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VORBEMERKUNG

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zusammengestellt und dort in einem Vortrag präsentiert. Sie ist in den "Topical Meeting Proceedings" dieser Konferenz enthalten.

Da diese Veröffentlichung schwer zugänglich ist und außerdem (wegen der Verkleinerung) gerade in den Tabellen schwer lesbar ist, wird die Arbeit hier als KfK-Bericht vorgelegt.

Herrn F. Bauer danke ich für die sorgfältige Ausarbeitung der Tabellen und Abbildungen.

April 1979 K. Kummerer

Abstract

The German Oxide Fuel Pin Irradiation Test Experience for Fast Reactors

In the time since 1965 our fast reactor fuel development activities have dealt with many experimental oxide fuel pin specimens irradiated in thermal, epithermal and fast neutron flux. Most of the important parameters in view of the forthcoming prototypic fuel pins were implemented by the different experiments including fuel density and diameter, cladding type, linear rod power, neutron dose, burnup and temperature. Also the pin behaviour at operational power change and under abnormal conditions were studied to some extent. The experiments divided in more than 30 test groups were carried out or are underway in the reactors FR-2 and KNK-II in Karlsruhe, BR-2 in Mol, HFR in Petten, DFR in Dounreay, RAPSODIE and CABRI in Cadarache, SILOE in Grenoble.

After a short introduction concerning features and problems in oxide fuel pin design, the paper describes the single experiments in some details, including the design of the experimental pins, the parameter variations within the test groups, the irradiation conditions, and also some characteristic results.

In order to get an easy survey, a lot of tables combined with schematic design drawings are presented. After that a nomographical synopsis indicates the regions of parameters covered. Finally conclusions are drawn concerning the experimental basis for a sound reference oxide fuel pin design. Out of the body of present knowledge the future trends and needs in developmental effort are indicated.

Zusammenfassung

Die deutschen Erfahrungen mit Oxidbrennstab-Test-Bestrahlungen für schnelle Reaktoren

Unsere Arbeiten zur Entwicklung von Schnellbrüter-Brennelementen haben sich seit etwa dem Jahr 1965 mit vielen Oxid-Brennstabprüflingen, die in thermischen, epithermischen und schnellen Reaktoren bestrahlt wurden, befaßt. Die meisten für einen Prototypreaktor bedeutsamen Parameter wurden experimentell verifiziert wie z.B. Brennstoffdichte, Stabdurchmesser, Hüllmaterial, Stableistung, Temperatur, Abbrand und Neutronenfluenz. Auch das Stabverhalten bei betrieblicher Leistungsänderung und unter abnormalen Bedingungen wird mit einigen Experimenten belegt. Die Versuche, unterteilt in mehr als 30 Versuchsgruppen, wurden ausgeführt bzw. sind in Bestrahlung in den Reaktoren FR-2 und KNK-II in Karlsruhe, BR-2 in Mol, HFR in Petten, DFR in Dounreay, RAPSODIE und CABRI in Cadarache, SILOE in Grenoble.

Nach einer kurzen Einführung über Merkmale und Probleme bei der Auslegung von Oxidbrennstäben beschreibt der Bericht detailliert die einzelnen Experimente, einschließlich Prüflingsauslegung, Parametervariationen, Bestrahlungsbedingungen und einigen charakteristischen Ergebnissen. Einen leichten Überblick ermöglichen schematisierte Tabellen, kombiniert mit Auslegungsskizzen der Prüflinge. In einer Art nomographischen Synopse sind alle wichtigen Parameterbereiche zusammengestellt. Die Schlußfolgerungen behandeln die vorliegenden Ergebnisse mit Bezug auf eine technisch ausgereifte Oxid-Brennstabauslegung und geben die Linie weiterhin notwendiger Entwicklungsarbeiten an.

Inhalt:

1. FEATURES AND PROBLEMS OF OXIDE FUEL PIN DESIGN

The features and objectives in the design of oxide fuel pins for fast reactor application are governed by the goal of achieving a fuel element that can be operated reliably up to the high burnup levels characteristic of fast breeder reactors. In this consideration

- the normal operation conditions

as well as

- abnormal operation conditions due to irregularities

are to be taken into account. In the range of normal operation conditions we have to pay attention to

- startup power change,
- steady-state operation,
- possible power cycling,
- irregular power ramps,
- shutdown period.

Important and mostly unavoidable abnormal operation conditions for fuel elements in power stations can be

- operation under hot spot sonditions,
- operation of the core with some failed fuel pins,
- short-term overpower transients due to a sudden reactivity increase,
- reduction or loss of coolant-flow,
- coolant blockage in a fuel bundle.

All these possible facts - and also their combinations - constitute the field of fuel element development and fuel pin design. The objectives for the fuel pin performance in normal operation are that

- the pin shall remain tight,
- the pin shall remain stable mechanically,
- no gross fuel movement shall occur within the pin.

For abnormal operation conditions the objectives should be:

- no or only limited and slow interaction between the fuel of a failed pin and the coolant,

- no failure propagation to adjacent pins,
- no gross propagation from a blocked coolant channel region to the whole bundle.

All fuel pin and bundle design work follows these lines. In this context, well established irradiation experiments accompanied by sophisticated evaluations and modeling calculations are of decisive value.

