be recleaned and recounted.

(2) Welds must be checked with an Eberline scintillation counter or equivalent. Readings of greater than 50 counts/minute per probe area on any assembled fuel rod is cause for rejection.

C. Corrosion Test (Zirc rods only) - as per PS-293058 and PS-293055.

VIII. Packing and shipping per AEC requirements and Westinghouse specification.

IX. Inspection

A. Test and inspection shall be made at the place of manufacture in the presence of purchaser's representative.

B. The manufacturer shall afford the purchaser's representative, free of cost, all reasonable facilities to satisfy themselves that the material furnished is in accordance with this specification.

C. Material accepted by the purchaser's inspector at the place of manufacture which subsequently reveals imperfections not detected at the place of manufacture, or which subsequent tests or analysis show not to be in accordance with this specification, is subject to rejection.

X. Purchaser shall inspect at point of arrival.

A. 100% check for damage as per VI-B and VII-B.

XI. Compliance with Regulations

The manufacturer shall have appropriate licenses and clearances indicating that he is aware of and responsible for complying with all applicable regulations of Federal, State and local regulatory bodies with respect to receiving, accounting for, processing, storing, and shipping of PuO_2-UO_2 powder and pellets.

WESTINGHOUSE SPECIFICATION SAX-P004

FUEL ROD INSPECTION AND LOADING REQUIREMENTS
FOR VIBRATIONAL COMPACTION PROCESS

I. The purchaser shall supply all clad material, end plugs, springs, and Al_2O_3 spacers as specified on drawings.

II. The clad and end plugs shall be inspected by purchaser before shipment. Vendor shall inspect clad for cleanliness before loading.

III. Shipment to Vendor

A. Each rod shall be individually bagged and shipped to vendor for loading. Identification of materials and sizes, and inspection certification shall be included.

IV. Hardware itemized in Section I shall be inspected for shipping damages at Vendor's plant, in presence of purchaser's representatives.

V. Identification - Each rod shall be individually identified according to Westinghouse specifications.

VI. Rods shall be filled as per Westinghouse specification.

A. Each rod shall be weighed before and after filling and those weights recorded on rod identification form.

B. Each rod shall be measured for length as per drawing and that length recorded on rod identification form.

C. The average density of the fuel in the rod shall be 87.0 $\pm$ 1.0% T.D.

D. Plutonium Loading

(1) The weight of plutonium in each rod shall be controlled to $\pm$ 2.0% of the specified weights. (Weights will be provided at a later date.)

(2) The weight of plutonium in any 100 rods shall be controlled to $\pm$ 0.2% of the specified weight. (Weights will be provided at a later date.)

E. Samples from each lot shall be retained for reference. Sample identification shall include, Lot Number, Fuel Rod Numbers, Purchase Order Number, Name of Manufacturer, Name of Purchaser, Gross, Tare and Net Weight, Total gms U-235, Total gms Pu, and Pu Isotopic Concentrations.

VII. Completed Rod Inspection

A. Weld

(1) Weld and inspect - as per Westinghouse Process Specification 292712 (stainless steel clad) or CAP-292717-1 (Zircaloy clad) with following exceptions or revisions:

(a) Hanford welding procedures apply
(b) X-ray and dye penetrant test of welds is eliminated. X-ray of tube end is to be performed to verify installation of springs and alumina wafers.
(c) Helium leak test by drawing a vacuum (10^{-4} mm Hg pressure) around welded tubes and use most sensitive scale on CEC He leak detector to determine rejects.

(2) Weld diameter check - as per Drawings No. 540F555 and 882D154.

(3) Vendor shall submit for purchaser's approval details of inspection procedures for Item VII-A-2.

B. Contamination

(1) Each assembled rod must be free of alpha contamination as determined by a smear test.

(2) Welds must be checked with an Eberline scintillation counter or equivalent. Readings of greater than 50 counts/minute per probe area on any assembled fuel rod is cause for rejection.

C. Corrosion Test (Zircaloy rods only)-as per Westinghouse spec. 293058 and PS-293055 with following exceptions or revisions:

(a) Autoclave for 18 hrs at 1000 psi at approximately 400°C ± 5°C.
(b) Pickling 1-2 mils (1.5 mil average) off of tube wall is permitted.

VIII. To verify plutonium concentration and homogeneity along the length of the fuel rods, at least one fuel rod made with powder from each PuO_2-UO_2 blend must pass a gamma scan test. Vendor shall supply details of test procedure for purchaser's approval.

IX. Packing and shipping as per AEC requirements and Westinghouse specifications.

X. Inspection

A. Test and inspection shall be made at the place of manufacture in the presence of purchaser's representative.

B. The manufacturer shall afford the purchaser's representative, free of cost, all reasonable facilities to satisfy themselves that the material furnished is in accordance with this specification.

C. Material accepted by the purchaser's inspector at the place of manufacture which subsequently reveals imperfections not detected at the place of manufacture, or which subsequent tests or analysis show not to be in accordance with this specification, is subject to rejection.

XI. Purchaser shall inspect at point of arrival.

A. 100% check for damage as per VI-B and VII-B.

B. Check rods as per VIII on a sampling basis.

XII. Compliance with Regulations

The manufacturer shall have appropriate licenses and clearances indicating that he is aware of and responsible for complying with all applicable regulations of Federal, State and local regulatory bodies with respect to receiving, accounting for, processing, storing, and shipping of PuO_2-UO_2 powder and pellets.

PART B: FUEL FABRICATION

At the time inquiries were made (July 1964) only two laboratories, the Hanford Laboratories (now the Battelle Northwest Laboratories) and Numec had demonstrated the capability for fabricating the required quantities of fuel rods. The fabrication experience and available equipment at these laboratories indicated that Battelle be selected for fabrication of the vipac fuel and Numec for the pelletized fuel.

By pre-arrangement with the fabricators, Westinghouse inspectors were stationed at each laboratory and frequent visits were made by other Westinghouse engineers to monitor the various stages of manufacture. The inspectors and engineers assisted fabricators in properly interpreting specifications, in preparing test reports according to Westinghouse and AEC procedures, and in evaluating specification deviations.

I. PELLETIZED FUEL

The process used for fabricating pelletized fuel is outlined in Fig. 8. A brief description of the major steps follow:

PuO_2 Preparation

The surface of the plutonium metal received from Hanford was cleaned to remove impurities such as fluoride, which tend to settle in the outer layers during solidification of the metal. The metal was then cut into small cubes, and steam oxidized to oxide. The oxide was ball milled to pass through a 325 mesh U.S. standard sieve. Selected oxide lots were then blended to yield two oxide batches of nearly equal isotopic concentrations. Criticality limitations rendered blending of all lots into one common batch impractical.

Mechanical Mixing

Weighed portions of the PuO_2 and of purchased ceramic grade UO_2 were first dry blended in a V-type blender for 15 minutes in 30 Kg batches. The mixture was then treated in a Fitz mill to initiate dispersion of PuO_2 agglomerates which may have formed during blending. The final step required to achieve a satisfactory homogenous mixture was wet blending for 30 minutes. To maintain criticality control each batch of material was divided into 7 sub-lots at this step. It should be

