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A SUMMARY REPORT OF THE USE OF
THERMIONIC CONVERTERS IN A NATURAL CIRCULATION
BOILING WATER REACTOR

July 1962

Babcock and Wilcox Co., Lynchburg, Va.

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ATOMIC ENERGY DIVISION

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A SUMMARY REPORT OF THE USE OF
THERMIONIC CONVERTERS IN A NATURAL CIRCULATION
BOILING WATER REACTOR

① July: 1962

①

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①

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ABSTRACT

~~This report is a summary of the studies made concerning~~
the use of thermionic converters in a natural circulation, boiling
water reactor, ^{are presented,} The first two phases of the study were concerned
with the reactivity available with Plasma-Triode and Ball-of-Fire
converters. The third phase included a nuclear parameter study
of two pressure tube concepts using the Ball-of-Fire converter.

The conceptual design of a 1-MW-e natural circulation
thermionic reactor was developed using a pressure tube fuel element
concept. Supporting fuel material studies were carried out which
show the oxide fuels, UO_2 or UO_2-ThO_2 , should be satisfactory for
the required thermionic design conditions.

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1. INTRODUCTION AND SUMMARY

1.1 Purpose

This report summarizes the nuclear analytic studies made concerning the use of thermionic converters in a 1-MW-e natural circulation boiling-water reactor.

1.2 Scope

The nuclear studies were divided into three phases. In the first phase, which dealt with the use of the Plasma-Triode converter¹, it was shown that sufficient excess reactivity could be obtained with triode converters of cylindrical geometry to meet the performance requirements imposed by the specified 1-year design life and the 10-MW-e power level. In the second phase, similar studies were made for the Ball-of-Fire converter².

In the third phase, parameter studies using the Ball-of-Fire converter³ were performed to establish reactor configurations for different applications and to indicate the best method of reactor development. Also, certain supporting material studies were made.

1.3 Summary of Results

A comparison of the nuclear characteristics of the two converters studied, showed the Ball-of-Fire converter to have a number of important nuclear advantages over the Plasma-Triode converter. These advantages include reduced parasitic neutron absorpton, inherent higher reliability, wider temperature tolerances leading to less stringent power flattening requirements, and reduced magnetic field effects.

After the Ball-of-Fire converter was selected for further development, a pressure tube reactor concept was developed. In this concept the fuel

element is made up of Ball-of-Fire thermionic converters stacked end-to-end and contained within pressure tubes. Pressure tubes enable the converter anode and cesium reservoir temperatures to be maintained at their proper values while using a low pressure, low temperature coolant.

The conceptual design of a 1-MW-e natural circulation thermionic reactor was prepared. Parameter studies were conducted using synthetic experiment design techniques. The results of these studies are expressed in an empirical response equation. By using this equation, other configurations can be sized quickly for different applications.

Oxide fuels, UO_2 or $\text{UO}_2\text{-ThO}_2$ were selected in the evaluation of possible fuel materials since they are considered best with respect to burnup, fuel temperature, power rating, fission product retention, dimensional stability, and compatibility. UO_2 was selected for the reference design because a smaller U-235 fuel loading is needed to obtain the required reactivity.

Table 1 shows the calculated physical, nuclear, and thermodynamic characteristics of a 1-MW-e reactor core using an insulated pressure tube configuration. Figure 1 is a cross section of the assembly. The reactivity of the insulated pressure tube design can be calculated by the following empirical response equation.

$$\begin{aligned}
 k_{\text{eff}} = & 1.161327 + 0.0872312X_1 - 0.138794X_2 + 0.0749222X_3 \\
 & + 0.0072183X_4 - 0.0340730X_1^2 - 0.0029085X_2^2 \\
 & - 0.0287953X_3^2 - 0.0320173X_4^2 + 0.0140151X_1X_2 \\
 & + 0.00487106X_1X_3 + 0.0005189X_1X_4 - 0.00786094X_2X_3 \\
 & + 0.0228542X_2X_4 + 0.00197969X_3X_4,
 \end{aligned} \tag{1}$$

where X_1 , X_2 , and X_4 are the four independent variables in coded form

X_1 = fraction of the UO_2 in the fuel which is fully enriched

X_2 = molybdenum cathode thickness, inches

X_3 = core diameter, inches

X_4 = metal-to-water volume ratio, where metal includes the pressure tube and everything within.

Figure 2 is a conceptual drawing of the pressure tube.

Table 1. Characteristics of the Reference Core

Core diameter, in.	44.08
Core length, in.	42.00
Metal-to-water ratio	0.70
Power density, kw/liter	9.5
Pressure tube heat transfer area, ft ²	745
Average pressure tube heat flux Btu/hr-ft ² (9 MW-t 1 MW-e)	41250
Cathode surface area, ft ²	441
<u>Fuel Loading</u>	
Fuel	UO ₂
Enriched fraction	0.124
UO ₂ , kg	991
U-235, kg	107
Fuel burnup (MWD per ton of ceramic per full power year)	3340
Calculated k_{eff} at 400 F	1.10
<u>Coolant</u>	
Temperature, F	400
Pressure, psia	250
<u>Fuel elements</u>	
Total	826
Element composition	8 converters stacked vertically within a Zircaloy pressure tube

Table 1 (Cont'd)

Fuel cell

Total	6608
-------	------

Composition

<u>Region</u>	<u>Materials</u>	<u>OD, in.</u>	<u>Area fraction</u>
Fuel	UO ₂	0.05000	0.10631
Cathode	Mo	0.72000	0.11414
Anode, insulation, and gaps	Nb, Al ₂ O ₃	0.92000	0.13948
Pressure tube	Zr	0.09400	0.05182
Coolant	H ₂ O	1.53347	0.58825

Converter

Total	6608
-------	------

Length, in.	5.25
-------------	------

Cathode fuel length, in.	4.25
--------------------------	------

Cathode surface area, cm ²	62.006
---------------------------------------	--------

Assumed electrical characteristics

Output voltage, v	0.5
-------------------	-----

Current density, amp/cm ²	5
--------------------------------------	---

Power density, w/cm ²	2.5
----------------------------------	-----

Radial reflector

Material	Beryllium
----------	-----------

Thickness, in.	4.0
----------------	-----

Volume fraction	1.0
-----------------	-----

Figure 1. Reactor Assembly Cross Section

	<u>Region</u>	<u>Outer Radius, in.</u>
Core of Fuel Elements	22.04
Water Gap	22.29
Beryllium Radial Reflector	26.29
Water Return Annulus	31.29

Figure 2. B&W Pressure Tube Concept

2. THERMIONIC CONVERTER, REACTOR ASSEMBLY, AND PRESSURE TUBE DESCRIPTIONS

2.1 Thermionic Converter

The analytic studies are based on a nuclear model derived largely from an RCA Ball-of-Fire thermionic converter design. The principal differences between the nuclear model and the design converter are the anode thickness and the use of nickel instead of Kovar at the ends of the converter. Figure 3 shows a sectional view of the model with its materials composition and principal tube dimensions. The converter consists of two concentric cylinders that form the cathode and anode. The molybdenum cathode is assumed to operate within a temperature range of 1200 to 1350 C (2192 to 2462 F). The anode, which is to operate at a temperature of approximately 625 ± 50 C (1157 ± 90 F), is maintained within this temperature range by heat conduction through an insulation region between the anode and a Zircaloy pressure tube. The space between the cathode and anode is filled with cesium gas at low pressure. The design temperature for the cesium gas reservoir is 325 ± 15 C (617 ± 27 F).

