Details of design, irradiation and fission gas release for the Danish U02-ZR irradiation test 022

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DETAILS OF DESIGN, IRRADIATION AND FISSION GAS RELEASE FOR THE DANISH UO_2-ZR IRRADIATION TEST 022

by

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Abstract

Test 022 comprised three UO_2-Zr test fuel pins which were irradiated in the DR 3 reactor at Risø at 7.2 MPa (70 ato) system pressure. A burnup of approximately 3530 GJ/kg U (36,000 MWD/te UO_2) was accumulated at heat loads in the range 35 to 53 kW/m (350 to 530 W/cm) (test avg. values). Fission gas analysis for two of the pins showed that the releases were 48 and 36%. The experimental data are presented in sufficient detail for use in the validation of fuel performance codes.

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DETAILS OF DESIGN, IRRADIATION AND FISSION GAS RELEASE FOR THE DANISH UO_2-ZR IRRADIATION TEST 022

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INTRODUCTION

Fission gas release data at very high burnup from the Danish UO_2-Zr irradiation test 022 are presented in this report, together with the design and irradiation data required as input for fuel performance code calculations. Although fission gas data were obtained for two fuel pins only (PA29-4 and M2-2C), design details are included for all three pins constituting the test, because part of this information is used in the local power and burnup calculation.

A first analysis of the experiment was published elsewhere(1). Since then, the power history has been re-evaluated to provide a more detailed description of the experiment, and an additional radiochemical burnup determination has been obtained. These details were previously reported in the Metallurgy Department report B-464; the data of the present report are identical to those of B-464 except for a change to SI units and an additional remark about end pellet effects in the section on Irradiation Conditions.

FUEL PIN DESIGN

The three almost identical test fuel pins had 12.6 mm sintered UO_2 pellets of 2.28% enrichment (end pellets with natural ^{235}U content) in 128 mm long stacks. The cladding was cold-worked and stress-relieved Zr-2 tubing of approximately 0.55 mm wall thickness which had been autoclaved on both sides. The diametral pellet-clad clearance was 0.24 mm, and the pins were backfilled with 0.1 MPa (1 ata) He. Further design details are given in Table I.

IRRADIATION

Facility

Each irradiation was performed in a water-cooled rig (see Refs. (2) and (3)) in the 10 MW heavy-water materials testing reactor DR 3 at Risø. The normal reactor cycle comprises 2 Ms (23½ days) at full reactor power and 0.4 Ms (4½ days) shut-down for exchange of experiments and maintenance.

The irradiation rig was loaded in a hollow, highly enriched U-Al driver fuel element in a core position corresponding to the desired heat load. In this rig type, the fuel pin is cooled by natural convection inside the rig of the primary water (H_2O) pressurized to 7.2 MPa (70 ato) with He gas. There is a small external circulation of the primary water for purification purposes. The rig thermal output is determined from flow rate and temperature increase of the secondary cooling water.

Conditions

The thermal output from the test (i.e. the three fuel pins screwed together axially) was obtained by correcting the rig thermal output for gamma heat generation.

Gamma scans on several fission products indicated that the fission density of the (initially lower enriched) end pellets had increased during the irradiation and approached the level of the central pellets. This is a result of different Pu build-up rates caused by different initial ^{235}U contents and corresponding differences in neutron capture. Gamma scans of this and similar irradiations have revealed a certain peaking effect near the pellet stack ends, too. This, however, usually applies to part of an end pellet only; it is thus considered an effect separate from the difference in Pu build-up rate. The gamma scans were supplemented with physics calculations of the ratio between fission densities in end and central pellets as a function of burnup. From this, local heat load and burnup levels were obtained, as described in the appendix. The data reported in the next section are corresponding values on a test average basis.

The appendix gives further details about the irradiation conditions including cladding surface temperature and fast flux levels, as well as a comparison between burnup results from radiochemical analysis and calorimetry.

Irradiation History

The three fuel pins (M2-2D, PA29-4, and M2-2C) were screwed together in the sequence given with M2-2D at the top. A burnup of approximately 3530 GJ/kg U (36,000 MWD/te UO_2) was accumulated over 46 reactor periods. The heat load was in the range 35-53 kW/m (350-530 W/cm). Fig. 1 gives an overview of the power history on a test average basis.