PELLETIZED FUEL PROCESS

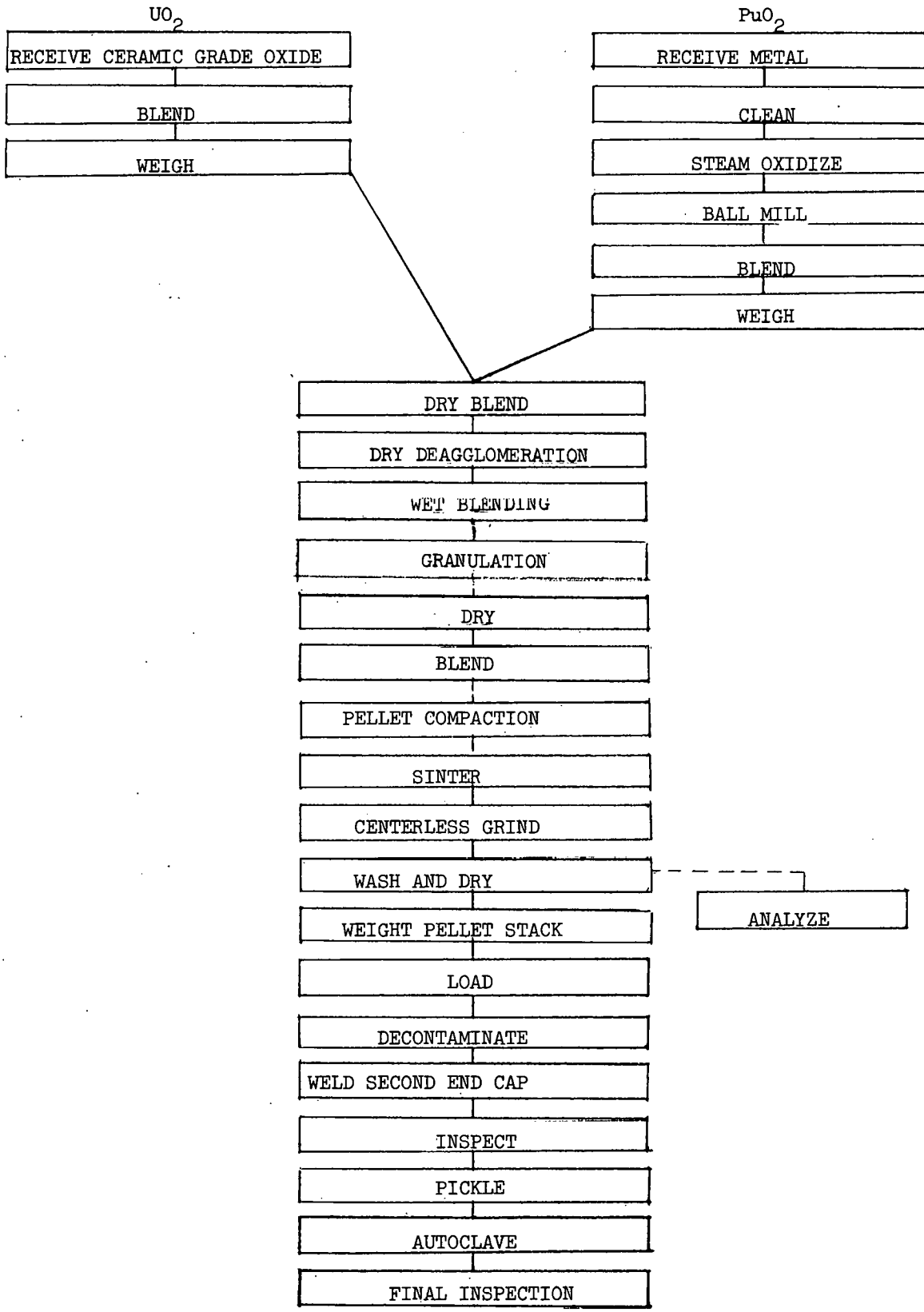


FIGURE 8

noted that ceramic grade powders tend to agglomerate when subjected to non-comminutive dry blending methods such as V-blending, and further treatment is usually required. When preparing mixtures of high density powders required for vibrational compaction, the agglomeration tendency does not pose a problem and wet blending is not required.

Re-Blending

Following vacuum drying of the wet-milled mixture, the various sub-lots were re-blended to reconstitute the initial batch size upon which the sampling plans were based. Re-blending at this point substantially reduced the number of samples required for quality control. One of the major concerns here was the possibility of poor mixing in some of the sub-lots. The blending would tend to redistribute such lots. To aid in evaluating the acceptability of the plutonium distribution three samples per batch, withdrawn from different portions of the batch, were analyzed for Pu content.

Pressing-Sintering-Grinding

Following slug pressing and granulation the material was pressed in a 20 ton Stokes automatic press to green densities in the range 4.5-4.8 gms/cc. One-half weight percent of sterotex lubricant was added to the mixture during granulation; no binder was employed. The green pellets were

sintered in an 8% H_2-N_2 atmosphere for 4 hours at 1700 ± 30°C. The pellets were then centerlessly ground on a belt type grinder to within ± .001 in. of specified diameter. A grinder capable of the closer tolerances normally used by Westinghouse was not available at Numec at the time this program was in progress.

Rod Loading

The ground pellets were washed, vacuum dried, and inspected before transfer to the loading station. Pellet stack weights and lengths were approved and recorded by an inspector prior to loading. A bag technique which permitted insertion of four tube tips into the glove box at a time was used to contain the plutonium during loading. The ends of the rods were decontaminated after loading by wiping with alcohol-wetted cotton tips.

Welding

Rods were sealed in the upright position using a modified fillet weld. The fillet weld was initially developed for plutonium fuels at the Hanford Laboratories. To avoid the possibility of excessive rejects due to weld blow outs, Numec requested that the end plugs be positioned in the rods by a press fit made possible by raised metal shoulders of three punch marks equally spaced circumferentially on the inserted portion of the end plugs. In addition to supporting the plugs, the

punch marks provided an annulus for gas escape during welding. This method was accepted, provided the raised shoulders of the punch marks would be inspected to insure than no sharp edges existed which could scratch the tubing walls during insertion and provided that the punch marks were located below the weld zone to avoid possible thinning of the wall during welding by expansion of gases trapped in the punch indentations. Welding was done in-box using a 10% argon-helium atmosphere, 24 amps, 15 sec/revolution, and an arc gap of 0.02-0.03 inches.

The pickling and corrosion procedures and the inspection procedures used to ensure integrity of the rods after welding are described in the Quality Control Section III.

II. VIPAC FUEL

The process used for fabricating vipac fuel in outlined in Fig. 9. A brief description of the major steps follows:

PuO_2 Preparation

Plutonium dioxide was produced from metal buttons by controlled oxidation. Plutonium buttons were chosen on the basis of isotopic and impurity content. Selected buttons were vacuum melted and cast into thin strips. The strips were oxidized at 550°C in flowing moist air. The resultant PuO_2 powder was further calcined at 950°C in dry air for two hours. All powder passed through a U.S. Series 325 mesh (44 microns) sieve. Since critical mass limits prohibited the preparation of one individual oxide batch, a total of four oxidation runs were performed and each portion was sub-divided into four equal parts. Isotopic blending for all fuel material was accomplished by combining one part from each of the four runs to make four homogenous batches.

Mechanical Mixing

Arc-fused normal uranium dioxide was mixed with U_3O_8 to adjust the O/U ratio to 2.025. Battelle experience indicated that this O/U ratio is optimum for attaining a high particle density with impaction methods. Weighed quantities of UO_2, U_3O_8 and PuO_2 were hand mixed in a stainless

POWDER FUEL PROCESS

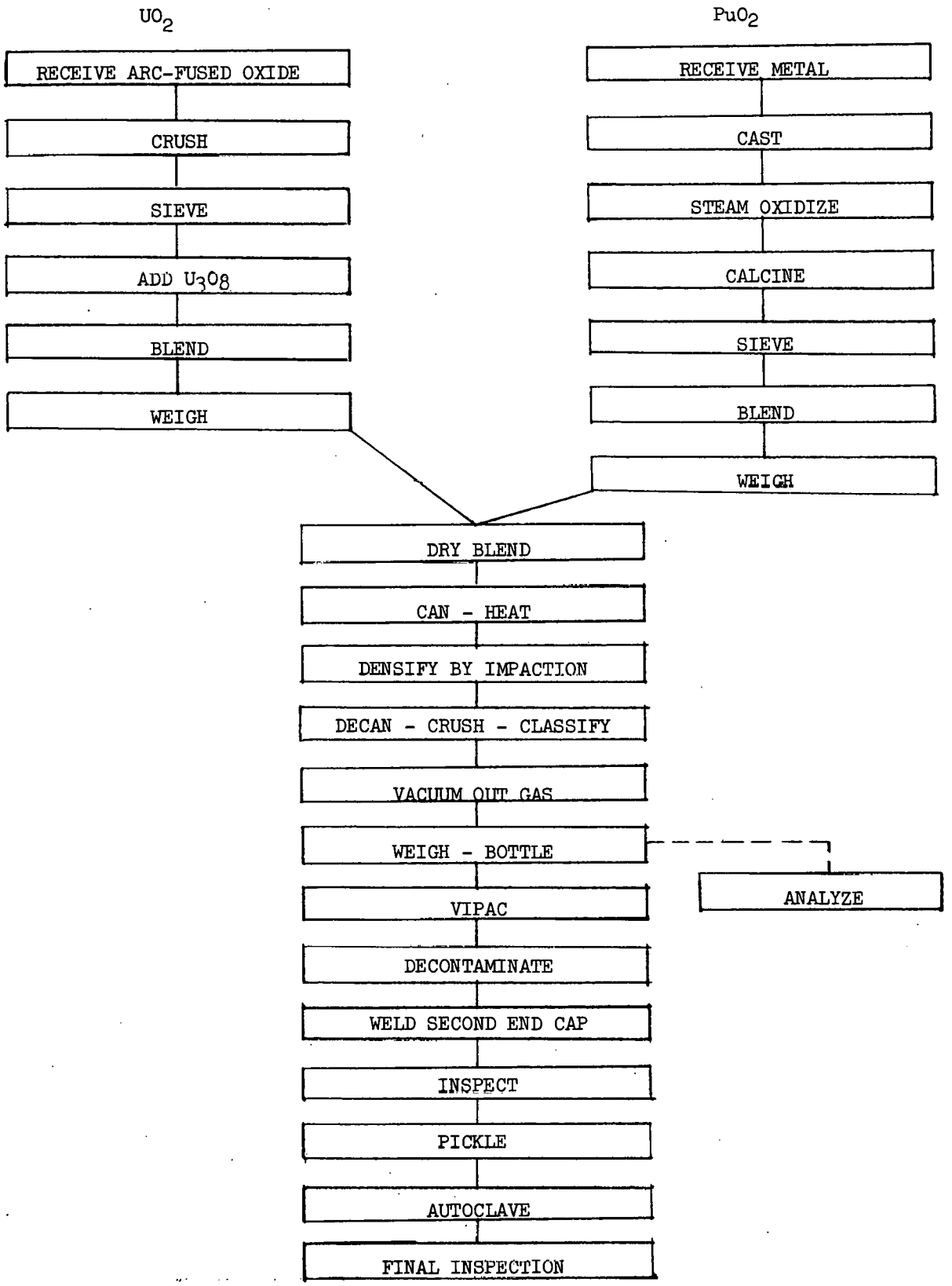


FIGURE 9

steel tray (12 Kg batches) prior to blending 24 Kg batches in a twin shell conical blender for 30 minutes.