This report will describe in a condensed manner all the essential irradiation experiments, including their basic results, which have been carried out for more than a decade under the German oxide fuel development program for fast breeder reactors.+)

2. IRRADIATION EXPERIMENTS UNDER STEADY STATE OPERATION CONDITIONS

This type of irradiation experiment shall produce the proof of pin integrity up to high burnup levels. Different parameter constellations are chosen in pin design (pin diameter, fuel density, pellet dimensions) and for the irradiation conditions (clad and fuel temperatures, linear rod power).

"Steady state operation" in this context means that - except for startup and shutdown - there are only a few additional power changes and interruptions due to the test reactor operation scheme. Many irradiation experiments of this type were carried out in the thermal test reactor FR 2 in Karlsruhe. Scheme I (in the appendix) gives a survey of the FR 2 capsule experiments with short fuel pins mounted into liquid metal filled capsules and irradiated up to high burnups. The main parameter variations concerned fuel density, pin diameter and burnup. More than 100 irradiated pin specimens showed the principal design features to be acceptable. Also a lot of special qualitative and quantitative results could be gained. For instance, the fission gas release was measured in most of the pins. For this feature, all the results of the test groups containing mixed oxide are plotted in Fig. 1. In spite of the large scatter (which certainly is due to design differences and non-uniform irradiation conditions), the overall trend of the release rate can be identified. Another important point is fuel restructuring. In the test group FR 2-Vg. 5a, the fuel column was composed of 4 pellet stacks of distinctly different densities. As the ceramography in Fig. 2 demonstrates, the central hole formation corresponds to the as-fabricated fuel density. According to the diagram in Fig. 3, there is a linear dependence, to a lesser extent also for the columnar grain zone. In these early experiments also the effects of longitudinal fuel movement, of U-Pu-redistribution and fission product migration were observed.

+) Some of the experiments are carried out in close cooperation with the partners of the DEBENE organization and the Interatom company in Germany, which is gratefully acknowledged.

Especially the small diameter pins of the test group FR 2-Vg. 5b with their extreme radial temperature gradients showed these effects distinctly.

The next series of experiments broadens the view from the thermal neutron spectrum in the FR 2 to the epithermal higher flux of the BR 2 reactor in Mol, see Scheme II. Also capsules are used as irradiation vehicles. They can accommodate longer pins up to about 1 meter length. The objectives of the first Mol-8A/B/C experiments were to realize a high burnup performance and - especially with Mol-8C - to determine the build-up of in-pile gas pressure in the fission gas plenum of the pin by a continuously operating device. As an example, Fig. 4 demonstrates for the pin 8C-4 the gas pressure up to an average burnup of about 95 MWd/kg M and the (calculated) total release rate. In the experiment Mol-8D the thermal behavior of the pin, i.e. mainly thermal conductivity of the fuel and the fuel clad heat transfer,is evaluated as a function of burnup. By the experiment Mol-16 the attempt is made to evaluate the chemical compatibility between fuel and clad in different chemical media. Parameters in this experiment are the O/M-ratio in the fuel, the clad temperature, the efficiency of local oxygen getters and gettering layers and, of course, the burnup. The evaluation of the first experiments showed that zirconium metal as local getter material is not active below a temperature of at least 600 °C.

In the BR 2 a rather well equipped sodium loop has been in operation. In this loop several bundle experiments were performed, see Scheme III. The Mol-7A irradiation comprised a 7-pin bundle up to a burnup of about 5 % and proved - in spite of one pin failure for reasons unknown - the feasibility of the 6 mm-pin concept at more than 500 W/cm rod power and a clad temperature of 630 °C. The Mol-7D experiment involved a bundle with 19 pins, spaced by helical fins integrated in the clad. A burnup of nearly 100 MWd/kg Me was reached without any remarkable effect.

The experimental experience in the real fast flux began with a series of pin and bundle experiments performed in the British Dounreay Fast Reactor, see Scheme IV. The DFR-304 experiment with 3 pins in an irradiation vehicle called "trefoil" constituted a monitor test for the DFR-350 bundle irradiation. In the latter test a 77-pin bundle including identical or very similar pins of different origins were irradiated up to the scheduled burnup of 6 %. The most remarkable result in this bundle experiment was the local pin diameter increase due to fast neutron induced stainless steel swelling. At a fast fluence of about 3.5×10^{22} nvt the claddings made of Nb stabilized stainless steel (1.4961) underwent an increase in diameter of more than 1 %, whilst the pin clad by a similar steel with Mo and V added (1.4988) showed quite a lower swelling rate,see Fig. 5. After the successful DFR-350 experiment some single pins were removed from this bundle and reirradiated in trefoils up to pin failure, experiment DFR-435. As expected from the design of the pins, the end of life was reached at burnups above 7 %. The last bundle experiment was DFR-455 comprising 60 pins in a grid spaced hexagonal array. At a burnup of about 5 % a distinctly different swelling behavior was observed due to the different cladding material and different pretreatment of the same material. A number of early pin failures in this bundle was traced down to a single fabrication batch where some impurities causing heavy internal corrosion remained in the pins during fabrication.

