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ALUMINUM-OXIDE TEMPERATURES OF THE MARK VB, VE, VR, 15, AND MARK 25 ASSEMBLIES

Introduction

Operational Planning Division (OPD) asked the Nuclear Engineering Division (NED) to compute the maximum aluminum-oxide and oxide-coolant temperatures of assemblies cladded in 99+ percent aluminum. The assemblies consiuered were the Mark VB[1], Mark VE[2], Mark VR[3], Mark 15[4] and the Mark 25[5]. These assemblies consists of nested slug columns with individual uranium slugs cladded in aluminum cans. The CREDIT[4] code was modified to calculate the oxide film thickness and the aluminum-oxide temperature at each axial increment. This information will be used by OPD to evaluate the potential for cladding corrosion of the Mark 25 assembly.

Summary

The maximum aluminum-oxide and oxide-coolant temperatures of the Mark VB, Mark VE, Mark VR, Mark 15 and the Mark 25 are given in Tables 1-8. The assembly powers, flows and axial flux shapes were taken from Works Technical Monthly Reports for the Mark VB, Mark VE and the Mark VR. The Mark 15 assembly flow and axial flux shape were taken from operating data acquired during the Mark 15 demonstration charge. The Mark 25 parameters are based on predicted values only. Assembly radial power profiles and slug power fractions were calculated using the GLASS code. These values were supplied by the Reactor Physics Group (Tables 11 and 12).

Discussion

Oxide Film Thickness

The Kritz Correlation[6] was used to calculate the aluminum oxide growth on the slug columns. The oxide film thickness is correlated as a function of time, oxide-coolant temperature, and heat flux. This relationship describes the oxide film thickness of some 600 measured points with a standard deviation of 0.33 mils. The empirical correlation is shown in Appendix A. The correlation was programmed into the DOTT subroutine of the CREDIT code.

The assemblies were assumed to operate at a constant power (heat flux) for fifty days. Fifty days was a typical fuel cycle length. The oxide-coolant temperature, heat flux, and oxide thickness were calculated at each axial increment for each slug surface. The oxide thickness was allowed to reach a maximum of 2 mils in the CREDIT calculations. Experiments at the Oak Ridge National Laboratory[7] have shown that spalling of an oxide film occurs spontaneously at thicknesses above 2 mils. The CREDIT calculations assumed no dissolution of the aluminum oxide.

Aluminum-Oxide and Oxide-Coolant Temperatures

The aluminum-oxide temperature was calculated in DOTT as a separate, decoupled calculation. The temperature profile across each slug column was computed without the presence of an oxide layer. Then the temperature rise across each calculated oxide film was computed using the Fourier Law of Heat Conduction (Appendix A). The surface heat flux at each axial increment was used in the equation. The oxide was assumed to have a thermal conductivity of 1.25 pcu/(hr)(ft)(°C)[7,8]. The oxide-coolant temperature was calculated in DOTT at each axial increment.

Remarks

The heat transfer calculations in the CREDIT code generate nominal values. These quantities do not incorporate any nonidealities or calculational uncertainties. An estimate of the overall uncertainty in the oxide film temperature rise over the bulk coolant is given in Appendix B.

Assembly Heat Transfer Model (CREDIT)

- Nominal assembly dimensions
- Axisymmetric plug flow and temperature profiles
- Constant thermal properties
- No axial conduction

Calculational Uncertainties	Estimate of Standard Deviation
Heat transfer coefficient	± 15%
Oxide film correlation	± .33 mils
Oxide thermal conductivity	± .2 pcu/(hr)(ft)(°C)
Thickness at spallation	± .25 mils
Axial flux shape	± 7% in Q/A
Moderator heat transfer	small
Assembly flow and power	

REFERENCES

1. Technical Data Summary - Mark VB Fuel Assemblies, DPSTD-VB, 8/62, Revised 11/22/63 (Secret).

2. Technical Data Summary - Mark VE Fuel Assemblies, DPSTD-VE, 11/63, (Secret).

3. Reactor Engineering of Mark VR Fuel Assemblies, DPSTM-VR, 9/68 (Secret).

4. J. E. McAllister, J. F. Knight, L. L. Hamm, CREDIT Documentation and the Mark 15 Subroutine, DPST-83-402, March 31, 1983.