Impaction

Six Kg of the blended fuel were loaded into a Type 310 stainless steel cylindrical can. This can was then inserted in and welded to another stainless steel cylindrical container which served as a contamination barrier. The total assembly was evacuated through an integral stem to 10^{-3} mm Hg and heated to 1200°C for 90 minutes to allow the oxygen to equilibrate throughout the can. The stem was pinched and the hot can was immediately pneumatically impacted at 200,000 ft/lbs. After cooling, the cans were sand blasted to remove scale and grease. The can was opened by first indenting one of the circular ends of the can with a specially designed device and then applying diametrical compression with a 100 ton press. Almost all of the densified material was broken away from the can and recovered.

Feed Preparation

The densified powder was classified by dry sieving into four size fractions-- -6 + 10 mesh, -20 + 35 mesh, -35 + 65 mesh and -200 mesh. Particles not falling in these categories were run through a rotating disc pulverizer. All the powder was passed through a magnetic separator and vacuum outgassed at 10^{-3} mm Hg for one hour at 250-300°C.

Weighed portions of fuel (65% of -6 + 10 mesh), 12.5% of -20 + 35 mesh, 12.5% of -35 + 65 mesh, 10% of -200 mesh) were packaged in plastic bottles (535 gm) for the Zr-4 rods and 586 gm for the 304 SS rods). Each container was tightly capped, stored in a dry air glove box and tumbled to assure mixing of the four size fractions prior to loading.

Fuel Rod Loading

The bottom end of the tube (end cap previously welded in place) was clampled to a resonating plate on the head of an electronic vibrating unit. The particle mixture was continuously fed into the tube through a flexible hose while the vibrating unit was cycling between 240 and 2000 cps at an acceleration level of 25 G.

The fuel column was tamped down with a weighted rod while the vibrating unit was manually cycled through the same frequency range at a 50 G acceleration level. Vibration cycling was continued until a hand gauge indicated fuel column length was within specification. The end of the loaded tube was decontaminated with alcohol-wetted cotton tips, and the Al_2O_3 spacers and coil springs were added.

Welding

The tubes were sealed in an upright position using a modified fillet weld. End closures were made in a welding grade helium atmosphere

with the following parameters: current 19 amps; rotation 6 rpm; and welding time 10 seconds.

The pickling and corrosion procedures and the inspection procedures used to ensure integrity of the rods after welding are described in the following section.

III. QUALITY CONTROL AND INSPECTION

The purpose of any quality control program is to insure that a manufactured product will be produced within the tolerances set in written specifications and drawings. The various tests and procedures employed to check the fuel and fuel rods fabricated under this program are summarized in this section.

A. Chemical Properties

Impurities

The mixed oxide fuel was analyzed by standard spectrographic techniques on a batch basis. The batch size was no greater than 30 Kg at Numec and no greater than 25 Kg at Battelle. A representative sample was collected from each batch for analysis. Results of these analyses are listed in Table V.

Oxygen-To-Metal-Ratio

The oxygen-to-metal ratio was determined by different means at Numec and Battelle. A thermogravimetric balance technique was employed at Numec. The sample was first oxidized to ensure a hyperstoichiometric state and then reduced in hydrogen to ensure a stoichiometric metal oxide state. Weight comparisons before and after the treatments were then used to calculate O/M ratios. At Battelle the O/U ratio and the O/Pu ratio were determined separately by coulometric titrations. The O/M ratios for each batch are listed in Table V.

TABLE V

RESULTS OF CHEMICAL ANALYSIS OF SAXTON PLUTONIUM FUEL

	Lot No.	Al (ppm)	B (ppm)	Bi (ppm)	Ca (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	In (ppm)	Mg (ppm)	Mn (ppm)	Mo (ppm)	Ni (ppm)	Pb (ppm)	Si (ppm)	Sn (ppm)	Ti (ppm)	V (ppm)	W (ppm)	Zr (ppm)	Total Gas Release	C (ppm)	CL (ppm)	F (ppm)	N (ppm)	H_2 (ppm)	O/M	Total Moisture	Pu Assay Front	Pu Assay Middle	Pu Assay End
PELLETIZED FUEL (NUMEC)	1	<10	<1	<1	<50	<1	1	10	<10	350	<1	7	8	<10	10	<1	10	1	<10	<1	<10	<10	.008 cc/gm	<20	7	9	43	0.1	1.978	2	5.79%	5.75%	5.79%
	2	20	<1	<1	50	<1	6	20	<10	400	<1	10	10	<5	10	<1	100	5	<10	<1	<50	<10	.012	<20	7	8	110	1.0	2.018	18 & 9	5.86%	5.85%	5.87%
	3	50	<1	<1	50	<1	6	20	<10	400	<1	15	10	<10	10	1	40	1	<10	<1	<50	<10	.004	23	<2	5	75	.54	1.981	18	5.79%	5.80%	5.79%
	4	40	<1	<1	50	<1	<1	10	<10	250	<1	10	5	<10	10	2	30	1	<10	<1	<50	<10	.006	25	<2	8	73	.27	2.009	2.5	5.75%	5.76%	5.75%
	5	20	<1	<1	<50	<1	1	10	<10	200	1	10	5	<10	15	3	50	1	<10	<1	<10	<10	.010	<20	9	5	47	.65	1.978	2	5.76%	5.74%	5.76%
	6	20	<1	<1	<50	<1	1	10	<10	300	<1	8	5	<10	15	1	30	<1	<10	<1	<10	<10	.045	<20	7	9	48	1.0	1.983	13	5.82%	5.80%	5.82%
	7	20	<1	<1	<50	<1	1	15	<10	350	1	30	8	<10	15	2	30	<1	<10	<1	<10	<10	.045	<20	9	6	58	1.3	1.991	8	5.81%	5.79%	5.82%
	8	20	<1	<1	<50	<1	1	10	<10	350	<1	10	8	<10	15	<1	15	2	<10	<1	<10	<10	.030	20	8	8	17	.6	1.979	3	5.09%	5.83%	5.83%
	9	10	<.5	1	<25	<1	1	30	<5	250	<1	10	5	10	10	<5	50	1	<10	<1	<10	<10	.035	<20	4	9	60	.5	1.979	<2	5.84%	5.89%	5.81%
	10	10	<.5	1	<25	<.5	1	40	<5	200	<1	10	5	10	20	<5	30	1	<10	<1	<10	<10	.020	35	3	6	48	.5	1.986	8	5.79%	5.82%	5.75%
	11	10	<.5	2	<25	<.5	<1	40	<5	120	<1	15	5	15	10	<5	30	2	<10	<1	10	<10	.033	<20	5	4	66	2.0	1.981	<2	5.81%	5.79%	5.83%
	12	40	<.5	1	<25	<.5	<1	40	<5	150	<1	15	5	20	20	<5	50	1	<10	<1	<10	<10	.029	<20	6	3	48	1.7	1.980	24	5.82%	5.82%	5.84%
	13	<10	<1	<1	<25	< 1	1	5	<20	300	<1	15	7	<10	15	<1	40	1	<10	<1	<25	<10	.038	32	8	6	82	1.0	1.996		5.79%	5.76%	5.78%
	A																													<2			
	B																													9			
	B1																													<2			
	C																													<2			
	OR-1	40	.3	<1	25	.3	5	30	3	450	<1	<10	10	15	20	2	40	2	<5	<1	<10	<10	.005	<20	6	6	42	<.2	1.970	7	5.88%	5.87%	5.89%
	OR-2	20	<.5	1	<25	<.5	1	<10	1	150	1	5	3	10	10	5	20	5	1	<1	<10	<20	.005	80	10	8	30	.3	1.970	7	5.84%	5.85%	5.83%
VIPAC FUEL (BATTELLE)	SX-C	500	<.1	ND	5	ND	ND	54	10	500	ND	<5	2	ND	29	1	64	42	ND	ND	ND	20	.067	55	<10	<10	74	CCl_4(oil) (ppm) <20		44	5.7	5.7	5.7
	SX-D2	500	<.1	ND	20	ND	ND	100	5	1000	ND	<5	5	5	75	2	200	19	ND	ND	ND	<50	.06	20	<10	<10	92	<20		33	5.7	5.7	5.7
	SX-D3	500	<.1	ND	10	ND	ND	97	10	560	ND	<5	5	5	45	2	100	16	ND	ND	ND	<50	06	20	<20	<10	92	<20		14	5.7	5.7	5.7

ND - None Detected

Pu/U Ratios

The Pu/U ratio was determined by an x-ray fluorescence technique on batch basis at Numec. At Battelle this ratio was determined from the separate coulometric titrations used to determine the O/M ratios. The Pu/U ratios are listed in Table VI.

Hydrogen Content

At Battelle the fuel samples were extracted with carbon tetrachloride (using a Soxhlet extractor) followed by an infrared examination of the extract to determine the ppm of C-H and Si-H groups. At Numec, a high temperature hydrogen extraction technique was used to directly determine the ppm of H_2 present. Results are listed in Table V.

Moisture Content

Analysis for moisture content at Numec was conducted in two stages. The samples were first weighed and vacuum dried at 100°C and reweighed to determine moisture content by weight difference. The samples were then heated at 700°C and the additional moisture released determined by adsorption on magnesium perchlorate. Battelle used a commercially available moisture analyzer which employed an electrolytic sensing technique. Moisture released at 700°C was carried by dry gas over a phosphorus-pentoxide-coated electrode.

TABLE VI

Pu/U Ratios for Saxton Plutonium Fuel

Batch No.	Pu/U Ratio
Numec	
1	0.0712
2	0.0715
3	0.0710
4	0.0710
5	0.0713
6	0.0699
7	0.0708
8	0.0714
9	0.0709
10	0.0712
11	0.0711
12	0.0708
13	0.0710
OR-1	0.0701
OR-2	0.0702
Battelle	
SX-C	0.069
SX-D2	0.069
SX-D3	0.069

The change in electrode characteristics upon adsorption of water was used to determine the moisture content.

