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COOLANT VOID EXPERIMENTS IN ECO IN 19 ROD U AND U-PU FUEL CLUSTERS

by

W. HAGE, H. HETTINGER, H. HOHMANN,
F. TINAGLI, F. TOSELLI and H. SCHNEIDER

1974

Joint Nuclear Research Centre
Ispra Establishment - Italy

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Commission of the European Communities
D.G. XIII - C.I.D.
29, rue Aldringen
Luxembourg
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ABSTRACT

Critical height variations of the D_2O moderated critical facility ECO as function of coolant void were measured. The void was generated in a test section of the central fuel element. The aim of the experiments was to study the void effect in a 19-rod fuel cluster with different isotopic contents of fissile and fertile U and Pu isotopes in the exchangeable fuel rods. The experiments were carried out with 3 coolants (D_2O, H_2O and D_2O-H_2O mixture) at 3 lattice pitches.

KEYWORDS

ECO REACTOR
FUEL ELEMENT CLUSTERS
CRITICAL SIZE
VOID COEFFICIENT
VOIDS
BUBBLES
VOID FRACTION
COOLANTS
WATER
HEAVY WATER
MIXTURES
URANIUM ISOTOPES
PLUTONIUM ISOTOPES
ISOTOPE RATIO

1. INTRODUCTION

In the D_2O moderated critical facility ECO (Ref.1) the critical height variation was measured as function of coolant void in test fuel assemblies with different isotopic composition of fissile and fertile materials. The experimental data are required to check the reliability of cell lattice codes in the calculation of the coolant void coefficient with Pu isotopes in the fuel.

During the experiments the fuel geometry of a 19 rod cluster with metallic fuel rods was retained, only the isotopic composition (U^{235}, Pu^{239}, Pu^{241} and U^{238}, Pu^{240}, Pu^{242}), the coolants (D_2O, H_2O, 0.3 H_2O+0.7 D_2O) and the lattice pitch were altered.
This report gives a description of the experimental installations, the measurement techniques and the experimental results in terms of a listing of critical height variations as function of coolant void for all investigated test cell conditions. The experimental program was established in a meeting of the D_2O reactor physics experts of the Community held at Ispra 17/18.6.71 and were performed early 1972.

2. EXPERIMENTAL EQUIPMENT

The central fuel position of the ECO reactor was occupied with a special test element, adapted for homogeneous void generation in the central test section. This element was surrounded by a buffer zone with eight U/19/12-D_2O elements, and two other zones with twenty-eight U/19/12-Air and fifty-two U/1/29.2 - D_2O elements (Ref.2). During measurements with H_2O and H_2O-D_2O mixtures the 8 buffer elements had H_2O coolant.

2.1. Test element

The central test element consists of 3 axial 19 rod cluster subassemblies with an active fuel height of 1450 mm for the top, 500 mm for the central and 500 mm for the bottom part (Fig.2.1). The fuel clusters of the different sections are housed inside leak tight pressure tubes and a calandria tube.
During measurements with D_2O coolant all subassemblies were filled with D_2O. The interspace between pressure and calandria tubes was in communication with the D_2O moderator. During other measurements the subassemblies were filled with H_2O or H_2O-D_2O mixtures. Here the interspace pressure-calandria tube contained D_2O over the full length of the fuel bearing zone.
100% void in the central test assembly was obtained removing completely the coolant. Voids between 0 and 50% were generated by N_2 bubbles, injected via hypodermic needles (about $5/cm^2$) arranged on the lower grid plate of the central test section, similar as in previous experiments (Ref.3,4). For this reason the test section was connected via 5 tubes to the bubble element circuit. These tubes passed in the interspace between pressure tube and calandria tube. Three ended near the lower grid plate and served for N_2 and coolant supply and the pressure difference measurement of the water-N_2 column. The two other tubes fixed to the upper grid plate were used as coolant-N_2 mixture exit and as pressure connection to the difference manometer. In Table 2.1 are summarized the characteristics of the void element geometry.

The composition of the test fuel rods used during the experiments is given in Table 2.2. The axial position of the test element inside the reactor was adjusted such that the lower edge of the fuel bearing zone of the test element coincided with those of the other elements.

Table 2.1. Characteristics of void element

Number of fuel rods/cluster	19
Fuel rod diameter (mm)	12
Al cladding inner/outer diameter (mm)	12.1/14.0
Diameter of inner ring with fuel rods (mm)	30.4
Diameter of outer ring with fuel rods (mm)	58.7
Al pressure tube inner/outer diameter (mm)	76.8/79.8
Al calandria tube inner/outer diameter(mm)	110/114
Coolants	D_2O; H_2O and 0.3 H_2O+0.7 D_2O

Table 2.2 Fuel rod composition of test section

Fuel identification	weight % ratios				
	U^{235}/U	Pu/U	Pu^{240}/Pu^{239}	Pu^{241}/Pu^{239}	Pu^{242}/Pu^{239}
UN	0.714	-	-	-	-
UE	0.804	-	-	-	-
UD	0.643	-	-	-	-
Pu 1	0.714	0.0573	6.22	0.57	-
Pu 3	0.714	0.046	25.52	4.22	1.1
Pu 4	0.227	0.256	27.80	0.79	1.0

2.2. Bubble element circuit

The bubble element circuit has three principal functions:

1. the generation of a defined void fraction
2. the adjustment of the coolant column to a constant height for all experimental conditions
3. the density measurement of the coolant column being a function of the void fraction.