The pin average and local pellet conditions were calculated as described in the appendix, the results are presented in Table II. Fig. 2 shows the gamma scans of which the ^{137}Cs scans (half-life 0.95 Gs (30 years)) were used to distribute the test average values for the whole irradiation. The $^{95}Zr/Nb$ (half-life 5.5 Ms (64 days)) are representative of the latest part of the irradiation period and shows little or no difference between central and end pellets. Both scans reveal the rather flat axial power shape.

The test was visually inspected at four intermediate reactor shut-downs, where a gradually increasing extent of surface corrosion was observed. Most of the cladding surfaces were covered with a very thin, "soot-like" surface deposit, as also seen with other tests in DR 3 (this surface deposit is easily removable, e.g. with a wet paper tissue).

FISSION GAS RELEASE

The two pins PA29-4 and M2-2C were punctured and the extracted gas analyzed; the results are shown in Table III. The calculated fission gas releases are 48.1 and 35.6%, respectively.

From the data in the table, a partial He pressure (after irradiation)of 0.16 and 0.20 MPa (1.6 and 2.0 ata) can be calculated for the two pins PA29-4 and M2-2C, whereas the as-fabricated pressure was 0.10 MPa (1 ata). This observed increase in He content is attributed to ternary fission yield and alpha decay of heavy isotopes (in particular ^{242}Cm to ^{238}Pu). (8).

Ceramography on one sample from each of the pins PA29-4 (117 mm from the bottom of the pellet stack) and M2-2C (66 mm from stack bottom), showed that a fraction of 0.47 and 0.43 of the fuel had restructured to columnar grains. Using Nichols' model (4) for restructuring, these fractions correspond to fuel centre temperatures of 2200 and 2100 K (1927 and 1827^{o}C), respectively. Further, a small centre void of approximately 0.3 mm diameter was observed in PA29-4.

APPENDIX

DETAILS OF IRRADIATION CONDITIONS

The following sections describe the principles used to obtain the irradiation conditions and the results are provided in detail, so that input can be formulated for fuel performance code calculations. This applies to: Power history including burnup, fission gas generation, fast neutron flux in cladding, and cladding surface temperature.

Test Average Power History

Continuous measurement of flow rate and temperature increase of the secondary rig cooling water provided the rig thermal output. Subsequent corrections for gamma heat in the rig material and the non-fissile fuel pin materials (both obtained from measurements in the specific DR 3 positions) gave the fuel thermal output relevant to calculation of linear heat load and fuel temperature. After a further correction for gamma heat in the fuel, the fission heat output relevant to burnup calculation was obtained.

The resulting heat load and burnup values are shown in the third and fourth column of Table IIa.

Individual Pin Calculations

The gamma scans revealed that Pu build-up occurred faster in the natural end pellets than in the enriched central pellets, as already pointed out. As a consequence, the difference between heat generation in the end and central pellets decreased gradually and the ratio approached unity. Physics calculations (5),adapted to DR 3 conditions, of this ratio as a function of burnup, were used to separate heat load and burnup for central and end pellets.

The test average data were converted into pin average and local data by means of the ^{137}Cs gamma scans and the physics calculations of Ref.(5).The results are included in Table IIa.

Comparison of Calorimetric and Radiochemical Burnup Determination

The calorimetric calculations were checked by radiochemical analysis of three samples, one from each of the central pellet columns and one from the lower end pellet of PA29-4.

The above calculations provided the local calorimetric burnup values for the three samples. The physics calculations (5) showed that the following fission energies are relevant for the DR 3 fuel irradiation experiments:

Fissile isotope	^{235}U	^{239}Pu	^{241}Pu
pJ/fission (MeV/fission)	31.9 (199)	32.7 (204)	32.7 (204)

This, combined with the heavy isotope analysis of each sample, then provided the energy conversion applicable to the individual samples, considering the distribution of fissions between the three fissile isotopes. The resulting comparison between calorimetry and radiochemistry (6) is shown below:

Sample Pellet type	PA29-4-3 Central	PA29-4-6 End	M2-2C-4 Central
Calorimetry, GJ/kg U ($MWD/te\ UO_2$)	3997 (40,776)	3402 (34,712)	3586 (36,589)
Radiochemistry, GJ/kg U ($MWD/te\ UO_2$)	4011 (40,922)	3388 (34,564)	3591 (36,633)
Relative difference	0.4%	0.4%	0.1%

The agreement lends confidence in the calorimetry as well as the physics calculations (5).