Rare Earth Composition

Rare earth content of Battelle UO_2 samples were determined at the Westinghouse Atomic Power Division Analytical Laboratories. The elements were separated and precipitated from a nitric acid solution as fluorides using yttrium fluoride as a carrier. The precipitates were then blended with graphite and examined spectrographically. Two exposures were required to cover the required wavelength. The same procedure was employed by Numec.

Gas Release

Gas release exclusive of water was measured by out-gassing the fuel samples at 1000°C under a pressure of 1×10^{-6} mm Hg. Results are listed in Table V.

PuO_2-UO_2 Isotopic Composition

PuO_2-UO_2 isotopic compositions were determined by mass spectrometry both at Battelle and at Numec. Numec sub-contracted this work to the AVCO/Tulsa Laboratories. Results agreed with the isotopic composition calculated from the individual buttons.

B. Physical Properties

To demonstrate that both the pelletized and the vipac fuel blends were sufficiently homogenous, autoradiographs were taken of each batch of fuel. Numec autoradiographs were taken for each lot and Battelle autoradiographs were taken from each can of impacted fuel (6 Kg of fuel per can). Sample autoradiographs are shown in Figs. 10A and 10B.

Vipac Particle Density

Particle density after impaction was measured at Battelle by a vacuum-mercury displacement technique on a batch basis. Results of these tests follow:

a. Batch SX-D2; 98.7% T.D.

b. Batch SX-D3; 98.5%

c. Batch SX-C; 98.7%

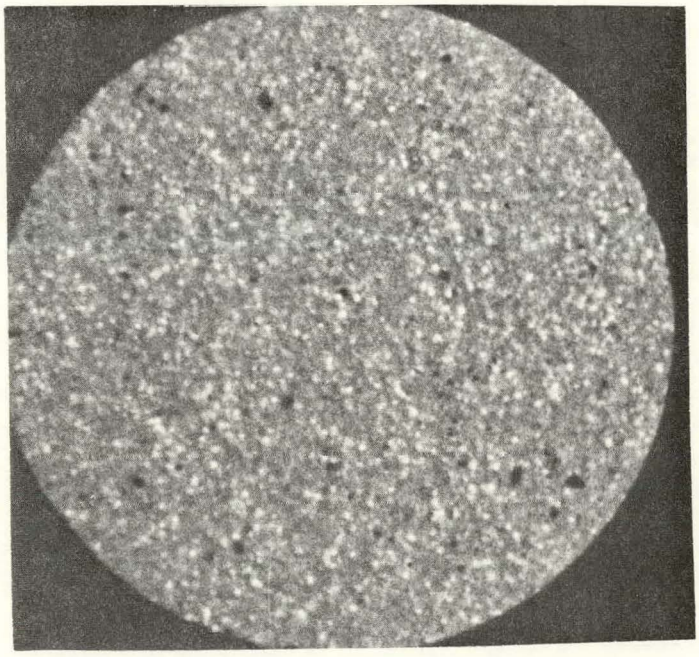
C. Fuel Rod Control

Plutonium Loading

The weight of plutonium in each pelletized rod was controlled by the plutonium assay of the batch and the pellet stack weight. The pellet stack was weighed before it was inserted into the tube. The plutonium content of each rod was calculated from the fuel weight and the Pu assay.

Dark Spots Are Plutonium Areas

A. VIPAC - BATTELLE



Light Spots Are Plutonium Areas

B. PELLETIZED - NUMEC

Typical Autoradiographs of Fuel

FIGURE 10

The weight of plutonium in each vipac rod was controlled by the plutonium assay of the batch and the weight of the fuel contained in the individual loading bottles. The weight of fuel vibrated into the rods was cross checked by weighing each tube before and after compaction.

Welding

To ensure the integrity of the welded end closures, one sample weld was destructively examined per lot of fuel rods. The maximum Numec weld lot was thirty-three plus one sample; the maximum Battelle lot was nineteen plus one sample. The welding sample was quartered at right angles to the circumferential weld and examined to ensure 100% weld penetration for the stainless steel rods and 90% penetration for the Zircaloy rods (as defined by wall thickness). Photomicrographs of the weld sample quarters are shown in Figs. 11A and 11B. Proper penetration was readily achieved once the detailed parameters were determined from weld qualification samples.

Weld Diameter

A simple ring gauge machined to drawing tolerances was used to fit over the weld. If the gauge slipped over the weld, the rod was accepted; if not, it was rejected. Mechanical design permitted the

A. VIPAC - BATTELLE

B. PELLETIZED - NUMEC

Macrophotographs of Typical Fuel Rod End Plug Weld Cross Sections

FIGURE 11

vendor to roll the weld crown down to the proper diameter provided the surface of the clad was not marred in the rolling process. Numec successfully rolled down weld crowns using a pipe cutter modified with rollers instead of cutters. Battelle chose to reject those rods which could not pass the ring gauge test and did not roll any welds.

X-Rays

Each fuel rod was x-rayed in the vicinity of the second end closure. This was done to be sure that the proper number of Al_2O_3 spacers had been included and that the spring had been properly placed. In addition, Battelle used the x-rays to determine gap length. Gap measurements at Numec were made with a gauge during fuel loading as described in the specifications. The x-rays were not used to determine weld penetration at either laboratory.

Leak Check

Each fuel rod was helium leak checked at Battelle and at Numec. The procedure used by both vendors was the standard evacuation test.

Dye Penetrant

Each weld on the pelletized fuel rods was dye penetrant tested at Numec to ensure integrity and freedom from surface cracking. Normal

Westinghouse procedures were employed. At Battelle, the fuel rods were re-inspected by their standard ultrasonic tube test and the weld zones were additionally inspected by a special ultrasonic technique (developed at Battelle) to ensure that vibrational cycling of the rod during loading did not affect weld integrity.

Gamma Scan

Two rods randomly chosen from each lot of vipac fuel at Battelle were examined by gamma scan to verify that no gross errors, such as double batching, were made during the PuO_2-UO_2 blending step and to verify that no gross Pu inhomogeneities existed. Four rods from each lot were examined by gamma absorptometry to verify that the density variation of the fuel along the length of the rods was within $\pm$ 1.5% of the average density.

Pickling

All Zircaloy fuel rods at Numec were cleaned with alcohol and etched at room temperature in a solution of 3-1/2% HF (60%), 39% HNO_3)(Sp. Gr. 1.42) and the balance tap water. Fuel rods remained in the solution for approximately 4 minutes. The rods were then rinsed in a cold tap water bath.

All Zircaloy fuel rods at Battelle were cleaned with acetone and alcohol and etched in a solution of 4% HF (48%), 39% HNO_3 (70%), and 57% demineralized water. The temperature of the etching solution was maintained at 22-25°C. Fuel rods remained in the solution for approximately 7 minutes to remove one to two mils of material from the surface.

The rods were rinsed in a bath containing 15 w/o aluminum nitrate maintained at 40°C, a tap water bath maintained at 60°C, and a demineralized water bath at 20°C.

Corrosion Testing

Corrosion testing of the Zircaloy-4 fuel rods were carried out under the following conditions:

a. Pressure: 1000 psi
b. Temperature: 399°C
c. Time: 24 hours (Numec); 20 hours (Battelle)

Each vendor was required to qualify the corrosion testing facility. Each rod was inspected and compared to a minimum standard. Numec was supplied with a set of standards. Battelle used standards approved by Westinghouse.

Fuel Rod Hardware

To facilitate the manufacture of the fuel rods at Numec and Battelle, Westinghouse supplied all materials, except fuel, to complete the rods. These consisted of cladding material, end plugs, springs, and alumina spacers. These materials were purchased to current Westinghouse specifications and, once found acceptable, were sent to the vendors for production use.

The tubing specification at Battelle is more strict than that of Westinghouse. Therefore, Battelle re-inspected the clad by ultrasonic techniques and used only what it considered acceptable.

IV. FUEL ROD ASSEMBLY

Following completion of fabrication and inspection at Numec and Battelle, the fuel rods were individually packed and shipped to Westinghouse. Upon receipt at Westinghouse the rods were visually inspected for shipping damage and assembled into Saxton enclosures. A typical 9 x 9 enclosure is shown in Fig. 12. Assembly procedures were the same as those used for U-235 enriched fuel rods. The loading pattern of the vibrationally-compacted and pelletized fuel enclosures and the locations of the rods within these assemblies were arranged to assure essentially equal exposures and linear power ratings for all combinations of fuel form and cladding. The arrangement was determined with the assistance of the Westinghouse Nuclear, Thermal and Hydraulic and Mechanical Design Sections.

Cross-section drawings recording the fuel rod identification letters and numbers as installed in lattice spaces in the nine fuel assemblies and in the one 3 x 3 subassembly are included in Figs. 13 through 21.