A final series of performance experiments is presented in Scheme V. In the French Rapsodie reactor, under the heading RAPSODIE I two bundles with 34 pins each were irradiated up to 50 MWd/kg M burnup with a monitor capsule irradiated before. All the pins remained tight and operable. The main quantitative results refer to mechanical interaction between the fuel and clad, the clad swelling and the cesium migration to the cold end and also to the hot end of the pins. Cesium migration, e.g., is highly dependent on fuel stoichiometry. As the graphical presentation in Fig. 6 demonstrates, at lower O/M ratios cesium migration is increased to the hot end of the fuel column whilst the migration to the cold end is stable. The main difference of the RAPSODIE II bundle compared to RAPSODIE I is the higher pin diameter of 7.6 mm and pin spacing by spiral wires. The 19-pin bundle - preceded by 3 monitor pins in capsules - was irradiated to the very high burnup of about 12 % without any failure. Thus, the design concept is principally confirmed also for the 7.6 mm pins. In the KNK II fast reactor the whole central test zone is now loaded with 7 bundles in order to get a statistically relevant performance test for the MK Ia fuel design of the SNR-300 prototype fast reactor under construction.

3. IRRADIATION EXPERIMENTS WITH OPERATIONAL POWER CHANGE

As already discussed, different modes of operational power changes are to be considered. In Scheme VI this type of irradiation experiment is described. In early FR 2 experiments (LOOP 2 and 3) fuel restructuring at startup and the short-term behavior were investigated, which is quite important for the radial temperature distribution in the fuel. As an example, Fig. 7 demonstrates the formation of the central channel in the first days of irradiation as well as the moving boundary of the columnar grain zone.

Another realistic condition may occur with operational power cycling. In this context, the mechanical interaction between the fuel and clad is the prominent feature. We determined the diameter increase of pins in various experiments under cycling conditions, e.g. in FR 2-LOOP 5 and in MOL-10. The post-irradiation evaluation (LOOP 5) and the direct in-pile diameter control (MOL-10) showed that with cycling between half and full nominal power no remarkable strain of the clad takes place. Only if the conditions are artificially tightened (e.g. by lowering the clad temperature while the power increases), a pin diameter increase is observed. Also under such extraordinary conditions the effect becomes visible only if the preceding low-load time is long enough to allow a characteristic, stable fuel structure to be formed. Fig. 8 shows the dependence of the increase in pin diameter on low-load time as found in such a special cycling experiment. In the startup and ramping experiments presently underway in the HFR Petten such operation conditions have been realized for longer fuel pins. Especially the HFR-KAKADU experiments shall furnish information on different steepnesses of the operational power ramps.

4. IRRADIATION EXPERIMENTS UNDER ABNORMAL CONDITIONS

This newer field of applied research has been initiated mainly by reactor safety requirements. Four aspects are being investigated, namely

- failed pin behavior,
- hot channel conditions,
- coolant blockage,
- power transients.

As Scheme VII indicates, five experiments were performed or are underway. First results of defective pin irradiations in the test group SILOE-S show a definite difference between the behavior of a fresh pin (S2) and that of a preirradiated pin (S4). Due to the embrittlement of the cladding in the course of preirradiation and due to the swelling forces of uranate phases, the diameter increase of pin S4 is remarkably higher, as Fig. 9 demonstrates. Also the original defect length was prolonged by an additional crack.

The MOL-7B bundle was aimed at operating under hot channel conditions, e.g. 680 ^{o}C of clad midwall temperature. At a burnup of about 5 % the first pin failure was detected by the activity in the cover gas stream. The irradiation was continued up to the scheduled burnup of more than 11 %. In the post-irradiation examination it became apparent that most of the pins had failed. The reason was probably the (not intended) high clad temperature of 720 ^{o}C which led to serious inner corrosion of the clad.

The coolant blockage test series MOL-7C is devoted to the investigation of failure propagation within a bundle, caused by different types of local blockage. First results prove that the propagation is limited to the neighborhood of the blocked coolant channel. The experiments VIC-1 and CABRI are to provide experience concerning the pin behavior under steep power transients, including the consequences of such an incident. It is intended to get a confirmation of transient pin failure models which predict limited or at least controllable consequences in such hypothetical cases.

5. SYNOPSIS OF THE DESIGN AND IRRADIATION PARAMETERS

The total oxide irradiation program up to now has comprised 32 test groups with more than 2000 test specimens and long test pins. The distribution of this "population" within the main design and irradiation parameters is made visible in the synopsis of the final Scheme VIII. Thus, the variety of pin diameters, fuel density, fuel length in the pin, rod power, clad temperature and burnup can be compared easily.

6. RESULTS AND CONCLUSIONS

From experience gathered in the German irradiation tests and from the applicable theoretical considerations the following results and conclusions can be indicated:

(1) As to the steady-state operation of representative oxide fuel, pins and bundles up to a burnup of 60 MWd/kg M and higher, many experimental results are available which cover a wide field of design and irradiation parameters.

(2) The shortterm behavior of pins during startup as well as power changes and power ramping were investigated by some specific experiments. This resulted in guidelines for proper pin design and limited power gradients.

(3) The experiments carried out under abnormal conditions indicated that pin failures caused by fabricational defects, coolant disturbances or power transients have only limited consequences on failure propagation and fuel coolant interaction.

(4) There is an acceptable experimental basis for a sound reference oxide fuel element design. Proof on a statistical basis, however, is not sufficient.

(5) The future development work is to be concentrated on
- the statistical proof of the reference design under normal operation;
- the consequences of operational and accidental power transients;
- the performance of further optimized fuel and pins;
- the prediction and explanation of failure limits.