2.1.1 Material and Geometrics Specifications

The material and geometric specifications of the converter are included in the parameter study description in Section 3.

2.1.2 Performance Specifications

One megawatt of electric power from direct conversion is to be produced using a natural circulation boiling water reactor. The assumed converter efficiency is 10%. A nominal value of 2.50 watts/cm^2 was used to establish the cathode surface area of the reference configuration.

Figure 3. Sectional View of Thermionic Converter

Materials

Molybdenum Cathode
Niobium Anode
UO ₂ Fuel
Nickel End Materials
Cesium Reservoir
Al ₂ O ₃ Insulators

2.2 Reactor Assembly

The physical, nuclear, and thermodynamic characteristics of the reactor assembly are given in Table 1. Figure 1 is a cross section of the assembly.

The core is composed of pressure tubes terminating in a support plate at each end of the core. Each pressure tube contains eight Ball-of-Fire thermionic converters stacked end-to-end to form a 42-inch-long fuel element.

In the radial direction, the core is reflected by a 4-inch-thick beryllium reflector followed by a water annulus representing the return path of the coolant. During operation, subcooled water at 385 F and 250 psia enters at the bottom of a stainless-steel core support plate, passes through the core between the pressure tubes, and exits as a steam and water mixture at 400 F into a chimney above the active core.

2.3 Pressure Tube

Figure 2 is a conceptual drawing of a pressure tube fuel element design. The use of pressure tubes is desirable for several reasons. First, a pressure tube with insulation or gas controls the anode and cesium gas reservoir temperature of the converter at the proper values while using a coolant at low temperature and pressure. The Ball-of-Fire converter requires a cesium gas reservoir temperature of approximately 600 F. If the water coolant is kept at a saturated temperature of 600 F, a reactor system pressure more than 1500 psia will result. By removing the converter from the water, the converter no longer must withstand the higher static pressure loading of the reactor system. Therefore, the converter structure is minimized, and the number of materials that can be used for the anode is greatly increased.

Since the temperature of the boiling water coolant in the pressure tube concept is low (400F), Zircaloy or other materials with adequate strength and low neutron cross section can be used for the pressure tube. Likewise, aluminum or another material with good electrical conductivity and a low neutron cross section can be used for the electrical conductors. The problem of isolating low heat flux areas, such as the ceramic seals, from the coolant is avoided, thus eliminating the possibility of undesired cesium condensation in critical areas.

With pressure tubes, the probability of a converter rupture under pressure is reduced. If a rupture should take place with the converter immersed in water, the resulting solution of cesium salts would lower the resistivity of the reactor water to a dangerous level. Within the pressure tube, such a failure would have no effect on the water and would do no more than deactivate one relatively small portion of the power generating unit.

3. PARAMETER STUDY OF INSULATED PRESSURE TUBE CONCEPT

The reference configuration, shown in Table 1, uses thermionic converters within Zircaloy pressure tubes to isolate the converters from the reactor pressure and coolant. Figure 4, a cross section of the cell used as the calculational model, lists the dimensions and volume fractions of the cell that represents the origin of the "n" dimensional space covered in the study.

The following specifications were established as a basis for the nuclear calculations:

1. The cathode is made of 0.5-inch ID molybdenum.
2. The coolant is natural circulation boiling water at a saturated temperature of 400 F and a pressure of 250 psia. The converter is contained within a Zircaloy pressure tube. The insulation inserted between the converter and the pressure tube to maintain the correct temperature drop between the anode and coolant was assumed to be Al_2O_3 .
3. The anode is made of 0.030-inch-thick niobium. Any coating on the anode to lower the work function is neglected.
4. The active fuel length is 4.25 inches.
5. One-half inch is allocated at each end of the converter for leads, seals, and thermal shields. Nickel is used in the analysis for these materials.
6. The core length-to-diameter ratio is one.

Figure 4. Cross Section of Insulated Pressure Tube Cell

Level X-3-X-3 Geometry

	Region		OD, in.	Volume Fraction
1		Fuel	0.50000	0.106314
2		Cathode	0.72000	0.114138
3		Anode-Insulation	0.92000	0.139484
4		Pressure Tube (Zr)	0.98400	0.051820
5		Coolant (H ₂ O)	1.53347	0.588244

3.1 Method of Analysis

Synthetic experiment design techniques⁴ were used so the results of the study could be expressed in equation form. Equations are convenient for sizing calculations and they simplify establishing an optimum relationship among the variables. This method, which originated in the field of statistical experiment design, is called a "synthetic" experiment design since a detailed calculation is substituted for each experimental point. In this study, the detailed calculations at each point consisted of the following steps:

1. The effective resonance integrals for molybdenum and niobium were determined from the resonance parameters of each element by using the narrow resonance approximation. The U-238 single pin resonance integral was determined from empirical formulae based on experimental measurements and corrected for the shadowing of adjacent fuel pins and for the Doppler broadening of resonances.
2. The flux depression across the fuel cell was determined by a transport theory calculation (P-3).
3. The spectral code was used to determine the reactivity of the system by using as the input the information in the two previous steps, the relative concentrations of the various materials, and an assumed value for the reflector savings. Previous calculations of similar configurations in which the radial and longitudinal savings were determined provided a basis for the savings estimate. A negligible error is introduced because of this assumption.

A composite or box experiment design dictates which independent variable combinations are needed to carry out the sequence of calculations. To simplify the evaluation of coefficients in the response

equation, the coordinates of each point in the box design are given as coded values of the independent variables at five levels. Level 1 corresponds to the minimum actual value of the variable, level 5 to the maximum value, and level 3 to the mean value. Coded values of -1 and +1 are assigned to the values of the variables at levels 2 and 4; the value of 0 is assigned to level 3. The end point coded values, δ and $-\delta$, are then established to give orthogonality; that is, to permit a separate and independent evaluation of each of the coefficients of an empirical response equation.