The description of the circuit (Fig.2.2) used during these experiments is given in Ref.3 and .5.

3. MEASUREMENT TECHNIQUES

3.1. Measurement of void fractions

Two methods were available for the void measurement : a volumetric and a pressure difference method.
With the volumetric method the void fraction is calculated from the relation :

$$\alpha = \frac{V_G}{V_T} = \frac{F_e \; \Delta h(\alpha)}{F_c \; H_v}$$

V_T = coolant volume in the channel at void $\alpha = 0$

V_G = N_2 volume in the coolant

F_e = cross section of coolant level meter

F_c = cross section of coolant in the coolant channel at $\alpha = 0$

H_v = height of voided region in the central test subassembly

$\Delta h(\alpha) = h(\alpha) - h(\alpha = 0)$

difference in the level meter reading between void fraction α and void fraction 0.

The cross sections of the coolant level meter and of the coolant channel were obtained from the geometrical dimensions. During the experiments this method proved not to be sufficiently accurate. The reading $h(\alpha)$ was very much dependent on the coolant flow in the coolant lines, or in other words on the coolant volume, which appeared to vary during the experiment in the piping system. An accuracy of about ±5% in void could be obtained with this method.

The pressure difference method led to much more reliable results. Here the pressure difference ΔP was measured between the top and bottom of the coolant column in the test subassemblies at void fraction α and $\alpha = 0$.

The relation used is

$$\alpha = \frac{\Delta P(\alpha = 0) - \Delta P(\alpha)}{K\, H_V\, \gamma\, (1 - \gamma_{N_2}/\gamma)}$$

$\Delta P(\alpha)$ = pressure difference of the coolant column measured with a difference manometer

γ = specific weight of coolant

γ_{N_2} = " " " nitrogen at the pressure of the system

K = calibration constant.

The calibration constant K was obtained measuring at different coolant levels H_V the pressure difference $\Delta P(H_V)$ existing between top and bottom of the element

$$K = \frac{\Delta P(H_1) - \Delta P(H_2)}{\gamma\,(H_1 - H_2)}$$

The correction factor γ_{N_2}/γ is small compared to the error of the void measurement which is less than $\Delta\alpha = \pm 1\%$.

3.2. Measurement of critical height differences

The experiments were started in the following manner. After the adjustment of a supercritical waterlevel and a following extraction of the horizontal control plates the reactor diverged with a positive reactor period at zero void in the test section of the central element. The critical waterlevel was determined after a reactor balancing time of about 20 minutes.
The reactivity coefficient of the moderator level was obtained from the two moderator levels H_p and H_c and the reactivities measured during the divergence ρ_p and the reactor stabilisation ρ_c .

$$\frac{\Delta H}{\Delta \rho} = \frac{H_p - H_c}{\rho_p - \rho_c}$$

Thereafter void was generated inside the test section and adjusted for about 5 minutes to a stable value. After three different void steps the zero void condition was repeated. From the reactivity $\rho(\alpha)$ obtained at void fraction α and $\rho(\alpha = 0)$ at $\alpha = 0$ the critical height differences were computed using the following relation

$$\Delta H(\alpha) = H(\alpha) - H(\alpha = 0) = \frac{dH}{d\rho}\left[\rho(\alpha = 0) - \rho(\alpha)\right]$$

The reactivity was measured "On Line" with a digital computer applying the Inverse Neutron Kinetics Technique (Ref.6). The error of the critical height determination was negligible compared with the error of the void measurement.

4. EXPERIMENTAL RESULTS

The experimental results of the void experiments are presented in Tables 4.1 to 4.9 giving the void fraction α in percent as function of the critical height variation $\Delta H(\alpha)$ for the six rod types (UN, UE, UD, Pu1, Pu3 and Pu4) used in the 19 rod test assembly.

Each table contains information on the core composition (lattice pitch, core loading, D_2O moderator concentration) and the coolant used in the central element.
For the case of 100% void the critical height difference was measured with the ECO levelmeter with an accuracy of ± 0.2 mm and with the inverse kinetics method, having an accuracy of better than ± 0.05 mm with the used measurement procedure. In most cases the void effect was calculated for the 100% case using the PLUTHARCO cell and the EQUIPOISE criticality codes (Ref.7). The agreement between theory and measurement is quite good for D_2O but not for the H_2O and H_2O - D_2O coolants. This is particularly true for the Pu bearing fuels in H_2O and H_2O-D_2O mixtures, because of the pronounced resonances just above the thermal region. As a consequence the spectrum will be hardened for low moderation and high absorption. Obviously the PLUTHARCO code, which is designed for well moderated lattices, cannot reproduce the hardening effect.