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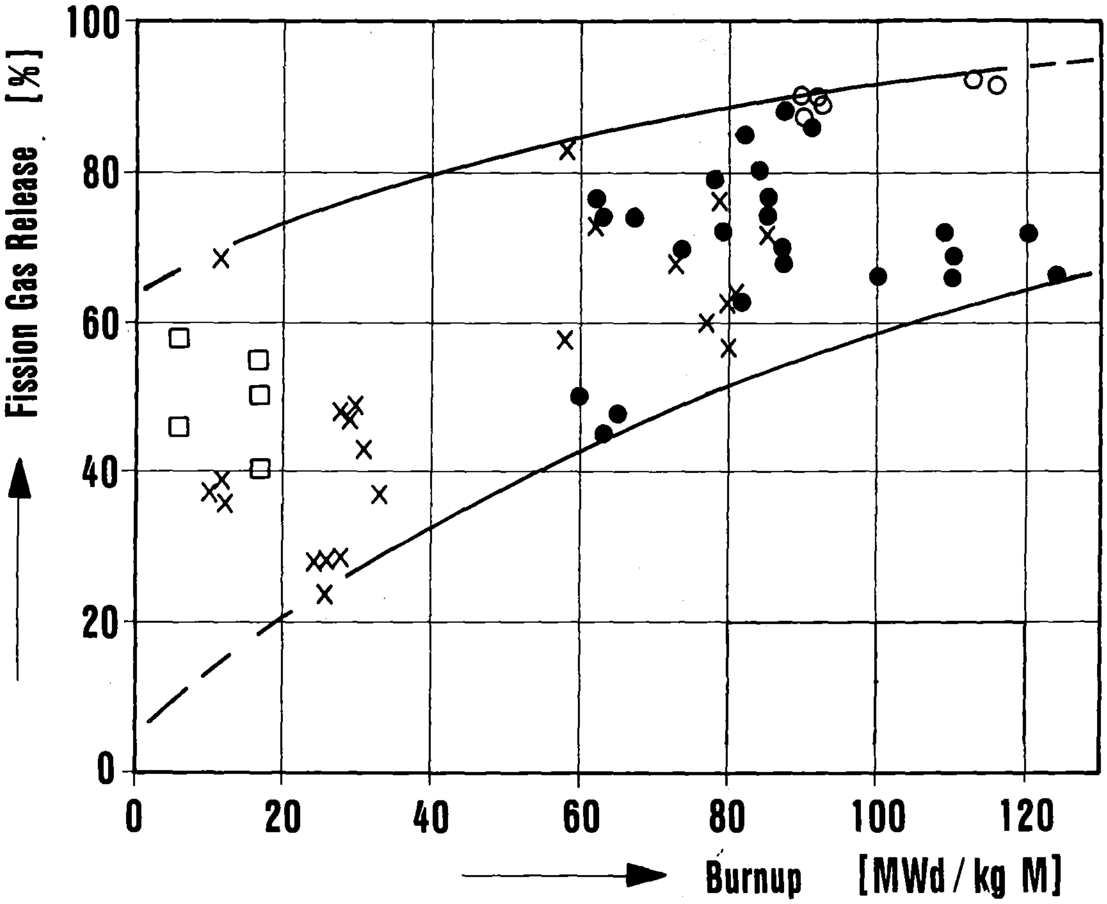