Fission Gas Generation

The fission gas quantity generated in each pin was calculated from the above pin average burnup and a generation rate of 0.347 cm^3 (273K, 0.1 MPa) per GJ (30.0 cm^3(0^{o}C,1 ata.) per MWD). This was then used to calculate the observed fission gas release from the measured gas quantities, see Table III.

Fast Neutron Flux in Cladding

Fast neutron flux levels in the centre of the hollow DR 3 fuel elements were obtained from Ni wire scans. These unperturbed fluxes were then modified by DR 3 physics calculations (7) to give estimates of the fast flux in the fuel pin cladding. The results were as follows:

DR 3 Period No.	Fast flux in Clad $n/m^2/sec.$	Total Irr. Time Ms (hrs.)	Fast Fluence at End of Period n/m^2
129-137	$3.5 \cdot 10^{17}$	17.74 (4928)	$6.2 \cdot 10^{24}$
138-150	$4.2 \cdot 10^{17}$	25.56 (7095)	$1.7 \cdot 10^{25}$
151-180	$5.3 \cdot 10^{17}$	50.00 (13888)	$4.3 \cdot 10^{25}$
		93.30 (25915)	

Cladding Surface Temperature

The temperature of the cladding surface depends on the system pressure and the surface heat flux. Above a heat load of approximately 20 kW/m (200 W/cm), there will be boiling on the pin surface at the 7.2 MPa (70 ato.) system pressure. The cladding surface temperature is to be calculated from the following expression:

$$T[K] = 554 + 1.45\ (Q[kW/m^2])^{0.25}$$

or

$$T[^\circ C] = 281 + 2.57\ (Q[W/cm^2])^{0.25};$$

this includes an estimated 4 K (4°C) depression of coolant boiling point due to dissolved He.

ACKNOWLEDGEMENT

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REFERENCES

1. H. CARLSEN, "Fission Gas Release in LWR Fuel Rods Exhibiting Very High Burn-up", paper presented at the IAEA Specialists' Meeting on "Fuel Element Performance Computer Modelling", Blackpool (U.K.), 12-17 March 1978; to be published in "Nuclear Engineering and Design".

2. H. H. HAGEN, K. HANSEN, and J. A. LETH, "Design and Experience with Rigs Simulating LWR Conditions in a Research Reactor", IAEA-Sm-165/8, International Atomic Energy Agency, Vienna (1972).

3. K. H. HANSEN and J. A. LETH, "Danish High Pressure Irradiation Facilities Used for Overpower Testing of Experimental UO_2-Zr Fuel Pins", Risø-M-1862, Risø National Laboratory (1976).

4. F. A. NICHOLS, "Theory of Columnar Grain Growth and Central Void Formation in Oxide Fuel Rods", J.Nucl. Mat., 22, 214-222 (1967).

5. P. HØJERUP and T. PETERSEN, Risø, personal communication.

6. N. R. LARSEN, Risø, personal communication.

7. G. K. KRISTIANSEN, Risø, personal communication.

8. H. CARLSEN, "Xenon,Krypton and Helium Release in High Burn-Up UO_2Zr Fuel Rods", paper presented at the "Workshop on Fission Gas Behaviour", Karlsruhe, 26-27 Oct. 1978, organized by the Joint Research Centre of the European Community.