5. S. E. Aleman, J. R. Chandler, L. L. Hamm, Mark 22S and Mark 25 Assembly Designs, DPST-84-674, to be issued.

6. DPSP-65-1-11, Works Technical Department, Nov. 1965 (Secret).

7. J. C. Greiss et al., Effect of Heat Flux on the Corrosion of Aluminum by Water Part IV, ORNL-3541, (February 1964).

8. Hydraulics and Heat Transfer of Mark 31 and Mark 30 Target Assemblies, DPSTM-31(30)(H).

Data from Works Technical Monthly Reports

Table	Assembly	Max slug pair power	Qmax/Qavg	Flow
1	Mark VB	400 kw	1.26	265 gpm
2	Mark VB	360 kw	1.26	280 gpm
3	Mark VE	405 kw	1.26	310 gpm
4	Mark VE	365 kw	1.26	315 gpm
5	Mark VR	400 kw	1.17	280 gpm
6	Mark VR	375 kw	1.17	300 gpm

$$\text{Assembly power} = \frac{\text{(No. of slug pairs)} \times \text{(Max slug pair power)}}{Q_{max}/Q_{avg}}$$

Table 1

OPERATING CHARACTERISTICS OF MARK VB ASSEMBLY

Assembly Flow, gpm	265
Channel 1 (Outer)	119.7
Channel 2 (Middle)	122.2
Channel 3 (Inner)	23.1
Assembly power, MW	6.3
Axial flux shape	Table 9
Channel effluent temp (PI - 30 C),[a]	
Channel 1 (Outer)	116.0
Channel 2 (Middle)	116.8
Channel 3 (Inner)	101.0
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	167.7
- inner surface	156.1
Inner column - outer surface	150.7
- inner surface	137.2
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	255.8
- inner surface	241.1
Inner column - outer surface	215.6
- inner surface	217.7
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	660.5
- inner surface	637.3
Inner column - outer surface	486.3
- inner surface	604.2
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	2.000
- inner surface	2.000
Inner column - outer surface	2.000
- inner surface	2.000
Maximum nominal core temp,[c] C	
Outer column	454.9
Inner column	402.7

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) *Assumes no oxide buildup on the cladding surface.*

Table 2

OPERATING CHARACTERISTICS OF MARK VB ASSEMBLY

Assembly Flow, gpm	280
Channel 1 (Outer)	126.5
Channel 2 (Middle)	129.1
Channel 3 (Inner)	24.4
Assembly power, MW	5.67
Axial flux shape	Table 9
Channel effluent temp (PI = 30 C),[a]	
Channel 1 (Outer)	104.5
Channel 2 (Middle)	104.0
Channel 3 (Inner)	90.5
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	151.8
- inner surface	141.0
Inner column - outer surface	135.7
- inner surface	124.4
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	231.1
- inner surface	217.5
Inner column - outer surface	182.5
- inner surface	187.5
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	594.3
- inner surface	573.8
Inner column - outer surface	437.8
- inner surface	543.5
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	2.000
- inner surface	2.000
Inner column - outer surface	1.601
- inner surface	1.742
Maximum nominal core temp,[c] C	
Outer column	410.2
Inner column	363.2