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Vg.	4a	4b	5a	5b

Fig. 1: Fission Gas Release of UO_2-PuO_2 Pins in FR 2 Capsule Tests

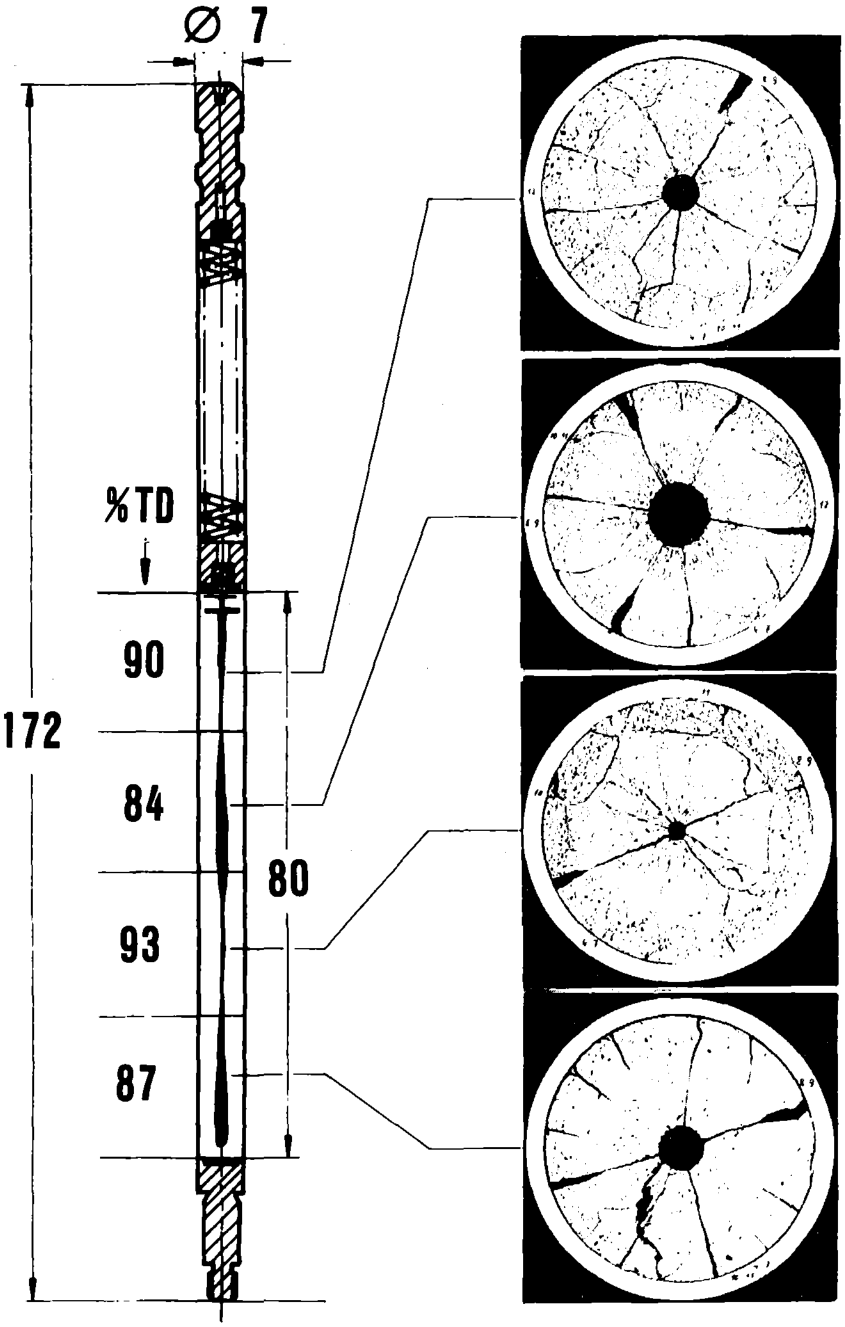


Fig. 2: Central Hole Formation versus Fuel Density
- Test Pin No. 5A/6 FR 2-Vg. 5a at 17 MWdays/kg M burnup

Left: Scheme of pin design including central channel contours after irradiation

Right: Micrograph cross section

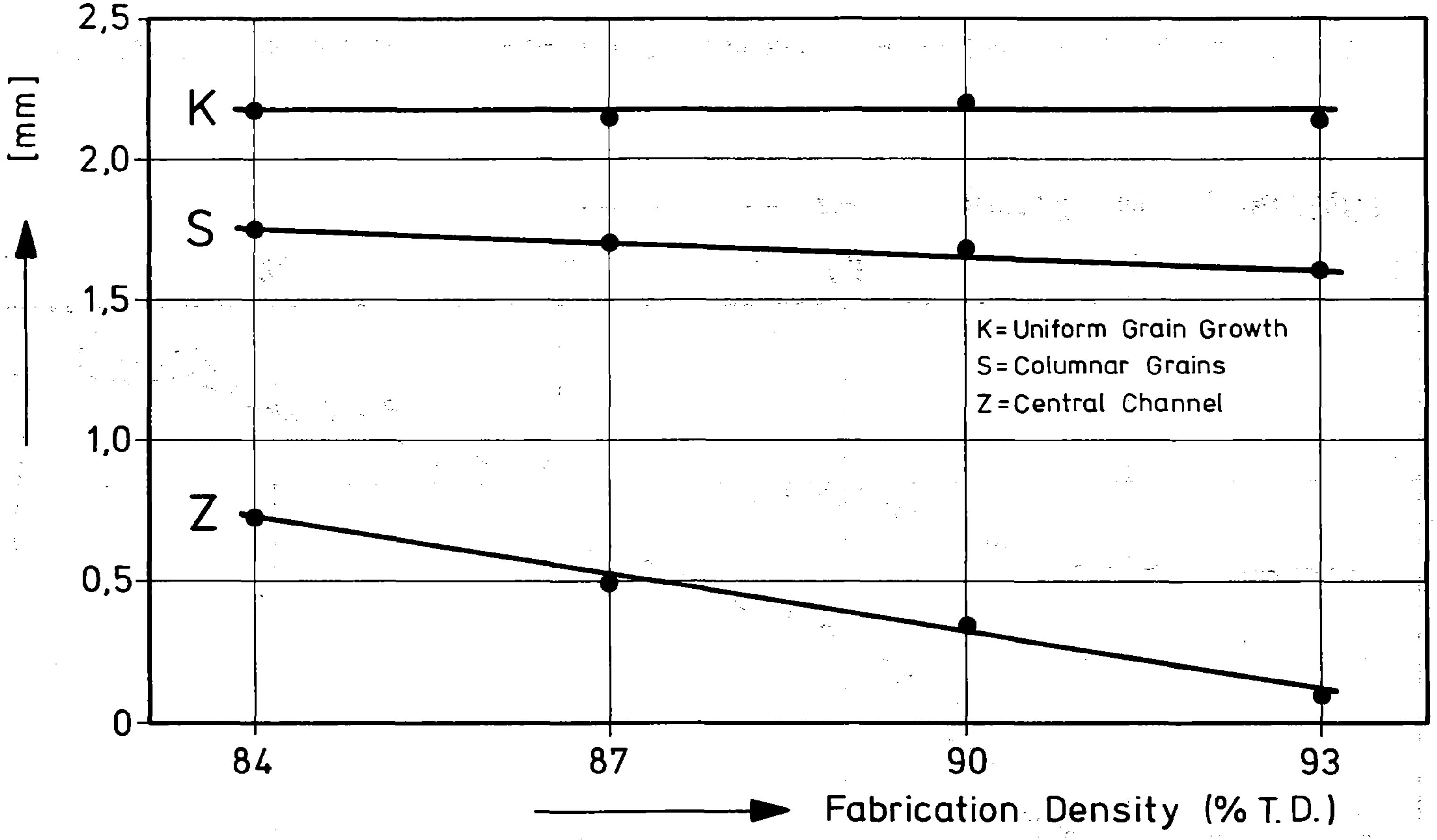


Fig. 3: Correlation between Structure Zones and Fuel Density - Test Pin No. 5A/6 -
K = Uniform Grain Growth; S = Columnar Grains; Z = Central Channel