For completeness of the data the critical heights measured at void fraction $\alpha = 0$ were included in the tables. The critical height differences existing between the cores with different test fuel composition cannot be derived from the quoted values. The experimental conditions were such that lattice pitch changes were performed before the exchange of fuel test sections. Under such conditions the reproducibility of the critical heights lies in the order of one millimeter.

For all coolants the critical heights decrease with increasing void fraction and this effect is more pronounced at larger pitches.

The smallest critical height variations as function of void were observed with D_2O coolant (Table 4.1 to 4.3). The effects were about 4 to 5 times larger with D_2O-H_2O coolant mixture (Table 4.4 to 4.6) and 7 to 10 times larger with H_2O coolant (Table 4.7 to 4.9). The void effect was more pronounced with the more reactive test sections and increased in the sequence Pu4, UD, UN, Pu1, UE, Pu3. For the 100% void fraction the critical height variation measured with the different test fuel rods are presented as function of the lattice pitch, for all coolant types (Fig.4.1 to 4.3).
For the case of D_2O coolant the critical height variation $\Delta H(\alpha)$ can be given as a linear function of the void fraction α up to 50% due to the negative influence of both the fast effect and the absorptions.
Table 4.10 gives the constants a and b of a linear fit of the form

$$\Delta H(\alpha) = a + b\alpha$$

and the maximum deviation of the worst measurement point α_w, $\Delta H(\alpha_w)$ from the fitted curve

$$\delta \Delta H(\alpha) = |\Delta H(\alpha) - \Delta H_w(\alpha_w)|$$

An extrapolation with the constants a and b to the α = 100% case leads to an underestimation of $\Delta H(\alpha = 100\%)$ indicating a non linear function of $\Delta H(\alpha)$ for the full void range.

For the case of D_2O-H_2O coolant mixtures the critical height variation could not be presented by a linear or parabula type function for all investigated fuel rod types. The $\Delta H(\alpha)$ curves have different forms for the cases with Pu and without Pu. For the fuel without Pu the $\Delta H(\alpha)$ values are decreasing steadily, while for the Pu containing fuel the $\Delta H(\alpha)$ values decrease asymptotically. In the first cases the spectrum hardening is of minor importance. The decrease in $\Delta H(\alpha)$ is determined by the reduced absorptions and the improved fast fissions. For the Pu containing cases the spectrum hardening effects outbalance the absorption effects on the critical height.

For the H_2O cases the $\Delta H(\alpha)$ curve has a point of inflection at about 50% void. The experimental values obtained could be fitted in the range of $0 \leq \alpha \leq 50\%$

$$\alpha = a^* + b^* \Delta H(\alpha) + c^* \Delta H^2(\alpha)$$

The constants of this least square fitted data are listed in Table 4.11 along with the largest deviation of the worst experimental value $\delta\alpha$ from the fitted curves. Here the spectrum hardening effect and the absorption influence the critical heights in opposite directions. In the last part of the curve (from 50% to 100%), the absorptions and the fast effect prevail.

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Table 4.1 CRITICAL HEIGHT VARIATION (Δ H) AS FUNCTION OF COOLANT VOID (α)

Pitch 18.8 cm

Fuel elements : 1 test element
8 U/19/12 - D_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

coolant in test element : D_2O

moderator D_2O-concentration 99.672 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	
6.8	- 0.05	4.5	- 0.03	4.7	- 0.04	5.2	- 0.04	7.6	- 0.06	8.0	- 0.05	from reactivity measurements
14.6	- 0.10	10.8	- 0.08	7.7	- 0.06	7.7	- 0.06	11.5	- 0.08	11.6	- 0.07	
26.7	- 0.17	25.4	- 0.20	12.3	- 0.09	13.7	- 0.10	14.8	- 0.11	18.8	- 0.12	
40.8	- 0.28	32.0	- 0.25	16.3	- 0.13	20.2	- 0.15	22.9	- 0.18	22.6	- 0.13	
46.9	- 0.31	42.7	- 0.33	20.9	- 0.14	28.3	- 0.20	33.3	- 0.25	28.6	- 0.17	
50.2	- 0.33	47.8	- 0.37	27.7	- 0.20	35.6	- 0.26	38.3	- 0.29	35.4	- 0.20	
58.8	- 0.39	55.2	- 0.43	51.5	- 0.36	43.2	- 0.31	48.2	- 0.37	40.4	- 0.23	
		56.4	- 0.45	56.1	- 0.38	51.0	- 0.36	48.5	- 0.37	49.2	- 0.28	
										52.5	- 0.30	
100	- 0.84	100	- 1.08	100	- 0.78	100	- 0.96	100	- 1.01	100	- 0.78	
100	- 0.8			100	- 0.8	100	- 1.0	100	- 0.9	100	- 0.8	from levelmeter measurements
100	- 0.6	100	- 1.1	100	- 0.7	100	- 1.0	100	- 1.1	100	- 0.8	from theory
1505.1		1498.3		1508.3		1501.6		1501.6		1518.5		critical height at =0(mm)

Table 4.2

CRITICAL HEIGHT VARIATION (Δ H) AS FUNCTION OF COOLANT VOID (α)