3.1.1. Response Equation Form

The results of the study are expressed in the following form:

$$\begin{aligned}
 k = & B_0 + B_1X_1 + B_2X_2 + \dots + B_nX_n \\
 & + B_{11}X_1^2 + B_{22}X_2^2 + \dots + B_{nn}X_n^2 \\
 & + B_{12}X_1X_2 + B_{13}X_1X_3 + \dots + B_{1n}X_1X_n \\
 & + B_{23}X_2X_3 + \dots + B_{2n}X_2X_n + \dots + B_{n-1,n}X_{n-1}X_n.
 \end{aligned} \tag{2}$$

where

k_{eff} is the dependent variable of interest (reactivity)

$X_1X_2, \dots, X_n$ are the n-independent variables in coded form

B_0 is the value of k_{eff} at the origin of the n-dimensional space

$B_1, B_2, \dots, B_n$ are the coefficients of the linear terms

$B_{11}, B_{22}, \dots, B_{nn}$ are the coefficients of the quadratic terms

$B_{12}, B_{13}, \dots, B_{n-1,n}$ are the coefficients of the interaction terms

3.1.2 Independent Variables

The following independent variables were selected:

1. X_1 = fraction of the fully enriched UO_2 in the fuel
2. X_2 = molybdenum cathode thickness, inches
3. X_3 = core diameter, inches (length-to-diameter ratio = 1.0)
4. X_4 = metal-to-water volume ratio, where metal includes the pressure tube and everything within.

The actual and coded values for each independent variable are listed in Table 2.

Table 2. Actual and Coded Values of the Independent Variables					
Level	1	2	3	4	5
Coded Value	- 1.4142	- 1.0000	0.0000	+ 1.0000	+ 1.4142
Actual Values					
X_1	0.050	0.086611	0.175	0.263389	0.300
X_2 , in.	0.010	0.039300	0.110	0.180700	0.210
X_3 , in.	15.000	23.054400	42.500	61.945600	70.000
X_4	0.200	0.346440	0.700	1.053560	1.200

Levels 1 and 5 of Table 2 represent the range covered and the region in which the final equation normally can be used. Table 3 lists the combinations of the independent variables in levels and the calculated value of k_{eff} for each synthetic experiment. Table 3 shows the actual values represented by the levels. Figure 5 shows the actual and coded values for each independent variable.

Table 3. Independent Variables and Calculated Reactivity for the Insulated Pressure Tube Synthetic Experiment

Synthetic Experiment	Box design in levels				Calculated k_{eff}
	X_1	X_2	X_3	X_4	
1	2	2	2	2	1.067913
2	2	2	2	4	1.036183
3	2	2	4	2	1.225604
4	2	2	4	4	1.195860
5	2	4	2	2	0.741939
6	2	4	2	4	0.782180
7	2	4	4	2	0.856986
8	2	4	4	4	0.911028
9	4	2	2	2	1.209758

Figure 5. Actual Vs Coded Values of the Independent Variables

Table 3. (Cont'd)

<u>Synthetic Experiment</u>	<u>X₁</u>	<u>X₂</u>	<u>X₃</u>	<u>X₄</u>	<u>Calculated k_{eff}</u>
10	4	2	2	4	1.167757
11	4	2	4	2	1.382832
12	4	2	4	4	1.340434
13	4	4	2	2	0.922230
14	4	4	2	4	0.976843
15	4	4	4	2	1.060812
16	4	4	4	4	1.131710
17	1	3	3	3	0.893416
18	3	1	3	3	1.345663
19	3	3	1	3	0.939067
20	3	3	3	1	1.020513
21	3	3	3	3	1.154867
22	3	3	3	5	1.123813
23	3	3	5	3	1.210706
24	3	5	3	3	0.968585
25	5	3	3	3	1.225590

3.1.3. Response Equation Coefficients

The coefficients used in Equation (2) for reactivity calculations are listed in Table 4. These coefficients are to be used with the coded values of the independent variables. Actual values of the variables are converted to coded values by Figure 5 or by the linear relationship,

$$X_c = \frac{X_A - X_A^3}{X_A^5 - X_A^3} \delta, \quad (3)$$

where

- X_c ▪ coded value of X
- X_A ▪ actual value at the desired point
- X_A^5, X_A^3 ▪ actual values at levels 5 and 3
- δ ▪ end point coded value (1.4142 for a 4-variable case)

Table 4. Reactivity Equation Coefficients

$B_0 = + 1.161327$	$B_{12} = + 0.0140151$
$B_1 = + 0.0872312$	$B_{13} = + 0.00487106$
$B_2 = - 0.138794$	$B_{14} = + 0.0005189$
$B_3 = + 0.0749222$	$B_{23} = - 0.00786094$
$B_4 = + 0.0072183$	$B_{24} = + 0.0228542$
$B_{11} = - 0.0340730$	$B_{34} = + 0.00197969$
$B_{22} = - 0.0029085$	Residual = 0.001149
$B_{33} = - 0.0287953$	Standard deviation = 0.0107
$B_{44} = - 0.0320173$	

3.1.4 Analysis of Variance

Table 4 includes quantities to show the accuracy with which the response equation fits the calculated data. The fundamental quantity in the analysis of variance is the square of the differences between the calculations and the response equation summed over all points. This quantity, designated the residual, equals 0.001149.

Table 4 also lists the standard deviation. At a 95% level of confidence, the equation is accurate enough throughout its range to determine the k_{eff} of the system within ≈ 0.02 of that which would result if the entire sequence were repeated at the desired point. To obtain a satisfactory fit to the calculated data in this study, it was necessary to reduce the range over which the equation is used. Coded values of X_1 , X_3 , and X_4 less than - 1.0 should not be used.

The reactivity response equation applies to reactors composed of typical cells like that shown in Figure 4. Cell dimensions are established by the values chosen for cathode thickness and the metal-to-water ratio. The number of cells is established by the

desired electrical power output, which, with the established cell dimensions, determines the required core diameter. The required reactivity depends on the desired system lifetime and performance requirements. Consequently, the reactivity equation is used usually to determine the required fraction of enriched UO_2 that results in a specified reactivity for specific cell and core geometries. An example of using this equation to size a 1-MW-e reactor is included in the following paragraphs.

3.1.5 Calculation Procedure

To use Equation (1) properly, it is necessary to understand the reactor composition to which it applies and the nuclear analysis methods upon which it is based. The following paragraphs describe the calculation procedure which was followed for each synthetic experiment.