TABLE I

Fuel Pin Design Details

Fuel Pin No.		M2-2D	PA29-4	M2-2C
Pellet				
Diameter	mm	12.60	12.60	12.60
Length (central avg.)	mm	18.3	18.3	12.0
Dishing depth *(both ends)	mm	.38	.38	.38
Dishing sphere radius	mm	41.5	41.5	41.5
Dishing shoulder	mm	.7	.7	.7
Surface roughness (OD),Ra	µm	.9	.9	.9
Density, central pellets	%TD	94.7	94.7	94.7
Density, end pellets	%TD	95.4	95.4	95.4
Enrichment, 8 central pellets	%U235	2.28	2.28	2.28
Enrichment, 2 end pellets	%U235	.72	.72	.72
Grain size (avg.)	µm	8.0	8.0	8.0
H_2O content		--- not determined ---		
N_2 content		--- not determined ---		
Shaping process		-- cold pres.-sinter, grind -		
Sintering temperature	K(°C)	1948(1675)	1948(1675)	1948(1675)
Sintering time (H_2-atm.)	ks(hrs)	7.2 (2)	7.2 (2)	7.2 (2)
Clad				
Inner diameter	mm	12.84	12.84	12.84
Wall thickness	mm	.53	.59	.53
Surface roughness (ID),Ra	µm	.9	.9	.9
Alloy supplier (Zr-2)		Sandviken	VDM	Sandviken
Temper		cold-worked and stress relieved		
Tensile strength (RT)	MN/m^2	740	630	740
Yield strength (RT)	MN/m^2	550	490	550
Elongation in 50.8 mm(2") (RT)	%	22	22	22
Pin				
Pellet-clad gap (diam.)	mm	.24	.24	.24
Total pellet stack	mm	128	128	128
Total pellet stack	kg	0.163	0.163	0.161
8 central pellets	mm	109.9	110.0	108.0
8 central pellets	kg	0.140	0.140	0.136
2 end pellets	mm	18.1	18.0	20.0
2 end pellets	kg	0.023	0.023	0.025
End plenum spring, mat.		Inconel	Inconel	Inconel
End plenum spring, vol.	mm^3	466	495	495
Washer (between spring and end pellet)		Zr-2	Zr-2	Zr-2
Washer thickn.(12.4 dia.)	mm	1	1	1
Total free volume (cold, as fab.)	mm^3	2830	2800	2950
Helium filling gas	MPa(ata)	0.1 (1)	0.1 (1)	0.1 (1)

*Central pellets only.

TABLE IIa

Detailed Power and Burnup Distribution for Test 022

Per.	Time	Test Avg.		Pin PA 29-4				Pin M2-2C					
				Pin Avg. P	Pin Avg. BU	5=8	6=7	Pin Avg. P	Pin Avg. BU	1	2	3	4
N°	h	W/cm	MWD/te UO_2	W/cm	MWD/te UO_2	W/cm	W/cm	W/cm	MWD/te UO_2	W/cm	W/cm	W/cm	W/cm
129	550	482	846	534	937	267	578	503	890	218	478	578	267
130	558	518	1771	574	1961	333	613	541	1863	266	507	613	333
131	562	503	2675	557	2962	355	590	525	2814	284	488	590	355
132	560	451	3479	499	3852	337	525	471	3660	270	434	525	337
133	561	461	4304	511	4765	359	535	481	4228	287	443	535	359
134	463	451	4969	499	5502	362	521	471	5227	290	432	521	362
135	564	477	5827	528	6452	393	549	498	6130	314	454	549	393
136	558	477	6677	528	7393	403	548	498	7024	322	453	548	403
137	552	464	7493	513	8296	401	531	484	7882	320	440	531	401
138	560	502	8387	555	9286	442	573	524	8823	353	475	573	442
139	557	476	9230	527	10219	427	542	497	9710	341	449	542	427
140	562	460	10050	509	11127	419	523	480	10572	335	434	523	419
141	561	447	10846	495	12009	413	507	467	11410	330	420	507	413
142	561	424	11598	469	12841	397	480	442	12201	317	398	480	397
143	560	437	12373	483	13699	413	493	456	13016	330	409	493	413
144	394	476	12968	527	14358	454	538	497	13642	363	445	538	454
145	556	424	13714	469	15184	408	478	442	14427	326	396	478	408
146	556	408	14431	451	15978	396	459	426	15181	317	381	459	396
147	556	397	15129	440	16751	389	447	415	15915	311	371	447	389
148	556	353	15746	391	17434	348	396	369	16564	279	329	396	348
149	560	369	16396	408	18154	366	414	385	17248	293	344	414	366
150	560	374	17056	414	18884	374	419	390	17942	299	348	419	374
151	562	448	17844	495	19757	451	502	467	18771	362	417	502	451
152	732	490	18970	542	21003	498	548	511	19956	399	455	548	498
153	723	464	20020	513	22166	475	517	484	21061	381	430	517	475
154	559	456	20818	504	23050	471	508	476	21900	377	422	508	471
155	557	430	21565	475	23877	447	478	448	22686	358	398	478	447
156	554	422	22294	466	24684	441	470	440	23453	354	390	470	441
157	562	451	23087	498	25562	473	501	470	24287	379	416	501	473
158	557	529	24015	585	26589	560	588	552	25263	448	488	588	560
161	553	425	24748	469	27401	451	471	443	26034	362	391	471	451
162	558	412	25463	455	28192	440	456	429	26786	353	380	456	440
163	567	438	26238	484	29051	470	485	457	27602	377	403	485	470
164	560	399	26932	440	29819	430	441	416	28332	345	367	441	430
165	555	399	27620	440	30581	432	441	416	29056	346	367	441	432
166	556	373	28261	411	31290	405	411	389	29730	325	342	411	405
167	563	359	28887	397	31983	392	397	375	30388	315	330	397	392
172	522	448	29618	495	32793	491	495	467	31157	393	411	495	491
173	550	464	30418	513	33679	510	512	484	31999	407	425	512	510
174	520	477	31195	527	34539	526	526	497	32816	420	437	526	526
175	559	425	31936	469	35359	467	467	443	33596	375	389	467	467
176	694	422	32849	466	36370	464	464	440	34556	374	386	464	464
177	550	435	33596	481	37197	478	478	454	35342	388	398	478	478
178	554	435	34349	481	38031	478	478	454	36134	389	398	478	478
179	554	461	35149	510	38917	507	507	481	36976	414	421	507	507
180	667	435	36055	481	39920	478	478	454	37929	399	398	478	478