Pitch 23.5 cm
Fuel elements : 1 test element
8 U/19/12 - D_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : D_2O
Moderator D_2O-concentration: 99.672 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	
6.7	- 0.09	7.0	- 0.09	4.7	- 0.04	5.7	- 0.08	7.8	- 0.10	8.1	- 0.08	from reactivity measurements
9.8	- 0.12	12.0	- 0.18	8.3	- 0.08	14.0	- 0.19	10.5	- 0.13	14.5	- 0.13	
14.2	- 0.18	20.4	- 0.28	11.8	- 0.13	19.7	- 0.26	15.7	- 0.21	23.0	- 0.21	
21.0	- 0.25	23.0	- 0.32	15.6	- 0.19	27.9	- 0.38	17.7	- 0.24	25.0	- 0.22	
22.3	- 0.29	30.3	- 0.40	24.7	- 0.29	29.1	- 0.39	24.3	- 0.33	33.8	- 0.30	
36.4	- 0.44	37.7	- 0.51	33.1	- 0.37	30.2	- 0.41	31.6	- 0.42	34.9	- 0.30	
46.0	- 0.57	48.8	- 0.68	36.5	- 0.41	40.7	- 0.55	33.4	- 0.44	46.6	- 0.42	
50.9	- 0.62			41.9	- 0.45	44.6	- 0.64	39.2	- 0.53	49.0	- 0.43	
57.2	- 0.71			51.2	- 0.56	53.5	- 0.72	41.5	- 0.59	55.5	- 0.50	
				58.4	- 0.64			43.3	- 0.59			
								51.2	- 0.68			
100	- 1.50	100	- 1.78	100	- 1.34	100	- 1.65	100	- 1.69	100	- 1.15	
100	- 1.4	100	- 1.7	100	- 1.3	100	- 1.7	100	- 1.7	100	- 1.1	from levelmeter measurements
100	- 1.4	100	- 1.7	100	- 1.2	100	- 1.7	100	- - -	100	- 1.3	from theory
1410.3		1404.1		1415.5		1408.0		1407.5		1424.7		critical height at =0(mm)

Table 4.3 CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

pitch 28.05 cm

fuel elements : 1 test element
8 U/19/12 - D_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

coolant in test element : D_2O

moderator D_2O-concentration 99.672 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	
7.6	- 0.18	6.6	- 0.20	5.1	- 0.09	4.6	- 0.12	8.1	- 0.20	4.7	- 0.08	from reactivity measurements
11.0	- 0.25	11.5	- 0.31	9.9	- 0.25	11.1	- 0.27	16.8	- 0.44	7.9	- 0.13	
18.7	- 0.44	17.3	- 0.47	12.0	- 0.24	14.2	- 0.35	26.2	- 0.68	12.8	- 0.23	
27.9	- 0.73	24.8	- 0.67	15.0	- 0.33	19.6	- 0.50	34.9	- 0.88	15.5	- 0.27	
31.3	- 0.72	30.4	- 0.82	21.0	- 0.44	26.5	- 0.68	41.5	- 1.06	25.3	- 0.44	
40.8	- 0.94	36.5	- 0.98	28.4	- 0.67	33.5	- 0.88	49.1	- 1.26	31.6	- 0.54	
43.1	- 1.01	37.1	- 1.10	35.6	- 0.84	37.9	- 0.97			41.7	- 0.70	
44.8	- 1.04	43.0	- 1.18	41.4	- 0.91	41.1	- 1.05			44.0	- 0.72	
50.2	- 1.21	56.0	- 1.53	50.2	- 1.10	44.9	- 1.13			52.0	- 0.87	
				54.6	- 1.17					53.6	- 0.90	
				58.0	- 1.23							
100	- 2.69	100	- 3.15	100	- 2.35	100	- 2.94	100	- 2.99	100	- 2.00	
100	- 2.7	100	- 3.2	100	- 2.4	100	- 2.9	100	- 3.0	100	- 2.0	from levelmeter measurements
100	- 2.7	100	- 3.1	100	- 2.1	100	- 3.0	100	- 3.0	100	- 2.0	from theory
1590.9		1582.7		1598.0		1587.3		1586.2		1609.9		critical height at α=0(mm)

CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

Table 4.4

Pitch : 18.8 cm

Fuel elements : 1 test element
8 U/19/12-H_2O
28 U/19/12-Diphyl
52 U/1/29.2-D_2O

Coolant in test element: 0.7 D_2O+0.3 H_2O
Moderator D_2O-concentration 99.669 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	
3.8	- 0.19	7.6	- 0.39	8.6	- 0.40	7.5	- 0.37	9.1	- 0.50	7.9	- 0.39	from reactivity measurements
8.0	- 0.32	13.5	- 0.73	10.7	- 0.53	9.5	- 0.46	9.6	- 0.54	9.4	- 0.46	
10.4	- 0.50	26.2	- 1.43	25.2	- 1.27	20.0	- 1.17	23.9	- 1.41	12.5	- 0.55	
15.3	- 0.73	34.0	- 1.92	30.0	- 1.49	28.8	- 1.63	35.8	- 2.10	22.0	- 1.13	
21.4	- 1.06	37.3	- 2.08	45.0	- 2.26	40.0	- 2.35	44.5	- 2.64	33.2	- 1.58	
34.7	- 1.72	40.2	- 2.22	48.9	- 2.43	44.2	- 2.60	46.2	- 2.51	41.1	- 2.04	
37.2	- 1.79	41.6	- 2.26	54.3	- 2.61	47.8	- 2.75	48.9	- 2.74	46.4	- 2.14	
47.8	- 2.43	43.4	- 2.35			52.0	- 2.95			48.5	- 2.27	
49.0	- 2.50	47.9	- 2.58							52.8	- 2.45	
55.3	- 2.78											
100	- 5.61	100	- 6.55	100	- 5.52	100	- 6.17	100	- 6.30	100	- 4.99	
100	- 5.6	100	- 6.4	100	- 5.5	100	- 6.1	100	- 6.3	100	- 4.9	from levelmeter measurements
100	- 4.5	100	- 5.1	100	- 3.6	100	- 4.2	100	- 4.9	100	- 4.0	from theory
1863.2		1853.1		1869.8		1855.8		1855.0		1881.3		critical height at α=0(mm)

Table 4.5 CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

Pitch : 23.5 cm

Fuel element : 1 test element
8 U/19/12 - H_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : 0.7 D_2O+0.3 H_2O

Moderator D_2O-concentration : 99.669 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	
3.9	- 0.35	8.7	- 0.78	7.5	- 0.65	9.3	- 1.05	9.0	- 0.96	9.8	- 0.71	from reactivity measurements
10.1	- 0.90	14.6	- 1.45	13.0	- 1.11	14.7	- 1.41	14.1	- 1.48	13.9	- 0.99	
14.6	- 1.28	33.5	- 3.35	30.2	- 2.58	19.5	- 2.07	21.0	- 2.42	17.8	- 1.29	
17.4	- 1.47	36.8	- 3.79	44.2	- 4.01	36.2	- 3.80	29.4	- 3.12	24.7	- 1.72	
22.0	- 1.91	41.4	- 4.07	49.2	- 4.19	38.5	- 4.06	39.8	- 4.42	36.4	- 2.65	
34.7	- 3.09	42.7	- 4.17	53.7	- 4.50	50.6	- 5.25	44.5	- 4.32	48.8	- 3.49	
36.3	- 3.22	43.7	- 4.58			52.6	- 5.57	45.2	- 4.42	51.2	- 3.68	
47.2	- 4.21	44.5	- 4.37			55.8	- 6.18	47.2	- 4.87			
		48.5	- 4.73									
100	- 9.76	100	- 11.16	100	- 9.08	100	- 10.53	100	- 10.70	100	- 7.79	
100	- 9.5	100	- 10.8	100	- 8.9	100	- 10.1	100	- 10.2	100	- 7.9	from levelmeter measurements
100	-10.5	100	- 10.7	100	- 9.9	100	- 9.9	100	- 10.6	100	- 10.0	from theory
1953.4		1942.4		1962.6		1946.8		1945.5		1977.5		critical height at α=0(mm)

Table : 4.6 CRITICAL WEIGHT VARIATION (Δ H) AS FUNCTION OF COOLANT VOID (α)

Pitch : 26.55 cm

Fuel elements : 1 test element
8 U/19/12 - H_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : 0.7 D_2O+0.3 H_2O

Moderator D_2O-concentration : 99.669 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	α (%)	Δ H(mm)	
6.9	- 0.81	7.7	- 1.02	10.3	- 1.35	8.9	- 1.52	11.7	- 2.04	8.6	- 1.19	from reactivity measurements
9.8	- 1.85	11.1	- 1.40	12.9	- 1.56	12.1	- 1.78	15.8	- 2.47	11.6	- 1.32	
14.9	- 1.85	19.0	- 2.57	19.6	- 2.37	18.8	- 2.91	17.0	- 2.65	18.9	- 2.04	
19.7	- 2.44	23.1	- 3.21	23.2	- 2.75	27.4	- 4.01	24.4	- 4.18	19.4	- 2.21	
29.6	- 3.79	32.2	- 4.67	29.0	- 3.62	38.2	- 5.72	32.9	- 5.23	40.0	- 4.27	
35.9	- 4.61	38.3	- 5.42	38.2	- 4.68	50.5	- 7.14	33.8	- 5.41	52.1	- 5.61	
44.7	- 5.84	42.8	- 5.82	39.7	- 5.27	54.1	- 7.86	40.8	- 6.62	55.5	- 5.80	
53.5	- 6.92	43.6	- 5.95	46.4	- 5.74			46.8	- 6.96			
				52.3	- 6.29							
				53.9	- 6.39							
100	- 13.89	100	- 15.06	100	- 12.50	100	- 14.83	100	- 15.04	100	- 10.72	
100	- 13.8	100	- 14.5	100	- 12.3	100	- 14.5	100	- 14.9	100	- 9.9	from levelmeter measurements
100	- 11.5	100	- 13.1	100	- 9.7	100	- 13.0	100	- 12.5	100	- 9.2	from theory
2279.6		2265.5		2291.5		2272.4		2270.6		2311.7		critical height at =0(mm)