3.1.5.1. Calculation of Resonance Integrals

The effective resonance integrals for molybdenum and niobium were calculated by using the narrow resonance approximation from the resonance parameters of each element. Figure 6 shows the resonance integral as a function of the ratio of the cell macroscopic resonance scattering cross section to the number of resonance atoms present ($\Sigma_s^{\text{res}}/N_a$). The $\Sigma_s^{\text{res}}/N_a$ ratio was computed for each experiment where the cathode thickness or the metal-to-water ratio was varied. The resonance integral was read from the curve for each element.

The U-238 resonance integral was determined from

$$R = 5.25 + 26.2\sqrt{\gamma S/M}, \quad (4)$$

where

R = effective resonance integral of U-238 at 68 F

S/M = U-238 surface-to-mass ratio in the fuel pin

γ = Dancoff correction for shadowing of adjacent fuel pins

Figure 6. Resonance Scattering/Number of Resonance Atoms Vs Effective Resonance Integral for Molybdenum and Niobium

$$= \left[1 + \frac{VF}{2r \sum_s^{\text{res}} (M)} \right]^{-1} \quad (5)$$

VF = fuel pin volume fraction in the cell

r = fuel pin radius, cm

$\sum_s^{\text{res}} (M)$ = moderator macroscopic resonance scattering cross section

The U-238 resonance was corrected for Doppler broadening of resonances for an average fuel pin temperature of 2800 by

$$R_{2800_F} = R_{68} \left[1 + 0.6 (10^{-4}) \Delta T \right] \quad (6)$$

3.1.5.2. P-3 Calculations

The thermal flux depression across the cell was determined by a P-3 transport theory calculation for those synthetic experiments involving variations in the enriched fraction of UO_2 (X_1), the cathode thickness (X_2), and the metal-to-water ratio (X_4). For calculations, the cell was approximated by the five cylindrical regions shown in Figure 4. To determine the cell geometry, the following practices were observed:

1. The cathode diameter was determined from the 0.5-inch specified fuel pin diameter and the cathode thickness as prescribed by the experiment.
2. The anode region was assumed to consist of the cathode-anode gap (10 mils), the anode (30 mils), and an insulation region (60 mils).
3. The pressure tube thickness was determined from

$$P_{cr} = \frac{E t^3}{4(1 - \mu^2) R^3} \quad (7)$$

where

P_{cr} = critical pressure, 1125 psia (4.5 times the system pressure was assumed)

E = modulus of elasticity (13.8×10^6)

μ = Poisson's ratio (0.32)

R = radius, inches

4. The water region OD was determined from the following formula by using the metal-to-water ratio prescribed by the experiment.

$$D_{cell} = \sqrt{D_{PT}^2 (1/1/(M/W))}$$

D_{cell} = cell diameter (8)

D_{PT} = pressure tube diameter

M/W = metal-to-water ratio, where everything within the pressure tube is defined as metal.

Table 5 lists the region average-to-cell average thermal flux for the experiments requiring a P-3 calculation.

3.1.5.3. Spectral Code Calculations

The spectral code was used to calculate the reactivity of each synthetic experiment. In preparing the input data, the following practices were observed:

1. The material volume fractions in the fuel, cathode, and anode regions, determined from the cross section cell geometry, were corrected for the fact that they do not extend the full length of the converter (5.25 inches). The structure at each end of the converter was assumed to be nickel and to consist of the following:

Anode cylinder $t = 0.060$ inches $l = 0.5$ inches at anode OD

Closing disk $t = 0.060$ inches at anode OD

2. The flux in the end materials was assumed to be equal to the average flux in the water moderator. Since the spectral code calculation allows resonance input data for only U-238 and Th, a fictitious resonance integral of U-238 was computed to include the resonance absorption of molybdenum and niobium.

3. The total buckling was computed from the following formula:

$$B^2 = \left(\frac{2.405}{R + SR\delta} \right)^2 + \left(\frac{\pi}{L + 2SL\delta} \right)^2, \quad (9)$$

where

R = radius of the core, cm

L = length of the core, cm

SR δ = radial savings and extrapolation distance

SL δ = longitudinal savings and extrapolation distance

In this study, a value of 32 cm was used for SR δ , and 12.5 cm for SL δ . This savings assumption is based on a review of all studies carried out on similar systems throughout the range of core diameters. It is a conservative estimate of that which can be achieved with the specified reflectors.

3.1.6. Sample Calculation - 1 MW-e Configuration

To determine a reactor configuration for the specified performance requirements, it is necessary to define the converter output characteristics and the reactivity needed. The following assumptions were made in establishing the 1 MW-e configuration (Table 1):

1. System reactivity (k_{eff}) = 1.10.
2. Voltage drop in cathode = 0.012 volts.
3. Current density (J) = 5 amps/cm².
4. Voltage output of converter = 0.512 - 0.012 = 0.500 volts.
5. Parallel electrical convections with current removed from both ends (Figure 3)

**Table 5. Region to Cell Average Thermal Flux
for the Insulated Pressure Tube Synthetic Experiment**

<u>Region</u>	<u>Experiment 18</u> <u>3-1-X-3</u>	<u>Experiment 24</u> <u>3-5-X-3</u>	<u>Experiment 20</u> <u>3-3-X-1</u>	<u>Experiment 13</u> <u>4-4-X-2</u>	<u>Experiment 14</u> <u>4-4-X-4</u>
Fuel	0.45356	0.36963	0.33642	0.25617	0.29590
Cathode	0.79573	0.77760	0.64386	0.68774	0.80863
Anode	0.88874	0.93354	0.74937	0.82937	0.98830
Pressure Tube	0.98076	0.98692	0.79901	0.88074	1.05708
Coolant (H ₂ O)	1.20045	1.15594	1.07605	1.11645	1.21689
<u>Region</u>	<u>Experiment 22</u> <u>3-3-X-5</u>	<u>Experiment 17</u> <u>1-3-X-3</u>	<u>Experiment 21</u> <u>3-3-X-3</u>	<u>Experiment 2</u> <u>2-2-X-4</u>	<u>Experiment 5</u> <u>2-4-X-2</u>
Fuel	0.42290	0.69261	0.40535	0.62794	0.50363
Cathode	0.83308	0.85442	0.78556	0.85869	0.74694
Anode	0.99038	0.93959	0.92266	0.95492	0.85665
Pressure Tube	1.07060	0.98161	0.98966	1.02900	0.89688
Coolant (H ₂ O)	1.22759	1.09975	1.16834	1.17433	1.08790
<u>Region</u>	<u>Experiment 25</u> <u>5-3-X-3</u>	<u>Experiment 9</u> <u>4-2-X-2</u>	<u>Experiment 10</u> <u>4-2-X-4</u>	<u>Experiment 1</u> <u>2-2-X-2</u>	<u>Experiment 6</u> <u>2-4-X-4</u>
Fuel	0.27552	0.29948	0.34475	0.57227	0.56172
Cathode	0.76952	0.69363	0.82194	0.76811	0.84354
Anode	0.92241	0.79643	0.96213	0.84222	0.97800
Pressure Tube	0.99676	0.87076	1.06919	0.89634	1.03007
Coolant (H ₂ O)	1.19434	1.13649	1.27838	1.09101	1.15537

6. Metal-to-water ratio = 0.7.

The required fuel loading and core size is calculated by the following:

1. Cathode Thickness

$$\text{Cathode voltage drop} = 0.012 \text{ volts} = IR$$

$$I = \frac{J(\pi D_c L')}{2} \quad (6.45),$$

where

I = average current in 1/2 of the converter since current is removed from both ends

L' = 1/2 cathode length = 2.125 inches.