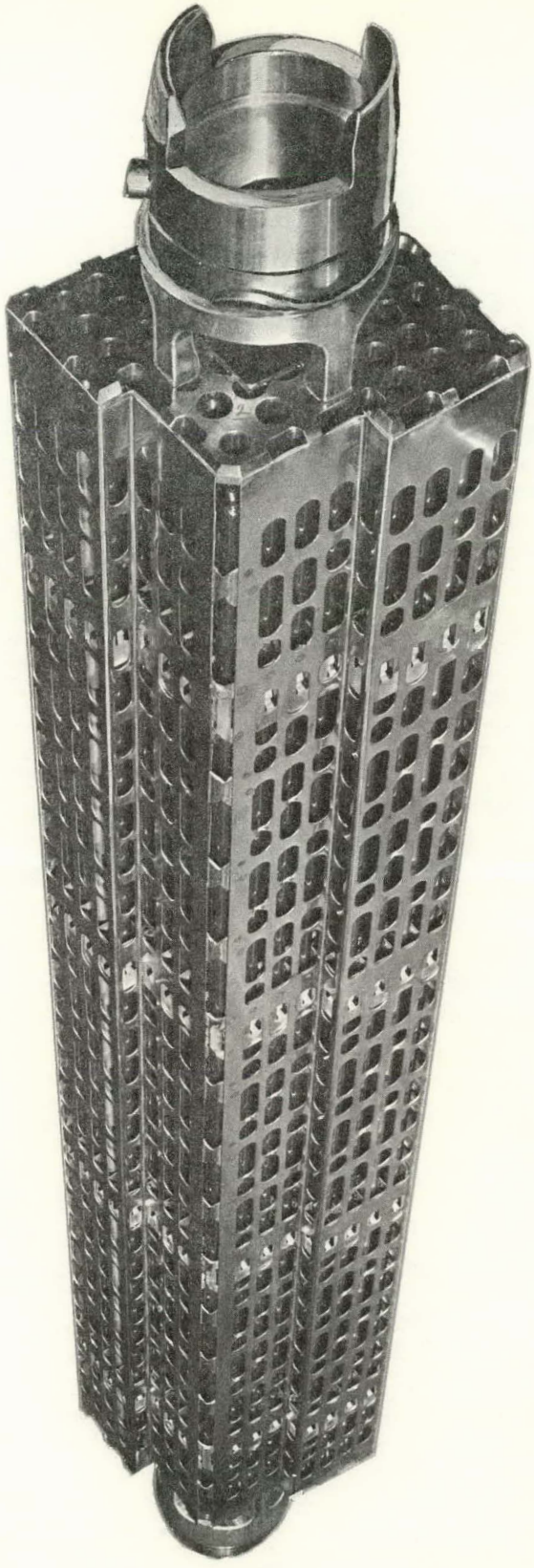
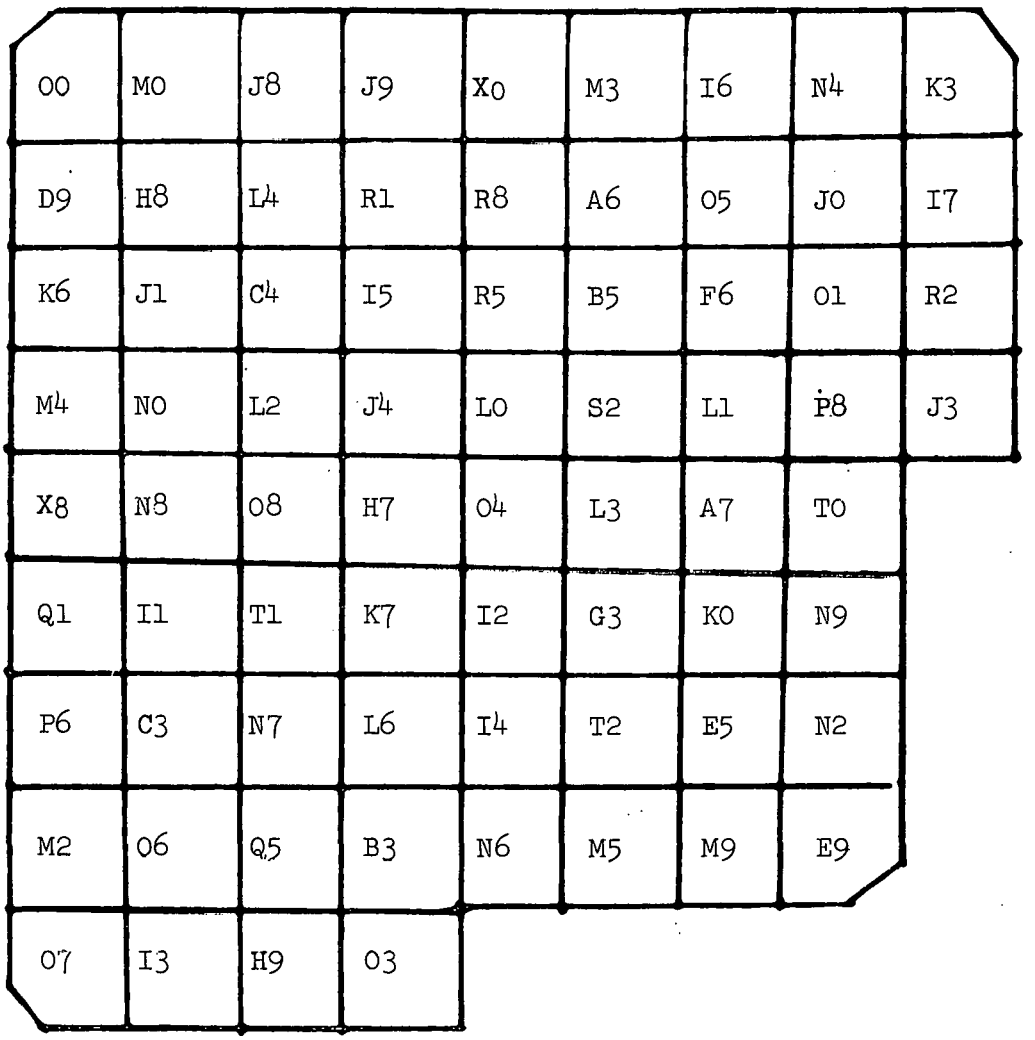
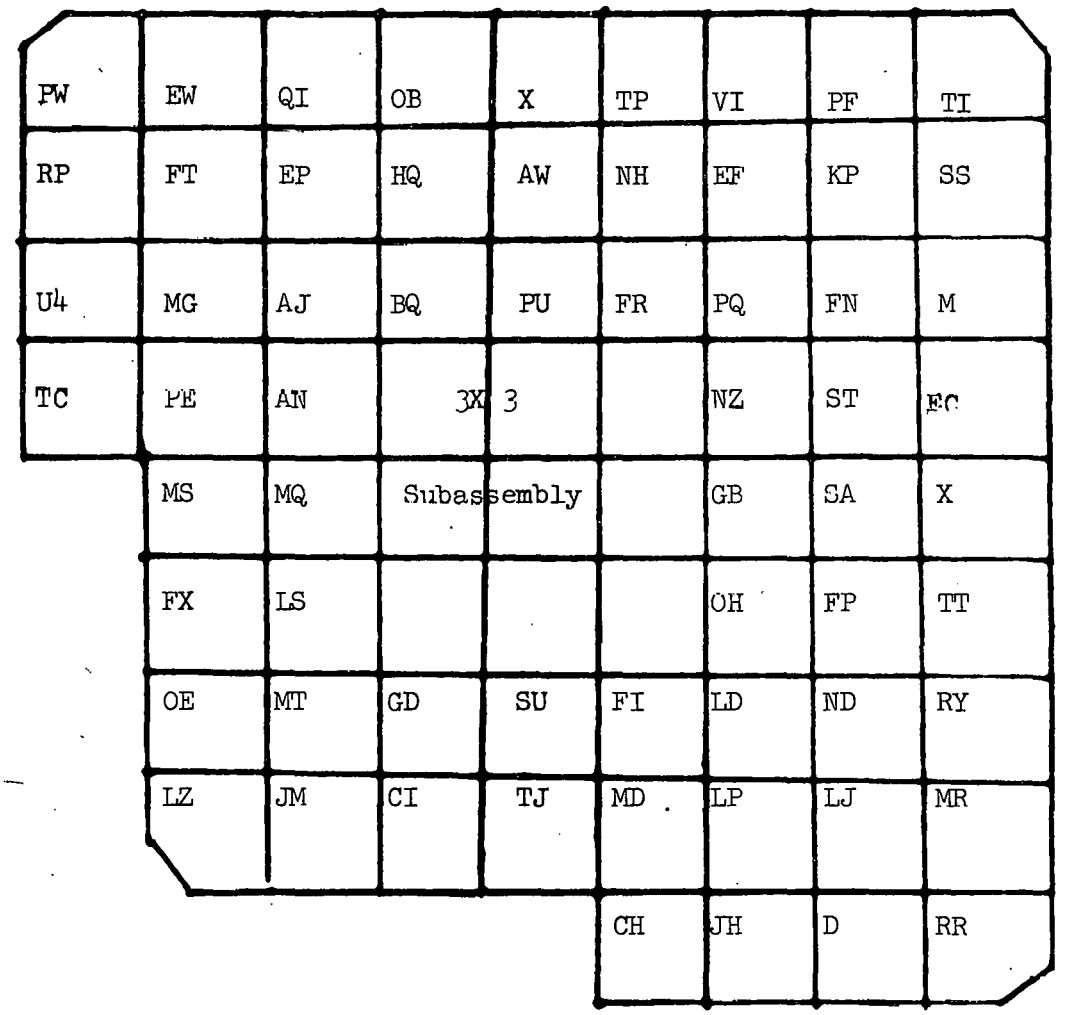