Table 4.7 CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

Pitch 18.8 cm

Fuel elements : 1 test element
8 U/19/12 - H_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : H_2O

Moderator D_2O - concentration : 99.667 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	ΔH (mm)	α (%)	ΔH (mm)	α (%)	ΔH (mm)	α (%)	ΔH (mm)	α (%)	ΔH (mm)	α (%)	ΔH (mm)	
6.0	- 0.96	8.6	- 1.32	7.8	- 1.16	9.6	- 1.21	9.1	- 1.21	6.9	- 0.62	from reactivity measurements
7.3	- 0.98	9.3	- 1.15	8.9	- 1.14	10.9	- 1.47	10.9	- 1.35	9.5	- 0.76	
11.0	- 1.53	15.9	- 2.16	12.5	- 1.63	20.6	- 2.43	17.2	- 2.11	12.1	- 1.11	
16.7	- 1.95	19.9	- 2.28	20.2	- 2.40	22.8	- 2.48	18.3	- 2.15	16.7	- 1.45	
19.7	- 2.47	21.3	- 2.71	25.1	- 2.76	30.6	- 3.40	25.1	- 2.95	19.4	- 1.86	
27.0	- 2.99	26.5	- 3.17	31.5	- 3.43	32.6	- 3.43	27.7	- 3.15	24.6	- 2.18	
29.9	- 3.45	30.6	- 3.54	41.0	- 4.32	41.4	- 4.36	33.1	- 3.79	27.6	- 2.60	
38.2	- 4.09	31.1	- 3.52	46.7	- 4.89	44.2	- 4.59	37.5	- 4.36	32.8	- 2.92	
39.7	- 4.41	35.5	- 4.02			49.6	- 5.15	42.4	- 4.77	38.2	- 3.44	
43.6	- 4.79	38.7	- 4.28									
100	- 12.29	100	- 13.05	100	- 12.02	100	- 12.79	100	- 13.07	100	- 10.92	
100	- 12.1	100	- 12.7	100	- 12.3	100	- 12.8	100	- 12.9	100	- 11.1	from levelmeter measurements
100	- 7.5	100	- 7.8	100	- 7.7	100	- 8.1	100	- 7.7	100	- 7.6	from theory
1872.5		1864.1		1881.3		1869.8		1867.5		1893.9		critical height at =0(mm)

Table 4.8

CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

Pitch : 23.5 cm

Fuel elements : 1 test element
3 U/19/12 - H_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : H_2O

Moderator D_2O-concentration 99.667 w %

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	α (%)	ΔH(mm)	
7.2	- 2.06	8.8	- 2.01	7.0	- 1.39	9.0	- 1.98	7.3	- 2.10	6.3	- 1.06	from reactivity measurements
7.8	- 1.82	16.4	- 3.40	9.2	- 1.71	10.3	- 2.53	9.7	- 2.11	9.3	- 1.28	
17.1	- 3.73	28.3	- 5.82	12.0	- 2.24	18.2	- 3.93	14.0	- 3.01	14.3	- 2.20	
19.1	- 3.73	33.9	- 6.59	14.3	- 2.55	22.0	- 4.28	18.2	- 3.94	18.1	- 2.45	
25.7	- 5.19	41.8	- 8.06	18.3	- 3.31	28.1	- 5.63	22.1	- 4.67	25.0	- 3.56	
31.0	- 5.81			22.2	- 3.87	32.8	- 6.13	30.7	- 5.97	27.8	- 3.91	
33.9	- 6.53			29.5	- 5.11	35.7	- 6.84	34.7	- 6.93	32.7	- 4.62	
39.7	- 7.30			32.5	- 5.53	38.6	- 7.21	40.3	- 7.87	40.3	- 5.60	
41.6	- 7.72			41.8	- 7.11	42.6	- 8.04	44.4	- 8.69	45.5	- 6.42	
46.0	- 8.46			46.1	- 7.74					46.7	- 6.55	
										50.3	- 7.14	
100	- 21.22	100	- 22.17	100	- 19.58	100	- 21.87	100	- 22.53	100	- 16.98	
100	- 20.5	100	- 22.5	100	- 19.4	100	- 21.9	100	- 22.5	100	- 17.0	from levelmeter measurements
100	- 20.1	100	- 20.9	100	- 19.6	100	- 21.1	100	- - -	100	- 19.4	from theory
1974.8		1964.8		1984.6		1971.9		1969.2		1999.5		critical height at =0(mm)

Table : 4.9

CRITICAL HEIGHT VARIATION (ΔH) AS FUNCTION OF COOLANT VOID (α)

Pitch 26.55 cm
Fuel elements : 1 test element
8 U/19/12 - H_2O
28 U/19/12 - Diphyl
52 U/1/29.2- D_2O