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 3

OPERATING CHARACTERISTICS OF MARK VE ASSEMBLY

Assembly Flow, gpm	310
Channel 1 (Outer)	113.4
Channel 2 (Middle)	151.0
Channel 3 (Inner)	42.5
Channel 4 (Axial)	3.1
Assembly power, MW	6.38
Axial flux shape	Table 9
Channel effluent temp (PI - 30 C),[a]	
Channel 1 (Outer)	107.6
Channel 2 (Middle)	104.3
Channel 3 (Inner)	97.9
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	142.8
- inner surface	133.3
Inner column - outer surface	128.3
- inner surface	128.0
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	206.7
- inner surface	181.6
Inner column - outer surface	169.3
- inner surface	176.2
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	492.1
- inner surface	451.2
Inner column - outer surface	427.9
- inner surface	464.8
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	1.946
- inner surface	1.605
Inner column - outer surface	1.437
- inner surface	1.555
Maximum nominal core temp,[c] C	
Outer column	309.2
Inner column	324.0

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 4

OPERATING CHARACTERISTICS OF MARK VE ASSEMBLY

Assembly Flow, gpm	315
Channel 1 (Outer)	115.3
Channel 2 (Middle)	153.4
Channel 3 (Inner)	43.2
Channel 4 (Axial)	3.1
Assembly power, MW	5.75
Axial flux shape	Table 9
Channel effluent temp (PI = 30 C),[a]	
Channel 1 (Outer)	100.0
Channel 2 (Middle)	96.0
Channel 3 (Inner)	90.3
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	132.7
- inner surface	123.4
Inner column - outer surface	118.8
- inner surface	121.8
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	179.0
- inner surface	158.4
Inner column - outer surface	148.5
- inner surface	154.0
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	443.1
- inner surface	407.2
Inner column - outer surface	385.8
- inner surface	394.2
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	1.566
- inner surface	1.291
Inner column - outer surface	1.156
- inner surface	1.226
Maximum nominal core temp,[c] C	
Outer column	282.5
Inner column	295.4

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 5

OPERATING CHARACTERISTICS OF MARK VR ASSEMBLY

Assembly Flow, gpm	280
Channel 1 (Outer)	101.1
Channel 2 (Middle)	139.1
Channel 3 (Inner)	37.0
Channel 4 (Axial)	2.8
Assembly power, MW	6.5
Axial flux shape	Table 10
Channel effluent temp (PI - 30 C),[a]	
Channel 1 (Outer)	117.0
Channel 2 (Middle)	112.6
Channel 3 (Inner)	108.6
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	161.6
- inner surface	145.0
Inner column - outer surface	139.7
- inner surface	145.7
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	220.6
- inner surface	197.3
Inner column - outer surface	183.5
- inner surface	193.6
Nominal heat flux,[b] $kpcu/hr-ft^2$	
Outer column - outer surface	442.5
- inner surface	440.0
Inner column - outer surface	414.4
- inner surface	419.5
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	2.000
- inner surface	1.782
Inner column - outer surface	1.584
- inner surface	1.712
Maximum nominal core temp,[c] C	
Outer column	310.7
Inner column	322.3

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 6

OPERATING CHARACTERISTICS OF MARK VR ASSEMBLY

Assembly Flow, gpm	300
Channel 1 (Outer)	108.3
Channel 2 (Middle)	149.1
Channel 3 (Inner)	39.6
Channel 4 (Axial)	3.0
Assembly power, MW	6.1
Axial flux shape	Table 10
Channel effluent temp (PI = 30 C),[a]	
Channel 1 (Outer)	107.4
Channel 2 (Middle)	102.3
Channel 3 (Inner)	98.9
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	148.6
- inner surface	132.9
Inner column - outer surface	128.0
- inner surface	133.7
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	196.8
- inner surface	173.1
Inner column - outer surface	161.7
- inner surface	170.5
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	414.5
- inner surface	412.4
Inner column - outer surface	388.3
- inner surface	393.0
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	1.745
- inner surface	1.460
Inner column - outer surface	1.300
- inner surface	1.405
Maximum nominal core temp,[c] C	
Outer column	288.3
Inner column	299.3