FIGURE 12 - Typical 9 x 9 SAXTON Fuel Assembly



Zircaloy-4 Clad PuO_2-UO_2 Vipac Fuel
X0 and X8 are 9 x 9 Removable Rods

Figure 13 - Assembly Location 2D
Assembly No. 503-12-5



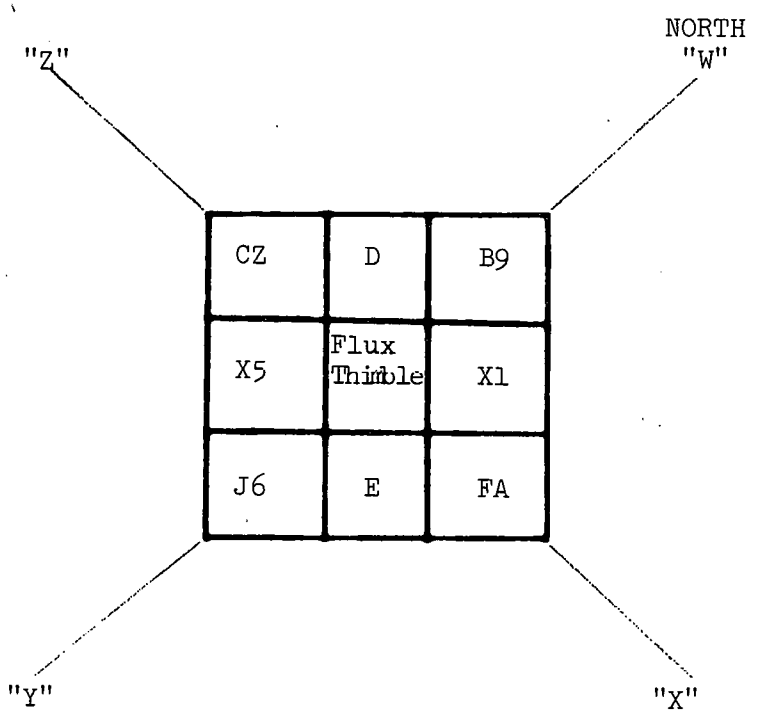
X Is A Flux Thimble

Rods U4, V1 304 Stainless Steel Clad PuO_2-UO_2 Vipac Fuel

Rods M, D 304 Stainless Steel Clad PuO_2-UO_2 Pelletized Fuel

Others - Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

Figure 14 - Assembly Location 3D
Assembly No. 503-13-1



Rods CZ, FA - Pelletized Fuel

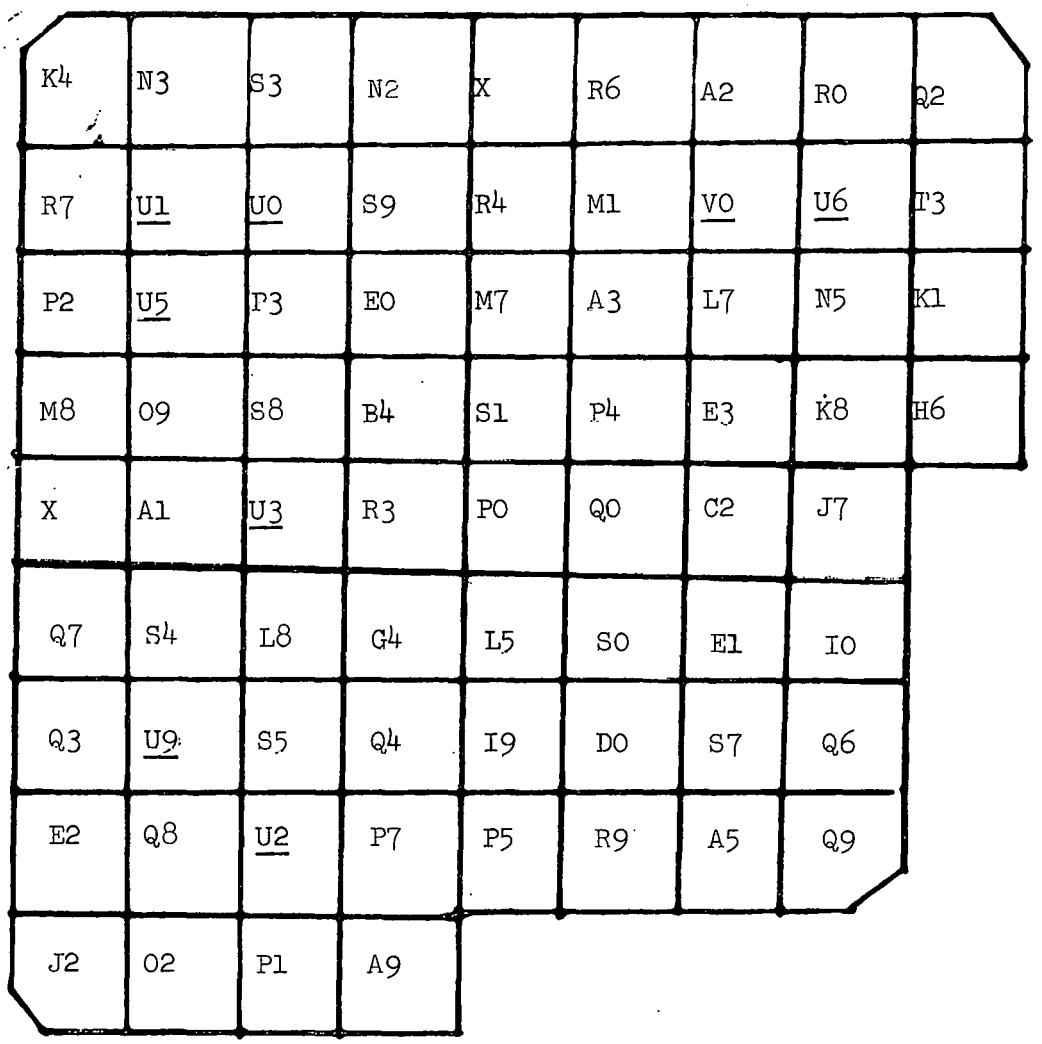
Rods D, E - Removable Rods - Pelletized Fuel

