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DETERMINATION OF LIFETIME OF THE
 B_4C -IN-TUBES CONTROL ROD

By
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July 19, 1961

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ABSTRACT

The lifetime of a " B_4C -in-tubes" control rod may be limited by either nuclear worth depreciation or internal gas pressure buildup as helium is formed and released from the B_4C particles. Nuclear life is enhanced by thin tube wall for any given O.D. of tubing and by high B_4C density, but the time to failure from gas pressure buildup is increased by the opposite. The optimum B_4C density and tube wall thickness were calculated for maximum control rod life, using several release fractions of generated helium and a number of allowable cladding stress values. It is estimated that lifetimes of ten or more years for B_4C -in-tubes control systems are achievable through the proper selection of tubing material and B_4C density values. The B_4C densities required for maximum lifetimes are in a range that can be obtained by vibratory compaction followed by swaging.

INTRODUCTION

The relative worth of B_4C compacted in stainless steel tubes, the relative worth of boron as a function of its surface density, and the relationship between surface density and fractional burnup for boron have been determined experimentally by VAL Physics; hence, an estimate can be made of the nuclear life of a control rod constructed of rows of small diameter tubes filled with boron carbide powder. An economic evaluation of reactor control rods based on the nuclear life of several absorber materials and various fabrication processes has shown that B_4C in tubes holds promise as a low cost rod. (1)

In determining the lifetime of a control rod, however, those factors which may affect the mechanical life of a rod must be taken into account in addition to nuclear worth. Considerable information has been compiled on the physical, mechanical, and chemical properties of B_4C related to its utilization in a reactor environment.(2) From a study of this information, it appears that the pressure of helium on the inner walls of the sealed tubes is the critical factor in the determination of the mechanical life of a B_4C -in-tubes control rod. This gas, generated through the $B^{10}(n,\alpha) Li^7$ reaction, can be expected to have a release value in the range of 10-40 percent.

The nuclear worth of a given tube is proportional to the weight of B_4C compacted therein, but an increase in the quantity of powder in a tube decreases the void volume available for released helium. The tube volume available for both powder and gas can be increased by increasing the inside diameter of tubing but, since tube O.D. is always limited to some maximum value by the basic control rod design, such an increase can be obtained only at the expense of wall thickness and, thus, the ability of the tubing to withstand the internal pressure.

The purpose of this study is (1) to demonstrate the effect of B_4C density, tube wall thickness, tubing material strength, and percent helium release on the lifetime of a B_4C -in-tubes control rod, (2) to develop a method of determining that combination of absorber density and wall thickness which will obtain the maximum lifetime from any B_4C -in-tubes control system by consideration of both nuclear and mechanical factors, and (3) to apply this method to a reference core and control rod system.

CONCLUSIONS

1. It is estimated that lifetimes of ten or more years for B_4C -in-tubes control systems are achievable through the proper selection of tubing material and B_4C density values.
2. The B_4C densities required for maximum lifetimes are in a range that can be obtained by vibratory compaction followed by swaging.

DISCUSSION

For a given tube design the longest lifetime will be obtained from a B₄C-in-tubes control rod when the fraction of tube volume occupied by the boron carbide particles is such that the nuclear and tube lifetimes are equal. Presented in the Appendix is the development of a general relationship among the various factors which determine, under the assumption of balanced nuclear and mechanical lives, the lifetime of any B₄C-in-tubes rod. Some of these factors are to a large extent fixed by the overall design and operating characteristics of a given core and control rod system. Others can be varied in the fabrication of the individual absorber tubes with much less dependence on the basic reactor design. Such factors as tube wall thickness, cladding material strength, and B₄C density fall into this latter category and can be optimized with respect to control rod life.

In order to show the effect of these three factors and that of helium release on control rod lifetime and to demonstrate a method of determining optimum combinations of tube wall thickness and B₄C density, the boiling water reactor design study reported in TID 8500 was selected as a reference control rod application.⁽³⁾ The core and control rod characteristics for this reactor are as follows:

CORE

Length	136"
Diameter (equivalent)	123"
Design thermal power	980 MW
Neutron diffusion length (cold), L_c	1.93 cm
k_{eff} , cold, clean (k_c)	1.24
k_{ex} for fuel burnup	0.06

CONTROL RODS

Number of rods	97
Size (nominal cross section)	3/8" x 8" x 8", cruciform
Absorber length	130"

In this particular study each cruciform rod consists of four single rows of stainless steel tubes encased in a stainless steel sheath as listed below and shown in Figure 1:

Number of tubes per row	14
Tube length	130"
Outside Diameter, d_o	0.25"
Wall thickness, t	variable
Material	type 304 stainless steel (ASTM A-269 TP 304, or similar)
Sheath thickness	0.060"

Figure 1
CROSS SECTION OF CONTROL ROD ABSORBER SECTION

Tube life is defined as the number of years required to realize a certain allowable, or limiting, fiber stress in the cladding through the gradual increase in internal pressure. Figures 2a through 2d are the results of calculations based upon several values of allowable stress, S^* . 17,000 psi was taken as a mean value of yield strength for annealed 304 stainless steel at operating temperature⁽⁴⁾, but the higher stress values could be reasonably specified in cold-drawn tubing. The temperatures of the tubing material and released gas were assumed to be 600 °F and 700 °F, respectively.