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 7

OPERATING CHARACTERISTICS OF MARK 15 ASSEMBLY

Assembly Flow, gpm	320
Channel 1 (Outer)	115.5
Channel 2 (Middle)	149.1
Channel 3 (Inner)	53.8
Channel 4 (Axial)	1.6
Assembly power, MW	7.0
Axial flux shape	Table 9
Channel effluent temp (PI = 30 C),[a]	
Channel 1 (Outer)	105.6
Channel 2 (Middle)	112.1
Channel 3 (Inner)	110.0
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	151.4
- inner surface	142.3
Inner column - outer surface	142.1
- inner surface	150.0
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	207.2
- inner surface	190.4
Inner column - outer surface	180.8
- inner surface	205.3
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	439.5
- inner surface	428.4
Inner column - outer surface	385.0
- inner surface	441.0
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	1.904
- inner surface	1.685
Inner column - outer surface	1.510
- inner surface	1.882
Maximum nominal core temp,[c] C	
Outer column	277.4
Inner column	303.6

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 8

OPERATING CHARACTERISTICS OF MARK 25 ASSEMBLY

Assembly Flow, gpm	300
Channel 1 (Outer)	109.5
Channel 2 (Middle)	144.6
Channel 3 (Inner)	42.9
Channel 4 (Axial)	3.0
Assembly power, MW	6.5
Axial flux shape	Table 9
Channel effluent temp (PI = 30 C),[a]	
Channel 1 (Outer)	104.2
Channel 2 (Middle)	111.6
Channel 3 (Inner)	110.8
Nominal oxide-coolant temp,[b] C	
Outer column - outer surface	146.4
- inner surface	142.6
Inner column - outer surface	147.4
- inner surface	152.1
Maximum nominal aluminum-oxide temp, C	
Outer column - outer surface	189.9
- inner surface	177.1
Inner column - outer surface	198.2
- inner surface	211.8
Nominal heat flux,[b] kpcu/hr-ft^2	
Outer column - outer surface	398.5
- inner surface	362.4
Inner column - outer surface	428.1
- inner surface	452.8
Nominal aluminum oxide thickness,[b] mils	
Outer column - outer surface	1.638
- inner surface	1.430
Inner column - outer surface	1.779
- inner surface	1.977
Maximum nominal core temp,[c] C	
Outer column	288.2
Inner column	396.5

(a) Includes heat transferred from bulk moderator (95 C).

(b) At the axial layer of maximum aluminum-oxide temperature.

(c) Assumes no oxide buildup on the cladding surface.

Table 9
Axial Flux Shape

Layer	N Value
1	0.35
2	0.60
3	0.78
4	0.93
5	1.05
6	1.15
7	1.23
8	1.25
9	1.27
10	1.27
11	1.26
12	1.25
13	1.22
14	1.18
15	1.14
16	1.08
17	0.98
18	0.84
19	0.66
20	0.44

Table 10
Axial Flux Shape

Layer	N Value
1	0.38
2	0.49
3	0.82
4	0.98
5	1.10
6	1.17
7	1.18
8	1.18
9	1.18
10	1.17
11	1.17
12	1.16
13	1.16
14	1.15
15	1.15
16	1.14
17	1.11
18	1.04
19	0.92
20	0.75

Table II

Relative Volumetric Heat Generation[1]
RPHI

MK #	Outer Slug OD	Outer Slug (OD + ID)/2	Outer Slug ID	Inner Slug OD	Inner Slug (OD + ID)/2	Inner Slug ID
VB	1.853	1.274	1.000	2.810	1.724	1.000
VE	1.674	1.195	1.000	1.784	1.257	1.000
VR	1.684	1.194	1.000	1.802	1.281	1.000
25	1.569	1.176	1.000	1.780	1.269	1.000

Mark 15 Assembly[2]

Outer Slug		Inner Slug	
OD	1.759	OD	1.248
	1.140		1.043
	1.036		1.000
	1.000		1.010
ID	1.122		1.325

[1] These values were supplied by John Chandler (Reactor Physics).