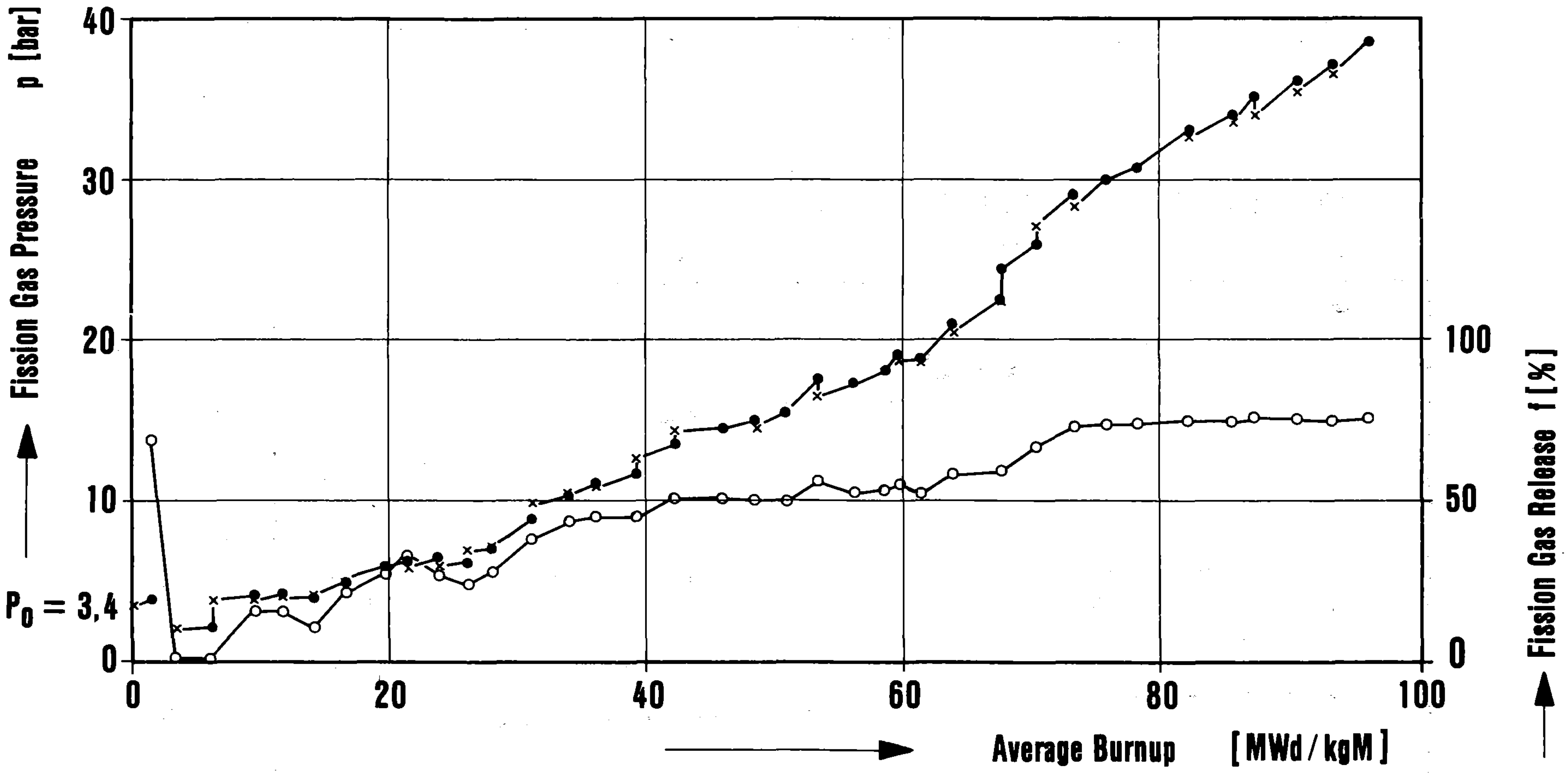


Fig. 4: Fission Gas Pressure Buildup —●— and Release Rate —○— Irradiation Mol-8C, Pin 8C-4