Coolant in test element : H_2O
Moderator D_2O-concentration : 99.667 w.%

U_{nat}		U_E		U_D		Pu_1		Pu_3		Pu_4		test element
α(%)	ΔH(mm)	α(%)	ΔH(mm)	α(%)	ΔH(mm)	α(%)	ΔH(mm)	α(%)	ΔH(mm)	α(%)	ΔH(mm)	
8.0	- 2.77	9.3	- 2.80	7.6	- 1.67	7.0	- 3.22	7.7	- 2.97	6.8	- 2.11	from reactivity measurements
17.5	- 5.08	15.2	- 4.36	10.2	- 2.23	9.1	- 3.02	11.0	- 3.07	10.5	- 2.67	
23.4	- 6.47	28.9	- 8.27	13.0	- 2.95	18.1	- 6.50	14.3	- 4.29	16.2	- 4.08	
30.7	- 8.35	35.8	- 9.97	16.5	- 3.80	18.7	- 5.40	19.3	- 5.38	18.4	- 4.19	
41.4	-10.76	43.4	-12.15	18.2	- 4.19	24.6	- 7.57	23.6	- 7.12	23.9	- 5.36	
44.5	- 11.49			23.0	- 5.29	26.6	- 7.43	32.3	- 9.37	26.4	- 5.65	
				25.9	- 5.98	31.1	- 8.89	43.8	-12.47	35.6	- 7.66	
				31.7	- 7.27	34.0	- 9.34	46.9	-13.28	39.6	- 8.27	
				35.3	- 8.15	39.0	- 10.89			43.1	- 8.98	
				39.5	- 8.15	42.9	- 11.84					
				42.3	- 9.73							
100	- 29.58	100	- 31.61	100	- 27.35	100	- 30.85	100	- 32.29	100	- 23.99	
100	- 30.3	100	- 31.9	100	- 27.1	100	- - -	100	- 31.9	100	- 23.1	from levelmeter measurements
100	- 21.7	100	- 23.5	100	- 18.7	100	- 23.5	100	- 23.4	100	- 17.8	from theory
2319.3		2305.3		2329.6		2313.0		2311.7		2347.6		critical height at α=0(mm)

Table 4.10   Constants of linear least squares fit of $\Delta H = a + b\alpha$ for D_2O coolant

Pitch (cm)		U_{NAT}	U_E	U_D	Pu_1	Pu_3	Pu_4
18.8	a	- 0.00189	0.00338	- 0.00730	- 0.00352	0.00157	- 0.00507
	b	- 0.00660	- 0.00790	- 0.00677	- 0.00707	- 0.00766	-0.00561
	$\sigma_{\Delta} H_{max}$	0.00896	0.0079	0.0124	0.00485	0.00651	0.0094
23.5	a	- 0.00293	- 0.0004	- 0.0009	0.0024	0.0049	0.00186
	b	- 0.0123	- 0.0137	- 0.0110	- 0.0137	- 0.0137	- 0.00886
	$\sigma_{\Delta} H_{MAX}$	0.0139	0.0157	0.0173	0.0301	0.0281	0.0108
28.05	a	- 0.00233	- 0.0021	- 0.0074	0.0028	- 0.0005	- 0.0069
	b	- 0.0236	- 0.0275	- 0.0217	- 0.0256	- 0.0256	- 0.0166
	$\sigma_{\Delta} H_{MAX}$	0.070	0.078	0.0607	0.0172	0.0105	0.0180

[a] = mm
[b] = mm/%void

Table 4.11 Constants of least squares parabula fit of $\alpha = a + b\Delta H + c\Delta H^2$ for H_2O coolant

Pitch (cm)		U_{NAT}	U_E	U_D	Pu_1	Pu_3	Pu_4
18.8	a*	- 0.8091	- 0.0069	- 0.7074	- 0.6040	- 0.3298	0.4093
	b*	- 7.8914	- 6.6363	- 7.8592	- 8.2301	- 8.1543	-10.6343
	c*	0.3192	0.5646	0.4011	0.3183	0.1594	0.0899
	$\sigma\alpha$	1.40%	1.85%	1.14%	1.23%	0.77%	1.10%
23.5	a*	-0.8080	- 0.0886	- 0.3475	- 0.4428	- 0.6782	- 0.4547
	b*	- 4.5013	- 4.3848	- 5.4981	- 4.4415	- 4.5228	- 7.2328
	c*	0.1310	0.1030	0.0655	0.1261	0.0845	0.0095
	$\sigma\alpha$	1.82%	0.62%	0.44	1.30%	1.89%	1.11%
26.55	a*	- 0.3843	- 0.0988	- 0.0934	- 0.6893	- 0.2951	- 0.7233
	b*	- 3.1681	- 3.4053	- 4.3381	- 2.8428	- 3.3112	- 3.9599
	c*	0.065	0.015	0.011	0.0764	0.0183	0.1076
	$\sigma\alpha$	0.90%	0.40%	3.32%	2.91%	1.30%	1.31%