The curves in Figures 2a-d show lifetime for different gas release values as a function of wall thickness and the corresponding B_4C density required to give identical nuclear and mechanical lifetimes. B_4C density is defined as

$$\frac{\text{Weight } B_4C \text{ in Tube}}{\text{Theoretical Density } B_4C \times \text{Total Inside Volume of Tube}} \times 100$$

It should be noted that some of the curves in Figures 2 through 5 have dotted branches. In all cases, such branches illustrate the assumption that the effectiveness of powder compaction techniques would limit the maximum B_4C density to 80 percent. The corresponding main (solid) branches were plotted on the basis that whatever density was required for equality of nuclear and tube lifetimes could be obtained.

The significance of Figures 2a-d can be shown by means of an example. If one assumed an allowable fiber stress of 12,000 psi and helium release of 30 percent, selected 14-mil. tubing, and loaded tubes with B_4C to a density of 50 percent, according to Figure 2a a rod life of 7.2 years would be realized. For this wall thickness; a higher density would result in earlier tube "failure", and with a lower density minimum nuclear worth would be reached in a shorter time. The figure shows, of course, the maximum life that could be attained under these same assumptions is 7.5 years. This lifetime would require the use of 19-mil. tubing with a B_4C density of 58 percent.

Figure 3 shows maximum life as a function of gas release. It is of interest to note that by combining these curves with the lines drawn through the peaks of the curves of Figure 2a through 2d, one could select for any one of the four stress values the tube wall thickness and B_4C density which would give maximum life for any value of helium release between 10 and 40 percent. From Figure 4a, b, on the other hand, one could determine for any one of the four helium release percentages the optimum combination of wall size and density for any value of allowable fiber stress between 12,000 and 50,000 psi. The maximum lifetimes for the reference system as a function of stress are given in Figure 5.

FIGURE-2a CONTROL ROD LIFETIME VS. TUBE WALL THICKNESS AND B_4C DENSITY
FOR VARIOUS PERCENTAGES OF GAS RELEASE

$S^* = 12,000$ psi

FIGURE-2b CONTROL ROD LIFETIME VS. TUBE WALL THICKNESS AND B_4C DENSITY
FOR VARIOUS PERCENTAGES OF GAS RELEASE $S^* = 17,000$ psi

FIGURE-2c CONTROL ROD LIFETIME VS. TUBE WALL THICKNESS AND B_4C DENSITY
FOR VARIOUS PERCENTAGES OF GAS RELEASE $S^+ = 30,000$ psi

FIGURE-2d CONTROL ROD LIFETIME VS. TUBE WALL THICKNESS AND B_4C DENSITY
FOR VARIOUS PERCENTAGES OF GAS RELEASE
 $S^+ = 50,000$ psi

FIGURE-3 MAXIMUM CONTROL ROD LIFETIME AS A FUNCTION OF THE AVERAGE GAS RELEASE THROUGHOUT LIFE OF ROD

FIGURE-4a,b. TUBE WALL THICKNESS AND CORRESPONDING B_4C DENSITY REQUIRED FOR MAXIMUM CONTROL ROD LIFETIME AS A FUNCTION OF ALLOWABLE FIBER STRESS IN TUBING MATERIAL

FIGURE-5 MAXIMUM CONTROL ROD LIFETIME AS A
FUNCTION OF ALLOWABLE FIBER STRESS

APPENDIX

I. Rod Lifetime Calculations

In a control element which utilizes B^{10} as the neutron absorbing material, helium is produced according to the net reaction

The total gram-moles of helium produced in the tubes of all of the control rods, n_o , can be expressed by the equation

$$n_o = \frac{(p-1) \times V}{f RT} \quad (2)$$

where p = internal tube pressure in atmospheres

V = total inside volume of empty tubes in cm^3

X = fraction of total tube volume available to released helium

f = fraction of He produced which is released from the carbide structure

T = temperature of He in $^{\circ}K$

R = gas constant = $82.06 \frac{cm^3-atm}{gm-mole^{\circ}K}$

The number of neutrons absorbed, $\bar{n}$, is given by

$$\bar{n} = \left(\frac{n}{N} \right)_a \frac{WA}{M} \quad (3)$$

where $\left(\frac{n}{N} \right)_a$ = average fractional burnup, defined as the number of neutrons absorbed divided by the total number of atoms of the chemical (B^N) present

W = total weight of absorbing chemical (B^N) in grams

A = Avogadro's number

M = molecular weight of absorbing chemical

From the above reaction, $\bar{n} = An_o$, and if ρ be defined as the density in gm/cm^3 of natural boron in a B_4C^O compact of theoretical density, then

$$W = \rho (1-X) V \quad (4)$$

Thence,

$$\frac{x}{1-x} = \frac{f RT \rho}{M (p-1)} \cdot \left(\frac{n}{N} \right)_a \quad (5)$$

The relationship between fractional burnup and fractional surface density, F , can be expressed by a linear equation

$$\frac{n}{N} = \frac{1-F}{5.06} \quad (5) \quad (6)$$

where F is defined as the ratio of the surface density of the absorbing material at any given time, S (gm/cm^2), to the initial absorber surface density, S_1 , where

$$S_1 = \rho (1-x) t^* \quad (7)$$

t^* , the effective thickness of a row of tubes, is defined as the cross-sectional area of B_4C in the tubes divided by the effective blade width (Figure 1).