Rods B9, J6 - Vipac Fuel

Rods X1, X5 - Removable Rods - Vipac Fuel

Zircaloy-4 Clad PuO_2-UO_2 Fuel

Figure 15 - 3 x 3 Subassembly
Assembly No. 503-4-26

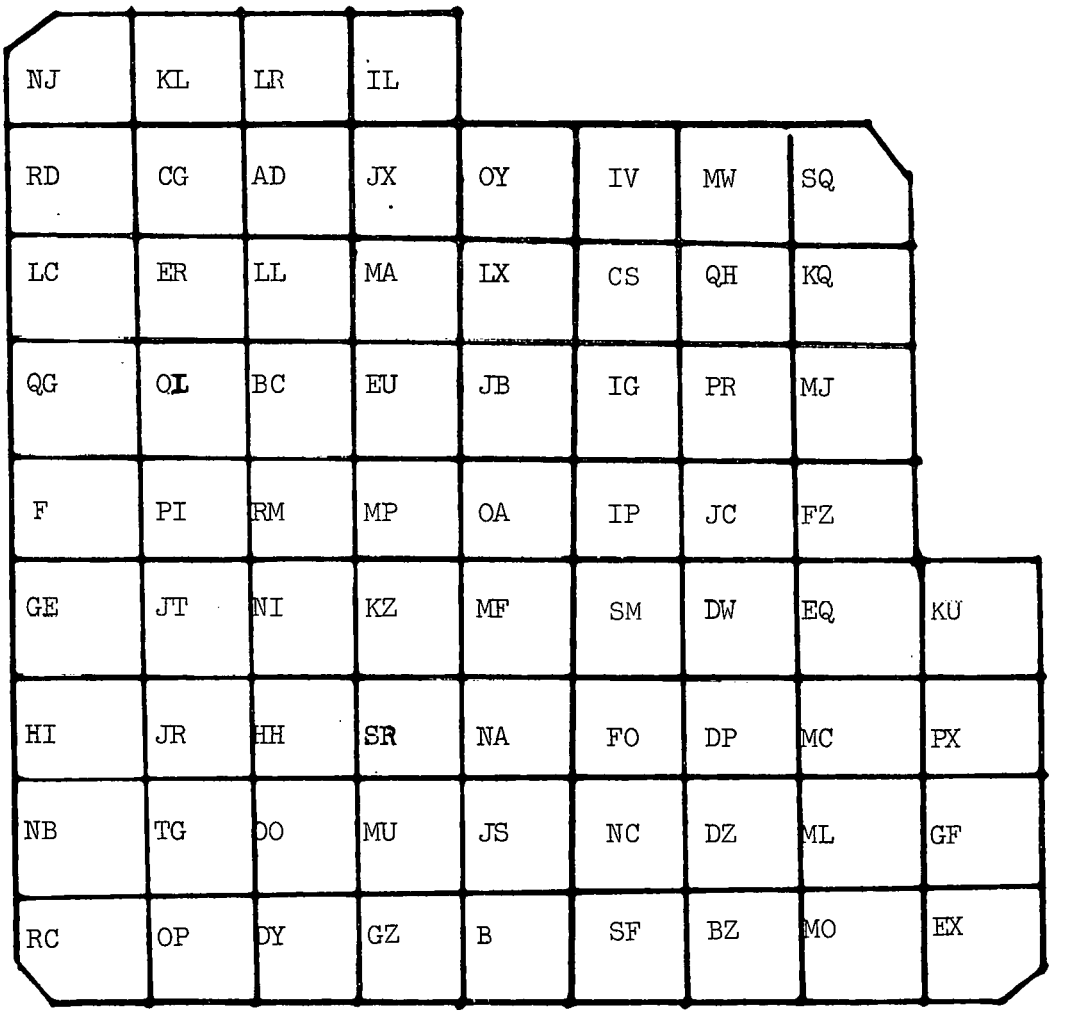


Zircaloy-4 Clad PuO_2-UO_2 Vipac Fuel

304 Stainless Steel Clad PuO_2-UO_2 Vipac Fuel (Underlined)

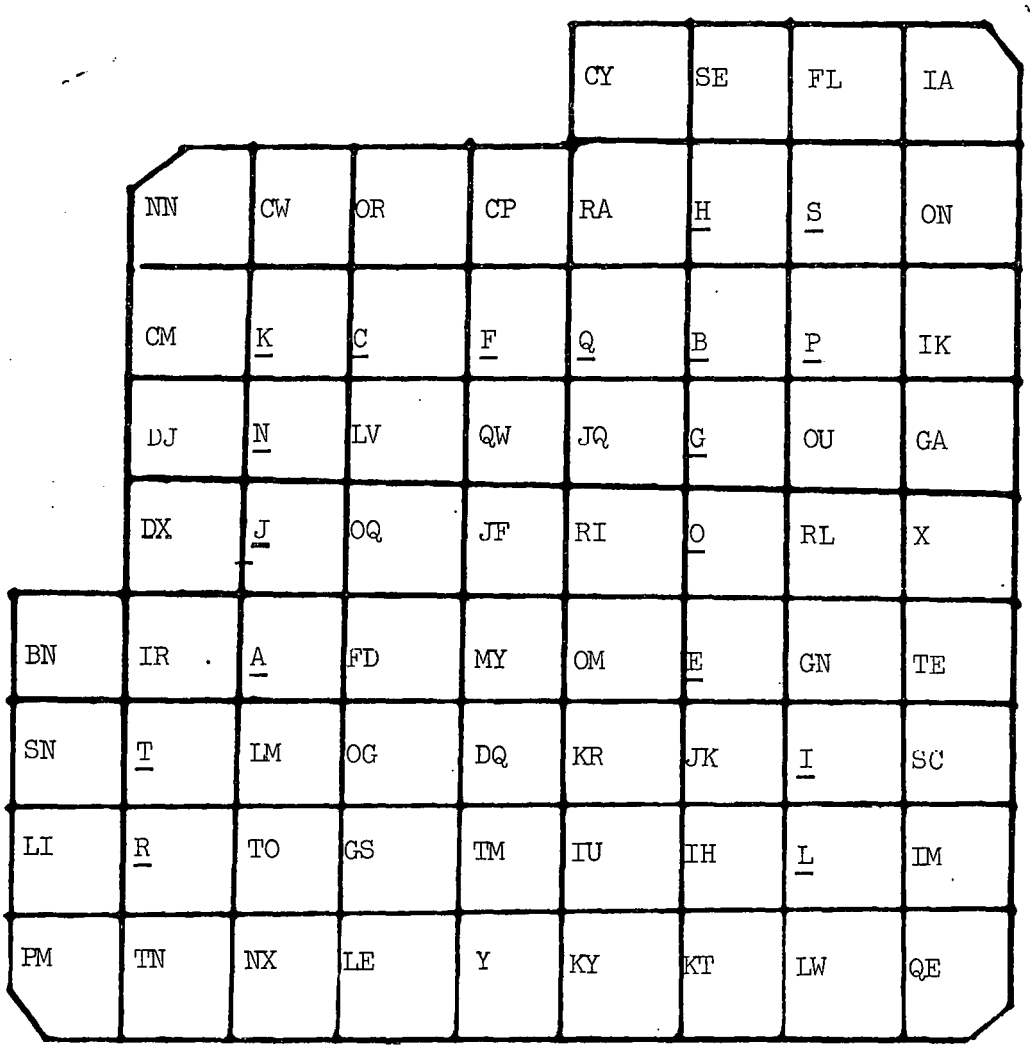
X Is A Flux Thimble

Figure 16 - Assembly Location 4D
Assembly No. 503-12-1



Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel
F and B are 9 x 9 Removable Rods

Figure 17 - Assembly Location 2C
Assembly No. 503-12-2



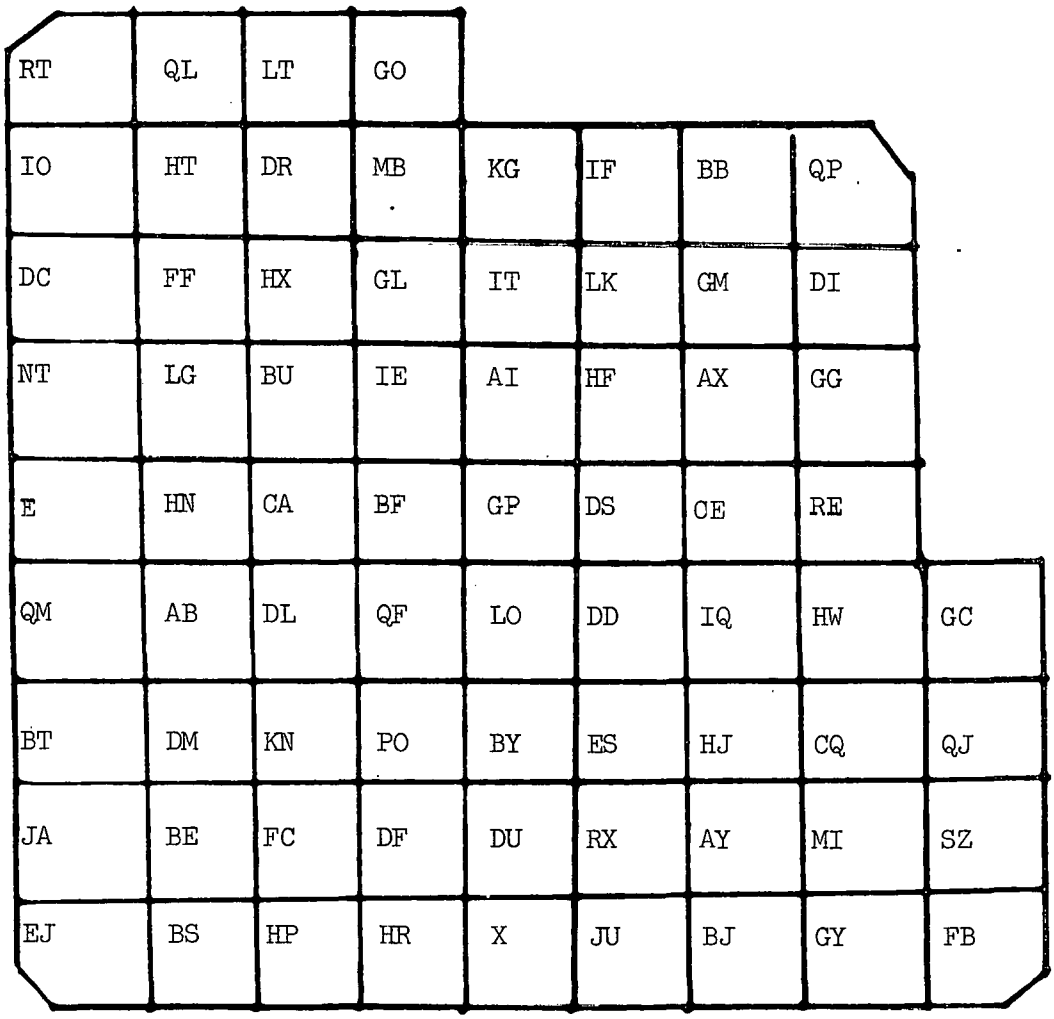
Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