D_c = cathode OD, inches

$$R = \frac{pL'}{A} = \frac{pL'}{\frac{\pi}{4}(D_c^2 - D_I^2)} \quad (2.54)$$

p = resistivity, ohms/cm

D_I = cathode ID, inches

$$0.012 = \frac{4587.9 \times 10^{-6} D_c}{D_c^2 - 0.25}$$

when $D_c = 0.720$ inches $V = 0.0123$ volts, therefore cathode thickness = 0.110 inches.

2. Cell Geometry

The cell geometry is determined by the procedure in Section 3.1.5.2.

The 0.110-inch cathode thickness and an 0.100-inch anode region thickness determines the inner radius of the Zircaloy pressure tube. Equation (7) for pressure tube thickness reduces to:

$$t_{Zr} = 0.06878R = 0.06878 (0.46) = 0.032 \text{ inches.}$$

The cell OD is determined by:

$$D_{\text{cell}} = \sqrt{D_{\text{PT}}^2 (1 + 1/(M/W))} = \sqrt{(0.984^2) (1 + 1/0.7)} = 1.53347 \text{ inches.}$$

Figure 4 lists these cell dimensions and the resulting volume fractions. The total volume of a 5.25-inch-long cell is 9.69618 in^3 .

3. Number of Converters

$$\text{Surface area per converter} = \pi (0.72) (4.25) (6.45)$$

$$= 62.00556 \text{ cm}^2$$

$$\text{Power density} = (5) (0.5) = 2.5 \text{ watts/cm}^2$$

$$\text{Power per converter} = 155.01 \text{ watts}$$

$$\text{Therefore, the number of converters} = 6451$$

However, the converter area near the end cap may not be an effective emitting surface.

To compensate: power per converter

$$= 155.01 \frac{4.15}{4.25} = 151.36 \text{ watts/cm}^2$$

$$\text{Number of converters} = 6608$$

4. Core Dimensions

$$\text{Core volume} = (9.69518) (6608) = \pi D^2 L = 64072 \text{ in}^3$$

$$\text{For an } L/D = 1, V = \frac{\pi}{4} D^3 \text{ and } D = 43.44 \text{ inches}$$

The actual assembly length must be integral multiples of the converter length. In this example, eight converters are stacked end-to-end which leads to revised dimensions of $D_{\text{core}} = 44.08 \text{ inches}$ and $L = 42.0 \text{ inches}$.

The total buckling entered as input to the spectral code for the reactivity calculation was determined from Equation (9) and an L/D ratio of one. Thus, the reactivity response equation would be correct for L and $D = 43.44 \text{ inches}$, but it would be slightly in error for the actual dimensions of $L = 42.0 \text{ inches}$ and $D = 44.08 \text{ inches}$. To account for this difference an equivalent diameter was found which results in the same total buckling as that calculated with the actual dimensions, $D_{\text{eq}} = 43.0 \text{ inches}$. However, the

calculation of the equivalent diameter is not justified (except for the smaller core diameters) because of the negligible error in reactivity which is introduced.

5. Solving the Reactivity Equation

The actual values of the variables are converted to coded values by Equation (3) or from Figure 5. In this example,

$$X_2 = 0, X_3 = 0, \text{ and } X_4 = 0.025713.$$

A coded value of -0.575 for X_1 was found by setting the reactivity equation equal to 1.10 and by substituting the coded values of X_2 , X_3 , and X_4 . The equivalent actual value of X_1 is 0.124 as obtained graphically from Figure 5.

6. U-235 Loading Calculation

$$\text{UO}_2 \text{ weight per converter} = \left(\frac{\pi}{4} D_f^2 \right) (L) \rho = \left(\frac{\pi}{4} \right)$$

$$(0.5^2) (4.25) (10.97) (16.387) = 150.012 \text{ grams}$$

$$\text{U-235 weight per converter} = \text{UO}_2 (F (0.82022) + (1-F) (0.00716))$$

$$\text{U-235 weight per converter} = \text{UO}_2 (0.81306 F + 0.00716) = 16.1982 \text{ grams}$$

where F = fraction of enriched UO_2 = 0.124

$$\text{Total core loading (U-235)} = (6608) (0.0161982) = 107.04 \text{ kg}$$

3.2 Analytic Results

The principal results of the parameter study are expressed in Equation (1). Figure 7 shows the effect on the calculated k_{eff} for varying each independent variable one at a time about the values of the reference synthetic experiment, Experiment 21.

3.3 Optimization Calculations

Calculations were made using Equation (1) and Figure 7 to determine the improvement in nuclear design that is possible if the cathode voltage drop is allowed to increase as the cathode thickness is reduced. Electrical power per kg of U-235 and electrical power per liter of core volume were chosen as the parameters to be optimized.

Figure 7. Calculated k_{eff} Vs Coded Value of X
 (UO_2 -Enriched Fraction = X_1 , Cathode
 Thickness = X_2 , Core Diameter = X_3 ,
 Metal-Water Ratio = X_4)

3.3.1 Maximum Electrical Power per kg of U-235

Figure 7 shows that a metal-to-water ratio of ≈ 0.7 , desirable from the standpoint of the thermal design, results in a maximum system reactivity. Consequently, the fuel loading requirement was computed as a function of cathode thickness for a specified power output of 1 MW-e, a metal-to-water ratio of 0.7, and a desired k_{eff} of 1.12. (A calculated k_{eff} of 1.12 allows for an increase in the reactivity requirement as the fuel loading is reduced.) Table 6 is a summary of the assembly characteristics for each cathode thickness while Figure 8 shows the variation of electrical power per kg of U-235. A minimum fuel loading is required at a cathode thickness of approximately 0.030 inches. (At low fuel loadings, Figure 7 was used to extend the range of X_1 to coded values less than -1.0.)