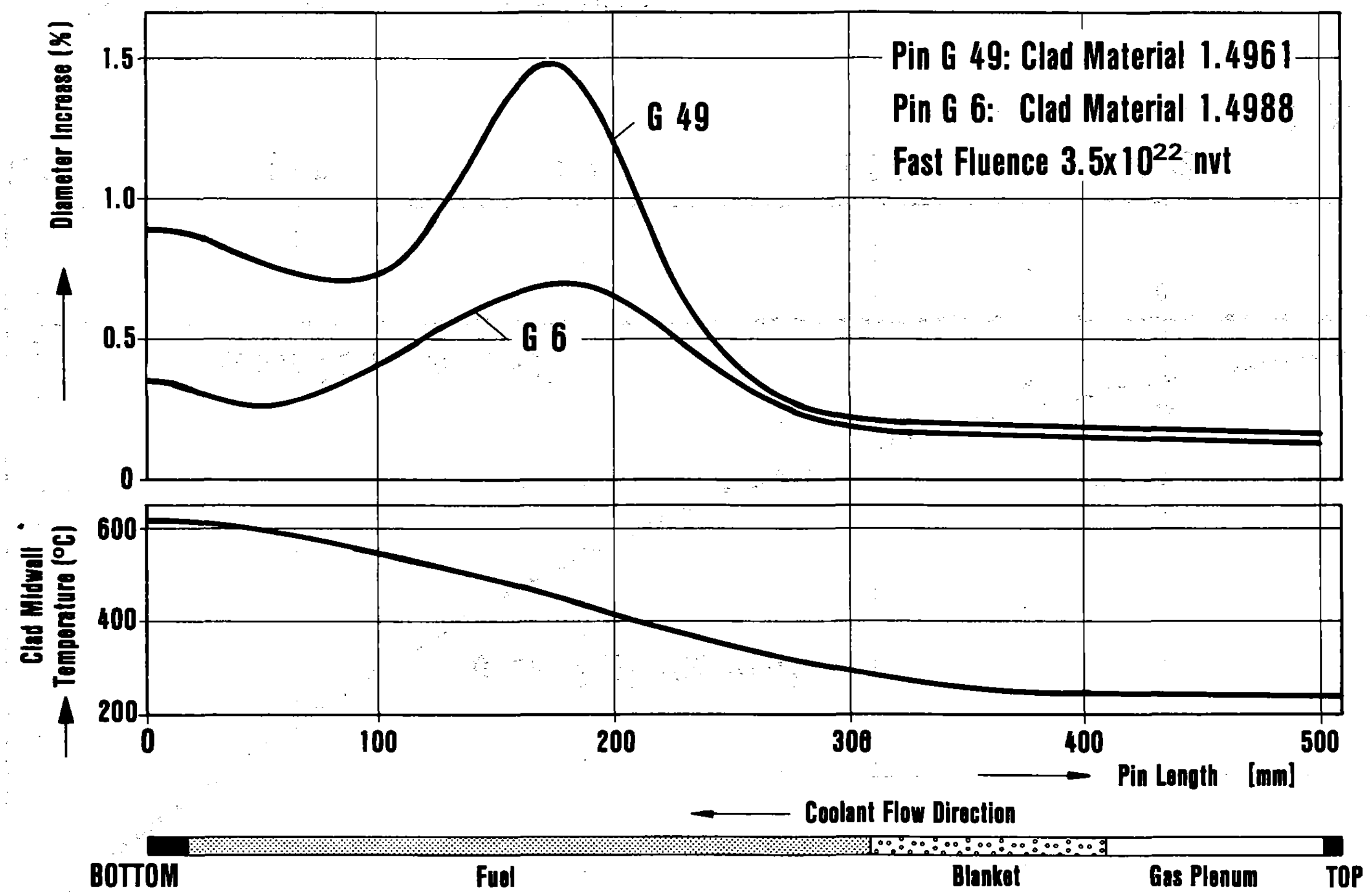


Fig. 5: Typical Pin Diameter Increase in the Irradiation DFR-350

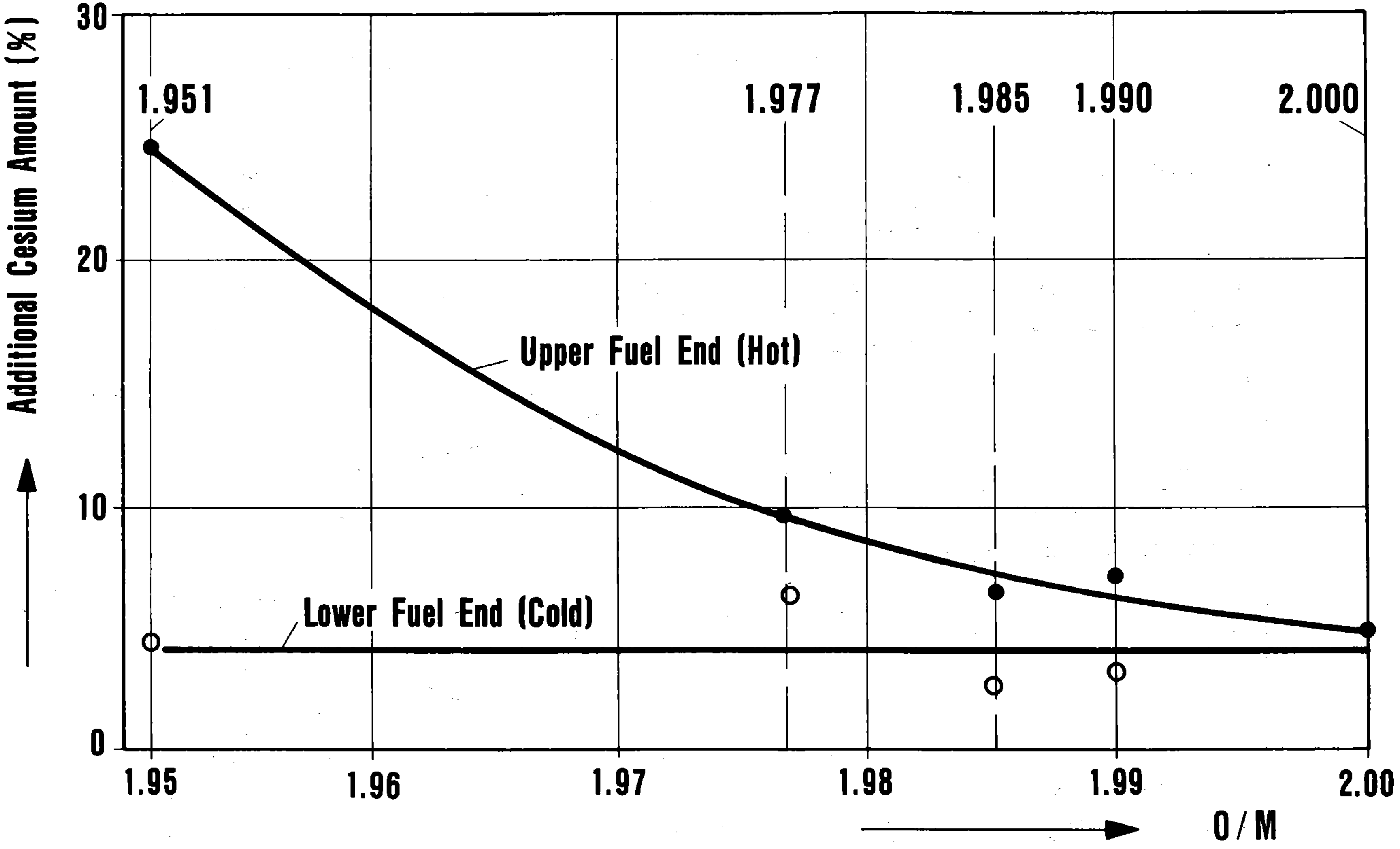


Fig. 6: Cesium Migration in Experiment Rapsodie I
Averaged Results of 33 Pins with Different Stoichiometry

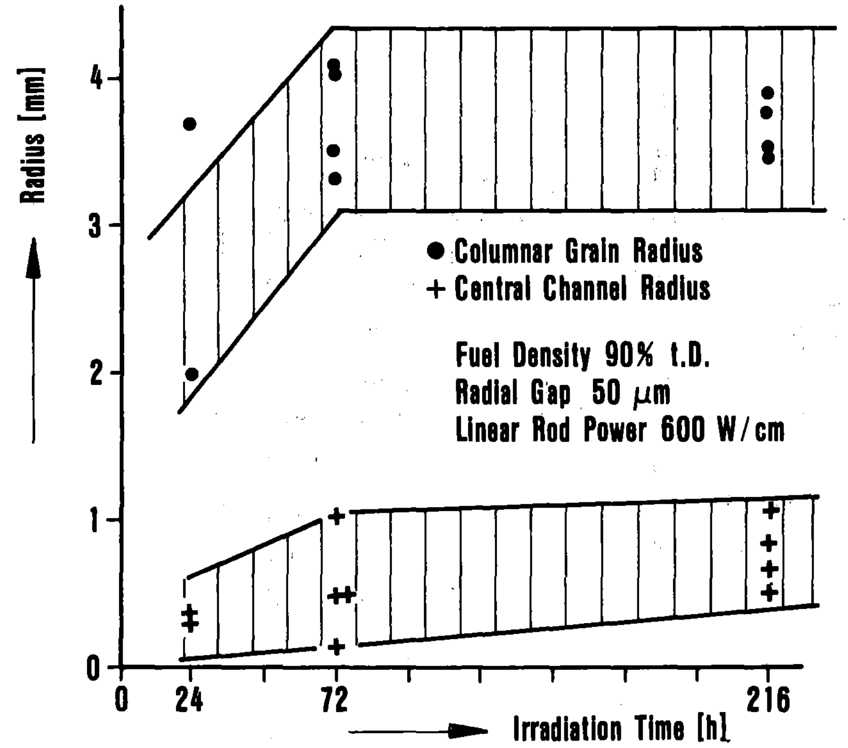