Conversion factors: 1 W/cm = 0.1 kW/m;
1 MWD/te UO_2 = 0.09802 GJ/kg U.

TABLE IIb

Notes

(i) The heat rating P is composed of P[fiss], representing the heat originating from fissions in the fuel, and P [γ, fuel] representing the heat originating from absorption in the fuel of radiation from the external gamma field.
P [fiss] is determined by subtracting from P the term G[γ, fuel] x $\frac{\text{fuel weight}}{\text{fuel length}}$. G[γ, fuel] (W/g) is given in Table IIc. The fuel weight and the fuel length apply to the fuel section in question and are found from Table I.

(ii) The local positions (1-12) refer to the axial locations shown on the sketch below of the gamma activity distribution.

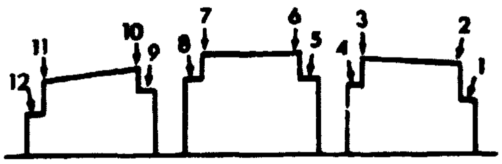

TABLE IIc

Heat Production in the Fuel of Test 022 Caused by the External Gamma Field

DR3 Period No.	129-137	138-150	151-180
G[γ, fuel] kW/kg	1.03	1.22	1.68

TABLE III

Fission Gas Analysis

Pin No.		PA29-4	M2-2C
Total gas content, cm^3 at 0.1 MPa, 273 K (1 ata, 0^oC)		101.	71.6
Free volume, post irr., cm^3		2.90	2.93
Calculated internal pressure MPa at 293 K (ata at 20^oC)		3.91 (38.6)	2.73 (26.9)
Gas composition, vol. %	H_2	0.647	-
	He	5.733	6.350
	D_2	-	-
	N_2+CO	0.300	2.025
	O_2	0.023	0.250
	Ar	0.006	0.025
	CO_2	0.317	0.050
	Kr-83	0.373	0.360
	Kr-84	2.797	2.845
	Kr-85	0.417	0.445
	Kr-86	3.707	3.805
	Xe-130	0.427	0.425
	Xe-131	4.307	4.145
	Xe-132	19.867	19.595
	Xe-134	23.033	22.675
	Xe-136	38.067	37.030
	Sum	100.021	100.025
	Kr	7.294	7.455
	Xe	85.701	83.870
	Kr+Xe	92.995	91.325
Calculated fission gas release, %.		48.1	35.6