3.3.2 Maximum Electrical Power per Liter

Table 6 shows that a small reduction in core volume occurs as the cathode thickness is reduced. However, a major volume reduction can be made by increasing the metal-to-water ratio to the maximum permitted by the thermal design. The maximum metal-to-water ratio that can be used in Equation (1) is 1.2. The assembly producing the maximum electrical power per liter of any assembly within the range of the parameter study is listed in Table 7. The volume of this assembly is approximately 70% of the reference configuration.

3.3.4 Optimization Conclusions

The analysis shows that a significant improvement can be made in the reference configuration (Table 1). A smaller fuel loading or core volume can be obtained depending on which parameter is important for the particular application.

Table 6. Assembly Characteristics for Variations
in Cathode Thickness (Metal-to-Water
Ratio = 0.7 Calculated k_{eff} = 1.12)

<u>Cathode thickness (in.)</u>	<u>Voltage drop (volts)</u>	<u>Converter power (watts)</u>	<u>Number of Converters</u>	<u>Core fuel loading (kg U-235)</u>	<u>Core volume (liters)</u>
0.110	0.0123	151.36	6608	116.74	1050
0.080	0.0163	137.46	7275	98.32	1010
0.065	0.0196	130.32	7673	85.92	997
0.050	0.0250	122.72	8149	80.31	980
0.035	0.0349	114.18	8758	76.70	976
0.020	0.0600	102.31	9774	77.25	1006

Table 7. Assembly Characteristics for Maximum
Electrical Power per Liter (Metal-to-
Water Ratio = 1.2, Calculated k_{eff} = 1.12)

<u>Cathode thickness (in.)</u>	<u>Voltage drop (volts)</u>	<u>Converter power (watts)</u>	<u>Number of Converters</u>	<u>Core fuel loading (kg U-235)</u>	<u>Core volume (liters)</u>
0.035	0.0349	114.18	8758	126.91	737

Figure 8. Electric Power/kw- U^{235} Vs Cathode Thickness

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4. NUCLEAR ANALYSIS

4.1 Reactivity Effects

Calculations were made using the nuclear model of Figure 3 to determine the reactivity effect for material substitutions at the ends of the converter, variations in active fuel length, and for using $\text{UO}_2\text{-ThO}_2$ instead of UO_2 as a fuel material.

4.1.1 Material Substitutions

Replacing the nickel at the ends of the converter with Kovar or niobium produces the following changes in reactivity:

<u>Replace</u>	<u>With</u>	<u>$\% \delta k_{\text{eff}}/k_{\text{eff}}$</u>
Nickel	Kovar	- 7.59
Nickel	Niobium	+ 5.48

Kovar was specified in earlier studies for the metal-ceramic seal regions. Replacing Kovar by nickel in the present design increases reactivity and makes it possible to reduce the fuel loading required to meet the same performance requirements. Nickel represents a conservative choice to simulate the nuclear effects of materials that may be used at the ends of the converter. Replacing nickel with niobium produces a further increase in reactivity that may be obtained by using low cross-section materials.

4.1.2 Active Fuel Length Variations

Figure 9 shows the change in reactivity occurring when the ratio of active-fuel-length to total-converter-length is changed from the

reference design with no change in core dimensions or cathode thickness. A ratio of 1.0 means that the nickel material at the ends of the converter has been removed completely and the cell volume fractions correspond to the cell cross section. For a ratio of less than 1.0, it was assumed that the same amount of material would be required at the ends of the converter regardless of converter length. Consequently, the length ratio equals the ratio of the cathode length to the cathode length plus the one inch allowed for both ends.

A change in length with no change in core dimensions produces an increase in total electrical power due to the larger surface area. However, increasing the length without increasing the cathode thickness results in a larger voltage drop in the cathode. In this particular cathode-fuel arrangement, the cathode thickness must be increased by the square of the ratio of the final-to-initial length to maintain the same voltage drop. However, the volume fraction of materials at the end of the converter is reduced and the volume fraction of fuel is increased linearly with a longer cathode. Increasing the cathode length in the reference design from 4.25 to 5.25 inches with the same voltage drop produces a loss in reactivity of more than $8\% \delta k_{\text{eff}}/k_{\text{eff}}$. Reducing the cathode length increases the available reactivity. The amount of the reactivity increase is determined primarily by the relative reactivity worth of the cathode and end materials. The use of low cross-section materials instead of Kovar at the ends of the converter reduces the optimum nuclear length.

The nuclear effect is one of several factors important in establishing the optimum converter length. However, nuclear considerations emphasize the importance of reducing the reactivity cost of the converter cathode. The following methods are available for improving the reactor design:

Figure 9. Calculated k_{eff} Vs Length Fraction

1. Increasing the cathode voltage drop permits a reduction in fuel even though more converters are needed for the same power output (Section 3.3).

2. Modifying the fuel-cathode arrangement to take advantage of fuel shielding reduces the neutron absorption in the cathode. Consequently, the fuel loading is reduced without an increase in the cathode voltage drop.

4.1.3 UO₂ and UO₂-ThO₂

Table 8 is a comparison of reactivity as a function of the UO₂ enriched fraction for two fuel materials, UO₂ and UO₂-ThO₂. Since either material is satisfactory with respect to burnup, fuel temperature, power rating, fission product retention, dimensional stability, and compatibility, UO₂ was selected for the reference design because a smaller U-235 fuel loading is needed to obtain the required reactivity.

Table 8. Reactivity Comparison of UO₂ and UO₂-ThO₂ Fuel

<u>UO₂-enriched fraction</u>	<u>Replace</u>	<u>With</u>	<u>% $\Delta k_{eff}/k_{eff}$</u>
0.0500	UO ₂	UO ₂ -ThO ₂	- 15.45
0.0866	UO ₂	UO ₂ -ThO ₂	- 9.71
0.1750	UO ₂	UO ₂ -ThO ₂	- 5.76
0.3000	UO ₂	UO ₂ -ThO ₂	- 6.16

4.1.4 Increased Anode Thickness

A change in niobium anode thickness from 30 to 45 mils results in a change in reactivity of $-1.12\% \Delta k_{eff}/k_{eff}$. This reduction is equivalent in its reactivity effect to a 6.74-mil change in the molybdenum cathode thickness as determined by solving Equation (1). Therefore,

Equation (1) can be used to evaluate further changes in anode thickness by assuming that the above relationship (1 mil Mo = 2.21 mils Nb) holds throughout the region where the equation is valid.