[a] = %void
[b] = %void/mm
[c] = %void/mm^2

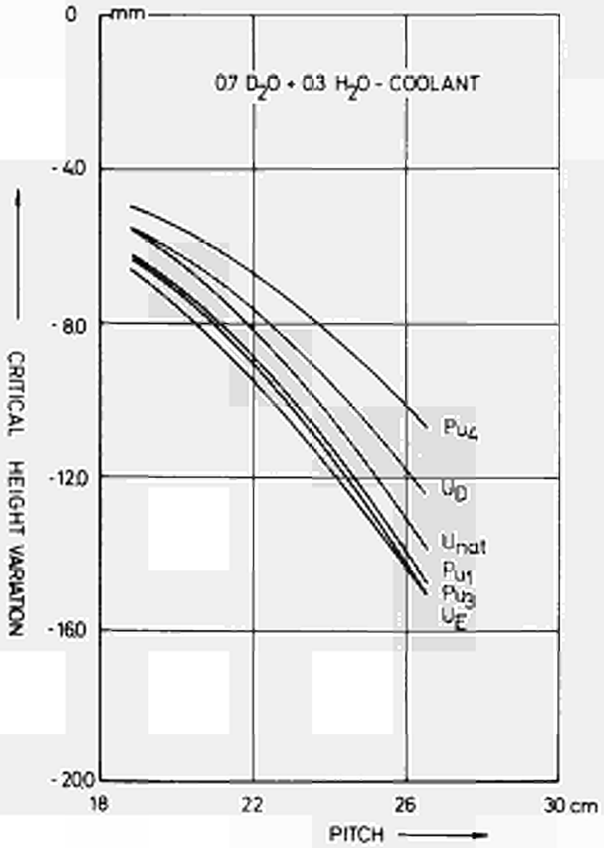

FIG. 4.2 ΔH AS FUNCTION OF PITCH FOR 100 % VOID

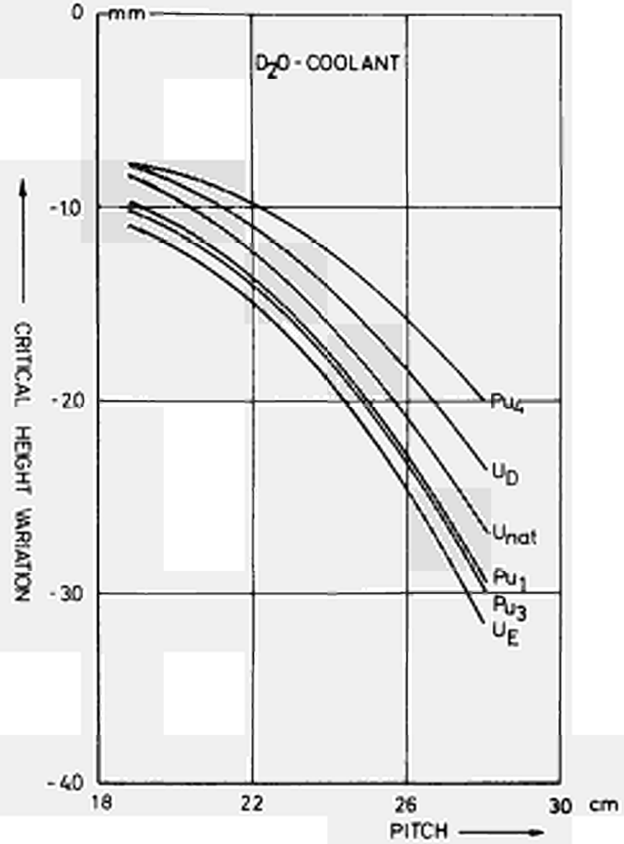

FIG. 4.1 ΔH AS FUNCTION OF PITCH FOR 100 % VOID

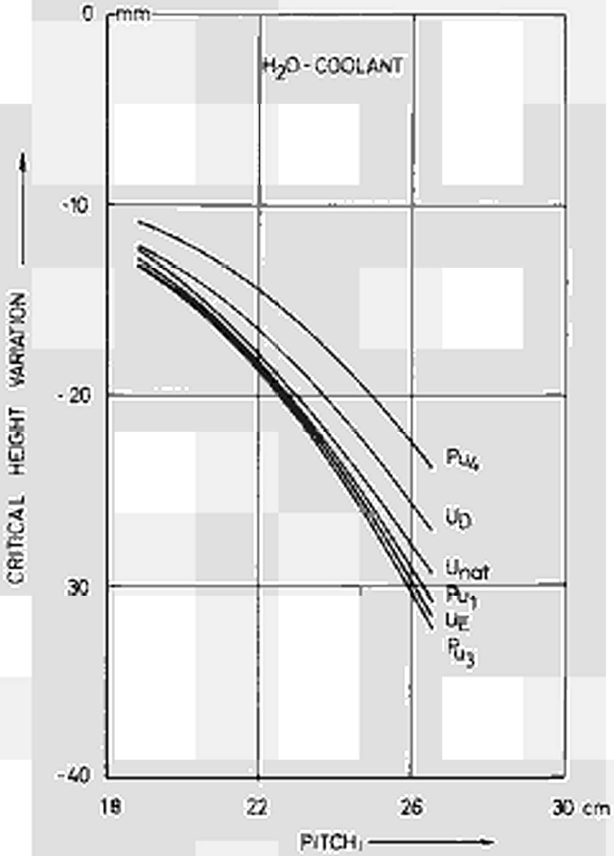

FIG. 43 ΔH AS FUNCTION OF PITCH FOR 100% VOID

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