It is assumed that the nuclear life of a control rod is determined when the surface density at the point of peak burnup is decreased to a value corresponding to the minimum relative worth for the control system required to hold down the core in the cold, clean condition. It is further assumed that the peak and average burnups for the rod are related by a constant, m , the hot spot factor, such that

$$\left(\frac{n}{N} \right)_p = m \left(\frac{n}{N} \right)_a \quad (8)$$

From Equations 6, 7 and 8 it follows that at the end of nuclear life

$$\left(\frac{n}{N} \right)_a^{\text{fin}} = \frac{1 - \frac{S_m}{\rho (1-x) t^*}}{5.06 m} \quad (9)$$

where S_m is the minimum surface density. By combining Equations 5 and 9 and letting $p = p_{\text{max}}$, the maximum allowable internal pressure, one can obtain

$$\chi = \frac{\left(1 - \frac{S_m}{\rho t^*}\right) \left[\frac{f RT \rho}{5.06 m M (p_{\max} - 1)} \right]}{1 + \frac{f RT \rho}{5.06 m M (p_{\max} - 1)}} \quad (10)$$

$p_{\max}$ can be determined from the equation

$$p_{\max} = \frac{2 S^* t}{14.7 d_o} \quad (11)$$

where S^* = allowable fiber stress in psi in the tubing material at a given metal temperature

t = tube wall thickness

d_o = outside diameter of tube

Having calculated the relative worth necessary to shut the core down in the most reactive condition, one can determine S_m from a plot of relative worth versus surface density (Appendix, II). If constant values are assumed for T , S^* , and d_o , the B_{1C} fractional density in the tubes, $1-\chi$, becomes a function only of tube wall thickness and fractional helium release at the optimum condition of equal nuclear and tube lifetimes.

The years of life for given values of t and f can then be determined from the expression

$$L = \frac{W A \left(\frac{n}{N} \right)_a^{\text{fin}} (6)}{M \alpha \left(\frac{\Delta k_{\text{ex}}}{k_{\text{eff}}} \right)_h \text{ PC}} \quad (12)$$

or, by using Equation 4 and combining constants,

$$L = K d_i^2 (1-\chi) \left(\frac{n}{N} \right)_a^{\text{fin}} \quad (13)$$

In Equations 12 and 13

L = rod lifetime in years

α = number of neutrons produced per kw-yr, $2.45 \cdot 10^{21}$

Δk_{ex} = hot excess reactivity to be controlled by rods

$\left(\frac{k_{\text{eff}}}{k}\right)_h$ = effective reactivity at operating conditions

P = total thermal reactor power in kw

C = load factor

d_i = inside diameter of tubes

K = constant

In this study the following values were assumed:

m = 4

T = 700°F (= 644°K)

S* = 12,000; 17,000; 30,000 and 50,000 psi

C = 0.80

II. Relative Worth and Surface Density

From GEAP 3344⁽⁶⁾ the relative worth required to give the necessary negative reactivity in a system of control rods to maintain the reactor core subcritical in the cold, clean condition can be calculated by the equation

$$R = \frac{V}{8 w l N L_c} \left(\frac{\Delta k}{k} \right)_c \quad (1)$$

where V = core volume

w = effective blade width, in which case the cruciform is considered as consisting of four blades

l = length of absorber section

N = number of rods

L_c = neutron diffusion length (cold)

$\left(\frac{\Delta k}{k} \right)_c$ = control system effective worth in cold, clean condition

By inserting the values pertaining to the reference application, one obtains

$$R = \frac{\pi \times (61.5)^2 \times 136 \times 2.54 \times .240}{8 \times 3.56 \times 130 \times 97 \times 1.93 \times 1.240} = 1.14 \quad (2)$$

The series of curves in Figure A II-1 show control rod worth, relative to a 0.020 inch cadmium slab, as a function of the surface density of natural boron. The boron slab curve was extracted from data in GEAP 3201 (7). Points A, B, C, and C' in this figure were obtained from blackness tests carried out in the VAL critical assembly facility. The curve for 20-mil wall tubing was obtained by means of an extension of the relationship between Point A and the boron slab curve. Curves for B_4C in tubes of other wall thicknesses were produced by considering the relative cross-sectional areas of B_4C and tube metal and estimating the effect of the 60-mil sheath from Point B and the curve C C'.

Having calculated R, from Figure A II-1 one can determine the minimum surface density S_m for boron as B_4C in tubes of various thicknesses.

FIGURE-AII-1 RELATIVE WORTH VS. SURFACE DENSITY FOR B₄C IN TUBES

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