4.2 Reactivity Requirements

Table 9 shows the calculated reactivity required to override the moderator temperature defect, Doppler, xenon, and fuel burnup equivalent to one full-power year. The change in reactivity with temperature was determined by two spectral code calculations. These calculations include the effects of moderator density change, changes in cross section and disadvantage factors, and Doppler broadening for an average fuel pin temperature of 2800 F. The requirements for xenon, fuel burnup, and long-lived poisons were determined from a two-group, radial dimension lifetime calculation in which the core was subdivided into three separate regions to account for spatial effects. Figure 10 shows the calculated reactivity as a function of time.

Table 9. Calculated Reactivity Requirements

	<u>% $\delta k_{eff}/k_{eff}$</u>
Temperature defect including Doppler	3.1
Xenon	1.2
Fuel burnup and long-lived poison buildup (one full-power year)	<u>2.0</u>
Total	6.3

Figure 10. Calculated Reactivity Vs Time

5. FUEL MATERIAL SELECTION

Since specific materials performance data are usually not available for a new reactor application, the selection of fuel material must be made from data which are not always exactly applicable. However, in the case of oxide fuels, there is extensive performance data on UO_2 and $\text{UO}_2\text{-ThO}_2$ where one or more thermionic design conditions were equaled or exceeded. Consequently, the oxide fuels were selected for use in a low temperature, separate cathode-separate fuel converter based on an evaluation of the performance of these materials with respect to burn-up, fuel temperature, power rating, fission product retention, dimensional stability and materials compatibility. Each of these factors is discussed in the following paragraphs.

5.1 Burnup

A fuel burn-up of approximately 3500 MWD/tonne is required for the thermionic reactor core shown in Table 1. Extensive in-pile testing of UO_2 and $\text{UO}_2\text{-ThO}_2$ have shown that these fuels are capable of burn-up substantially exceeding that needed. In fact, burn-ups of 40,000-60,000 MWD/tonne have been satisfactorily accomplished for UO_2 and 35,000 MWD/tonne for $\text{UO}_2\text{-ThO}_2$.

5.2 Fuel Temperature

The fuel surface temperature is fixed by the specified operating temperature of the cathode. In the current application of the Ball-of-Fire converter, the cathode temperature is expected to be 1200-1350 C which requires temperatures of the fuel to be higher by at least the temperature differential across the fuel-clad diametral gap. The required average and center fuel temperatures are determined by the specified fuel geometry, thermal conductivity, and power rating.

In-pile experiments to measure the effective thermal conductivity of UO_2 cylindrical pellets clad in stainless steel have been conducted.^{5,6} The effective thermal conductivity represents an averaged conductivity as measured between the inner clad surface and the fuel center, including the gap between pellet and clad. Measurements were made with several pellet-clad diametral gaps and types of gas filling the gap. An effective conductivity of 0.015 watt/cm-c is reported for the case having an initially evacuated 20-mil diametral gap⁵ with the thermal conductivity measured at temperatures greater than 1400 C. Since the pellet-clad gap in a practical design will be much less than 20 mils and may be initially filled with a low pressure gas, the above case represents an extreme. Even so, the maximum fuel temperature will be substantially below the melting temperature. (The melting point of UO_2 is approximately 2750 C; for 6.5 wt % ThO_2 in UO_2 , the melting point is 3300 C.)

5.3 Power Rating

The power rating of the fuel is determined by the power output and efficiency of the thermionic converter. An electrical output of 2.5 watts/cm² from the thermionic device, at 10% efficiency, was used to establish the fuel power rating. The fuel must deliver approximately 36 watts/cm² of fuel surface or 114,000 Btu/hr-ft²; and for a 0.5-inch OD fuel pellet, this results in a fuel power rating of 155 watts/cm and

$$\int K d\theta = 11.4 \text{ watts/cm.}^*$$

The low temperature thermionic application requires a low power rating, 11.4 watts/cm, compared to normal reactor service, 30 watts/cm. This means that even with a fuel of relatively low thermal conductivity, the average and central fuel temperatures will not be excessive, i.e., the fuel ΔT will be less than that of many conventional reactor cores.

* $\int K d\theta$ is a measure of the heat rating of a cylindrical fuel shape.

Data^{7,8} are available on UO_2 to power ratings, $\int \text{Kd}\theta$, of over 55 watts/cm, cold diametral gaps to 25 mils, and fuel surface temperatures to 1060 C. Central melting occurs only under the most extreme conditions. Even with central melting as with fuel redistribution by columnar grain formation no dimensional changes occurred which would be detrimental to converter operation.

5.4 Fission Product Retention

As much as possible, it is desirable for the fuel to retain the fission products generated. In the fuel for a low-temperature, clad-fuel thermionic device, the fission product density is low (low burnup) and a moderate percentage of the fission products generated can be released without developing a high fission gas pressure. The fission products released are mainly the gases xenon and krypton. To prevent excessive cathode voltage losses, a thick cathode (or fuel clad) is required because of the low voltage output of a thermionic device. Thus, the cathode serves as an effective barrier to fission gases entering the interelectrode space.

Existing data,^{7,8} which give a fuel surface temperature approaching thermionic requirements, also are accompanied by high power ratings and often by central melting of the fuel. Thus, these data are for conditions more severe than those required for thermionic service. However, data for the power ratings required for thermionic service are at fuel surface temperatures below those found in thermionic applications. Moderate fission gas release can be tolerated in a separate fuel-cathode fuel temperature device. A conservative calculation, assuming ideal gas behavior, the present Ball-of-Fire converter design, a released gas temperature equal to the average fuel temperature (including the gas in the end portions of the converter), a gas release of 7.3%, and an overpower average fuel temperature of 1750 C, results

in a pressure buildup due to fission gases of only 6.4 psia.

A release of 30% of the fission products generated was reported for the highest power rated experiment⁸ mentioned in Section 5.3, $\int Kd\theta > 55$ watts/cm. Even if the experimental value of 30% for this experiment were used, the pressure buildup due to fission gases is inconsequential.

5.5 Dimensional Stability

UO₂ and UO₂-ThO₂ have demonstrated good dimensional stability under irradiation. Thermal cracking and some grain growth will probably occur in thermionic service. The effect of thermal cracking on uniform heat transfer is not known. But, the cracking apparent in irradiated fuel is observed after the fuel has cooled and hot cell operations have been performed to obtain the specimen. The degree of cracking actually present during the fuel operation is not known. It seems reasonable that cracking effects on heat transfer will be reduced in thermionic service because of the reduced thermal gradient and stresses. Under any circumstances, the problems of dimensional stability and fuel cracking are inherently much less severe with the separate fuel-cathode approach than if an unclad fuel were used.

5.6 Compatibility

Data are not available in the open literature on the compatibility of UO₂ or UO₂-ThO₂ with molybdenum at both the expected cathode temperatures (1200-1350 C) and the length of time of the current application (1 year). However, several investigators have reported on short-term, high temperature experiments to evaluate UO₂-refractory metal compatibility.⁹⁻¹⁵ For example, NASA¹⁵ has conducted tests in which molybdenum was melted (2590 C) in contact with UO₂. No reaction at the interface was observed.