304 Stainless Steel Clad PuO_2-UO_2 Pellets (Underlined)

X is a Flux Thimble

Y is a Secondary Source Rod

Figure 18 - Assembly Location 3C
Assembly No. 503-12-3

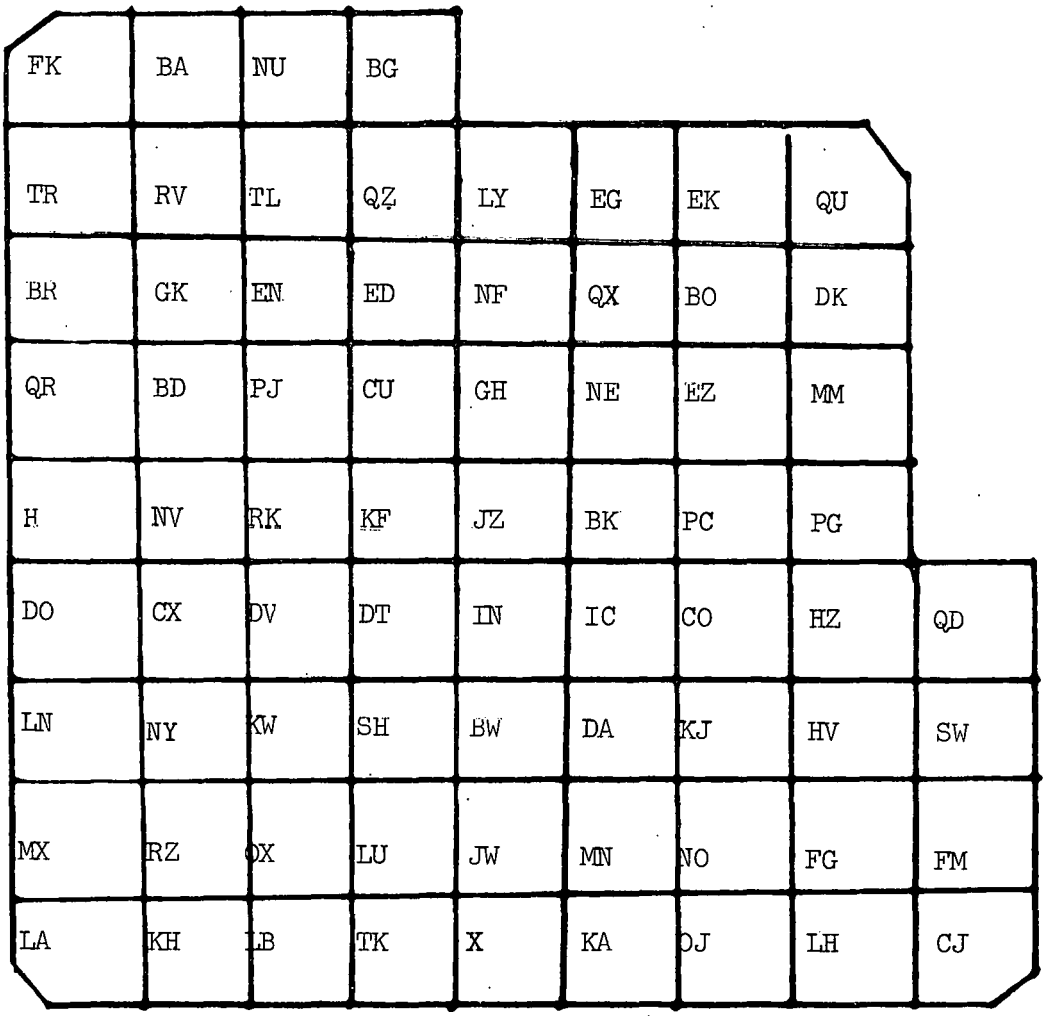


Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

X is a Flux Thimble

E is a 9 x 9 Removable Rod

Figure 19 - Assembly Location 4C
Assembly No. 503-12-7

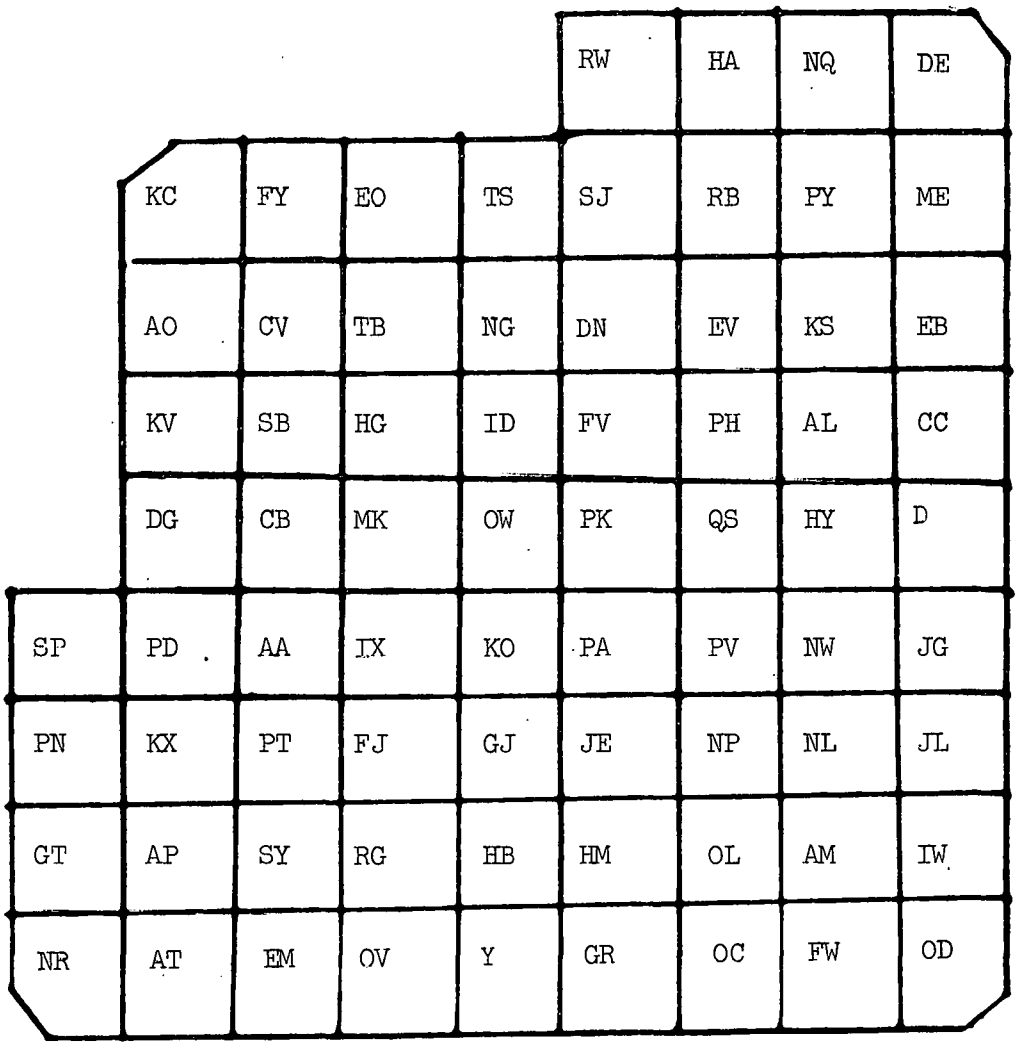


Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

X is a Flux Thimble

H is a 9 x 9 Removable Rod

Figure 20 - Assembly Location 2E
Assembly No. 503-12-4

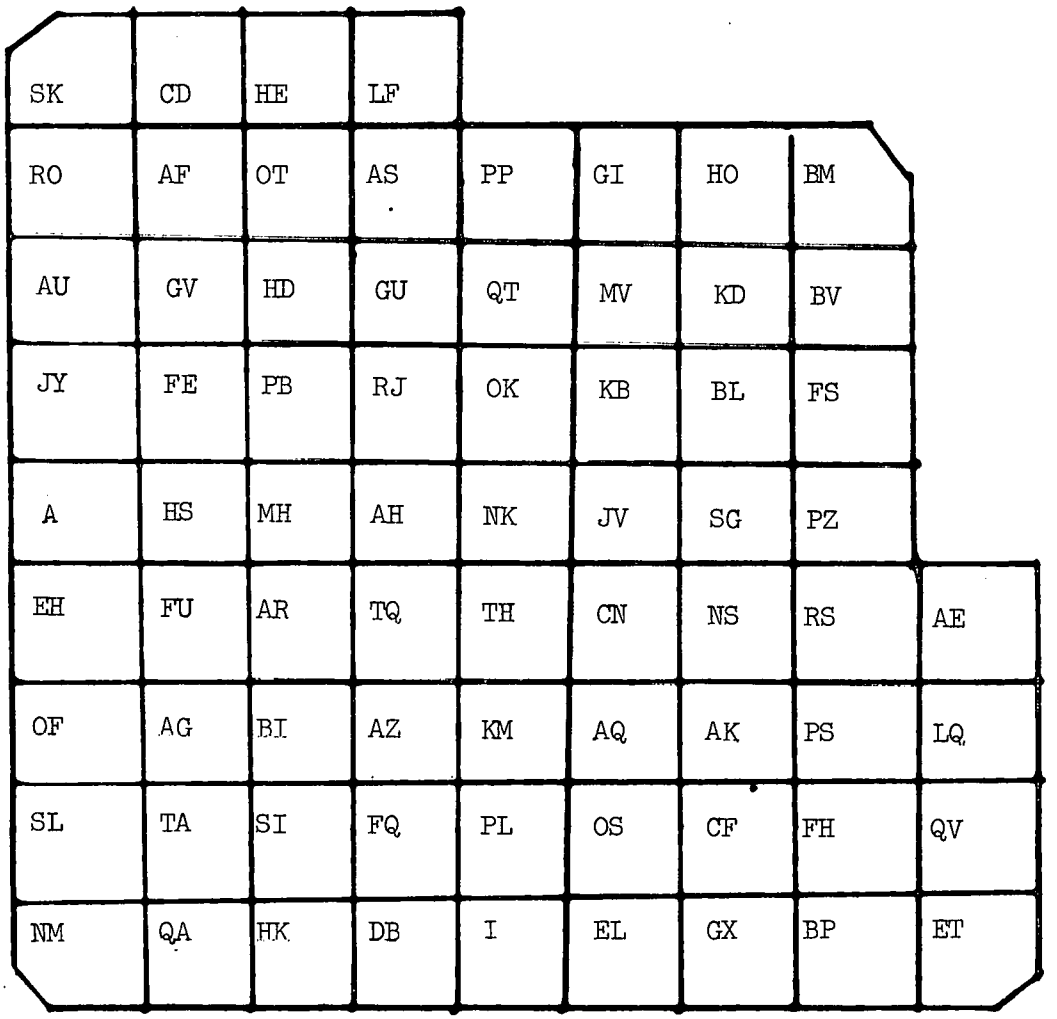


Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

Y is a Secondary Source Rod

D is a 9 x 9 Removable Rod

Figure 21 - Assembly Location 3E
Assembly No. 503-12-6



Zircaloy-4 Clad PuO_2-UO_2 Pelletized Fuel

A and I are 9 x 9 Removable Rods

Figure 22 - Assembly Location 4E
Assembly No. 503-12-8

CONCLUSIONS

The final phase of the materials portion of the Saxton Plutonium Project will consist of post-irradiation examination of selected fuel rods and evaluation of the information developed. Evaluation is expected to be completed in early 1969. Conclusions concerning the performance of PuO_2-UO_2 fuels in pressurized water reactors and the relative merits of vibrationally compacted and pelletized fuels will be included in a topical report to be issued at that time.

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