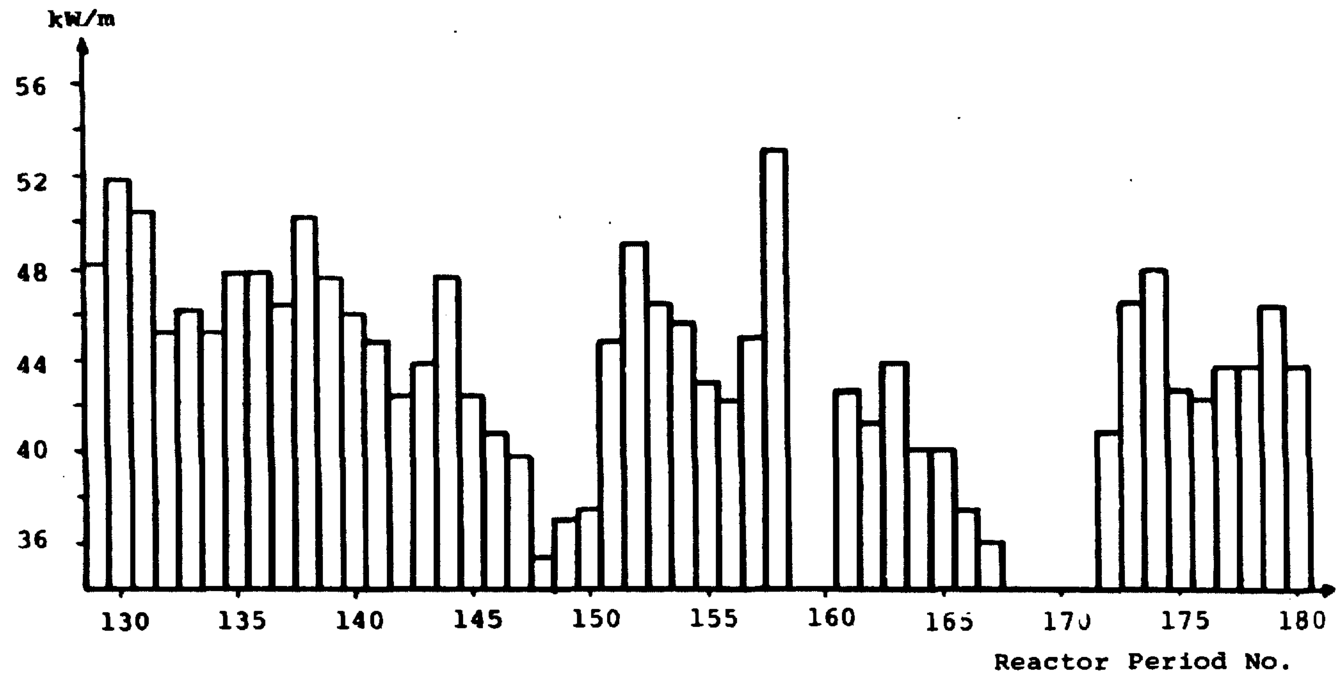

Fig. 1. Power History of Test 022.

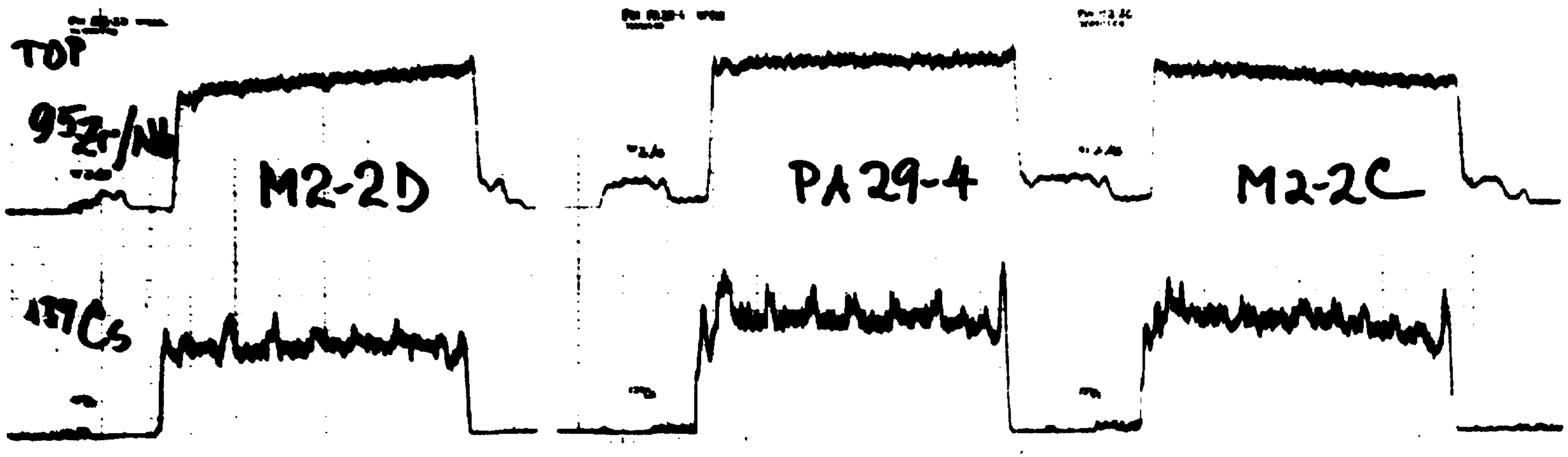

Fig. 2. Gamma Scans After Test 022.