[2] @ 14.5 % U^{235} burnup.

Table 12

Assembly Slug Power Fractions[1]

Assembly	Outer Column	Inner Column
Mark VB	0.747	0.253
Mark VE	0.649	0.351
Mark VR	0.649	0.351
Mark 15	0.600	0.400
Mark 25	0.588	0.412

[1] These values were supplied by John Chandler.

APPENDIX A

Calculation of oxide growth on slug columns

Kritz Correlation[6],

$$C = 17.3\,(Q/A)\,\Theta^{.778}\,e^{-1880/K}$$

where

C = oxide thickness, mils
Q/A = heat flux, 10^6 pcu/(hr)(ft^2)
Θ = oxide growth time, days
K = absolute temperature of oxide-coolant, °K

Aluminum-oxide temperature

Fourier Heat Conduction Law,

$$Q/A = K_c \frac{T_{ox} - T_c}{C}$$

where

Q/A = heat flux, pcu/(hr)(ft^2)
K_c = oxide thermal conductivity, 1.25 pcu/(hr)(ft)(°C)
T_{ox} = aluminum-oxide temperature, °C
T_c = oxide-coolant temperature, °C
C = oxide thickness, ft

APPENDIX B

1. <u>Overall uncertainty in (T_{ox} - T_{bulk}), $\sigma_{\Delta T}$</u>

$$\Delta T = T_{ox} - T_{bulk} = \Delta T_{ox} + \Delta T_{film}$$

$$Q/A = K_c \frac{\Delta T_{ox}}{C} \quad \text{(Appendix A)}$$

$$Q/A = h \ \Delta T_{film} \quad \text{(CREDIT)}$$

$$\Delta T = \left(\frac{Q}{A}\right)\left(\frac{C}{K_c} + \frac{1}{h}\right)$$

$$\sigma_{\Delta T} = \pm \left\{ \left(\frac{\partial \Delta T}{\partial Q/A}\sigma_{Q/A}\right)^2 + \left(\frac{\partial \Delta T}{\partial C}\sigma_c\right)^2 + \left(\frac{\partial \Delta T}{\partial K_c}\sigma_{K_c}\right)^2 + \left(\frac{\partial \Delta T}{\partial h}\sigma_h\right)^2 \right\}^{1/2}$$

$$= \pm \left\{ \left(\frac{C}{K_c} + \frac{1}{h}\right)^2 \sigma_{Q/A}^{\ 2} + \left(\frac{Q/A}{K_c}\right)^2 \sigma_c^{\ 2} + \left(-\frac{Q/A}{K_c^{\ 2}}\, C\right)^2 \sigma_{K_c}^{\ 2} + \left(-\frac{Q/A}{h^2}\right)^2 \sigma_h^{\ 2} \right\}^{1/2}$$

From page 3,

$$\sigma_{Q/A} = \pm .07\ Q/A$$

$$\sigma_c = \pm\sqrt{(.33)^2 + (.25)^2} = \pm .41 \text{ mils}$$

$$\sigma_{K_c} = \pm .2 \text{ pcu/(hr)(ft)(°C)}$$

$$\sigma_h = \pm .15\ h$$

2. <u>Example</u> (Using Table 1)

Outer surface - outer column of Mark VB

Q/A = 660500 pcu/(hr)(ft^2)
h = 7973 pcu/(hr)(ft^2)(°C) (CREDIT)
C = 2 mils = 0.000167 ft
$\sigma_{Q/A}$ = $\pm$ 46235 lpcu/(hr)(ft^2)
σ_h = $\pm$ 1196 pcu/(hr)(ft^2)(°C)

Overall uncertainty $\sigma_{\Delta T} = \pm$ 29°C at a given assembly power and flow.