An interaction between UO₂-molybdenum has been observed at 1800 and 2000 C.¹⁶⁻¹⁸ The observation was grain boundary broadening of the molybdenum at the UO₂-molybdenum couple interface apparently indicating that the UO₂

components are migrating along the molybdenum grain boundaries. Similar results were obtained for UO_2 -molybdenum after one hour at 2500°C .¹¹

However, no grain boundary changes were observed after 1000 hours at 1200°C .¹⁶

Long-term compatibility has not been proved. BMI, as a part of its fuel development program for the AEC, has irradiated a UO_2 -molybdenum compact containing 80 volume % UO_2 . The compacts, irradiated for total burnups of approximately 2 and 5%, have not been examined and information is not yet available. A suitable hot cell examination may provide additional information on long-term UO_2 -molybdenum compatibility.

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APPENDIX A

A.1 Summary of the Plasma Triode Study

An analytic study was made to determine the reactivity available in a 1-MW-e natural circulation boiling water reactor using cylindrical Plasma Triode converters. In this study, it was shown that sufficient reactivity (6.3% δ k/k) could be obtained to meet the performance requirements imposed by the specified 1-year design life and the 10-MW-t power level. Table A-1 shows the calculated characteristics of the resulting configuration:

Table A-1
Characteristics of the Plasma Triode Core

Core diameter, in	41.0		
Core length, in.	45.6		
Metal-to-water ratio	0.7		
<u>Fuel Loading</u>			
Fuel	UO ₂ - ThO ₂		
Enriched UO ₂ fraction	0.20		
UO ₂ , kg	249.0		
U-235, kg	208.5		
ThO ₂ , kg	996.0		
<u>Fuel Elements</u>			
Total	1110		
Element composition	12 fuel cells stacked vertically		
<u>Fuel Cell</u>			
Total	13,320		
<u>Composition</u>			
<u>Region</u>	<u>Materials</u>	<u>OD. in.</u>	<u>Area Fraction</u>
Fuel	UO ₂ -ThO ₂	0.500	0.1754
Substrate	Mo	0.600	0.0772
Cathode & Gap	Mo, W	0.706	0.0972
Anode	Zr	0.766	0.0620
Coolant	H ₂ O	1.194	0.5882

Table A-1 (cont'd)

<u>Converter</u>	
Total	13,320
Length, in	3.8
Cathode-fuel length, in.	3.0
Assumed electrical characteristics	
Output voltage, V	0.5
Current density, amp/cm ²	5.0
Power density, w/cm ²	2.5
<u>Radial Reflector</u>	
Material	Beryllium
Thickness, in	4.0
Volume fraction	1.0

Table A-2

Reactivity Effects for Variations in the Plasma Triode Core Parameters

<u>Parameter Varied</u>	<u>Variation</u>		<u>%$\delta k_{eff}/k_{eff}$</u>
	<u>From</u>	<u>To</u>	
Molybdenum Substrate Thickness (in)	0.050	0.100	- 8.76
	0.100	0.150	- 9.13
Tungsten Cathode Thickness (in)	0.025	0.040	- 7.84
UO ₂ Weight Fraction	0.20	0.25	+ 3.48
	0.20	0.15	- 5.84
Fuel Diameter (in)	0.50	0.40	- 5.25

A.2 Summary of the Ball-of-Fire Study²

An analytic study was made prior to the development of the pressure tube concept to determine the reactivity available in a 1-MW-e natural circulation boiling water reactor using cylindrical Ball-of-Fire converters. The converter for the study was assumed to consist of three concentric cylinders forming the cathode, the anode, and an outer shell. Radiant heat transfer from the anode to the outer shell was used as the method for anode temperature control. To increase the radiant heat transfer surface, it was

assumed that the outer surface of the anode and the inner surface of the shell were finned. Nuclear calculations, based on this arrangement, showed that sufficient reactivity could be obtained to meet the required performance. Table A-3 shows the calculated characteristics of the resulting configuration.

Table A-3

Characteristics of the Ball-of-Fire Core

Core diameter, in.	44.3		
Core length, in.	44.0		
Metal-to-water ratio	0.7		
<u>Fuel Loading</u>			
Fuel	UO ₂ -ThO ₂		
Enriched UO ₂ fraction	0.188		
UO ₂ , kg	195		
U-235, kg	160		
ThO ₂ , kg	845		
<u>Fuel Elements</u>			
Total	960		
Element Composition	11 fuel cells stacked vertically		
<u>Fuel Cell</u>			
Total	10,560		
<u>Composition</u>			
<u>Region</u>	<u>Materials</u>	<u>OD, in.</u>	<u>Area Fraction</u>
Fuel	UO ₂ - ThO ₂	0.500	0.1248
Cathode & gap	Mo	0.630	0.0734
Anode & shell	Nb, C, Zr	0.908	0.2133
Coolant	H ₂ O	1.415	0.5885
<u>Converter</u>			
Total			10,560
Length, in.			4.0
Cathode-fuel length, in.			3.0
Assumed electrical characteristics			
Output voltage, V			0.5
Current density, amp/cm ²			5.0
Power density, w/cm ²			2.5
<u>Radial Reflector</u>			
Material			Beryllium
Thickness, in			4.0
Volume fraction			1.0

Table A-4 summarizes the effects on reactivity for variations in the following parameters:

1. UO_2 weight fraction in the $\text{UO}_2\text{-ThO}_2$ fuel material
2. Fuel pin diameter
3. Kovar volume fraction
4. Cobalt resonance integral
5. Kovar cell correction
6. Beryllium reflector thickness

Table A-4

Reactivity Effects for Variations in Ball-of-Fire Core Parameters

<u>Parameter Varied</u>	<u>Variation</u>		<u>%$k_{\text{eff}}/k_{\text{eff}}$</u>
	<u>From*</u>	<u>To</u>	
Fuel Diameter (in)	0.50	0.40	-1.37
	0.50	0.45	-0.70
	0.50	0.60	+0.65
	0.50	0.70	-0.38
UO_2 Weight Fraction	0.20	0.15	-4.60
	0.20	0.10	-12.96
Kovar Volume Fraction	0.025	0.040	-6.50
Cobalt Resonance Integral	20 barns	50 barns	-1.82
Kovar Cell Correction	1.2	1.0	+1.87
Beryllium Reflector Thickness (in)	4.0	3.0	-0.81
	4.0	5.0	+0.40

* Values in this column represent reference case from which all changes were made.

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