Fig. 7: Fuel Restructuring at Begin of Life

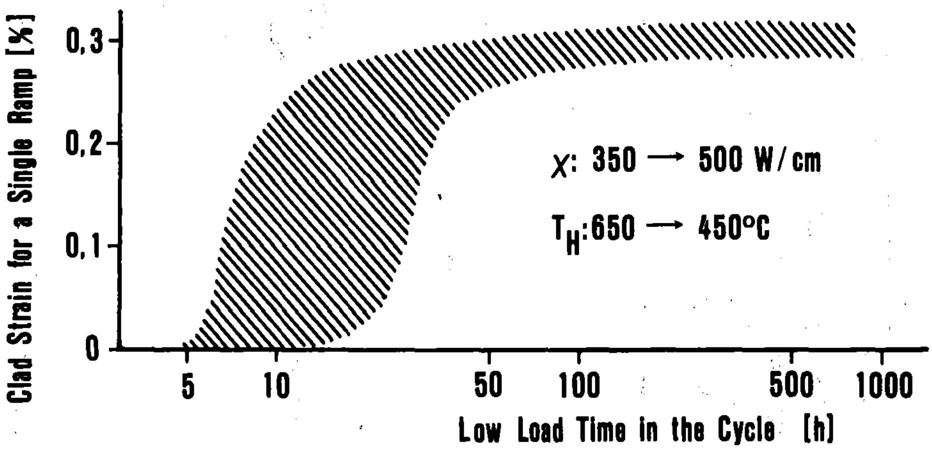


Fig. 8: Clad Strain at Power Ramping under Severe Conditions, Dependence on Preceeding Low-Load Time

- Extreme conditions because of low strength material (Incoloy 800 solution annealed) and counteracting temperature gradient.

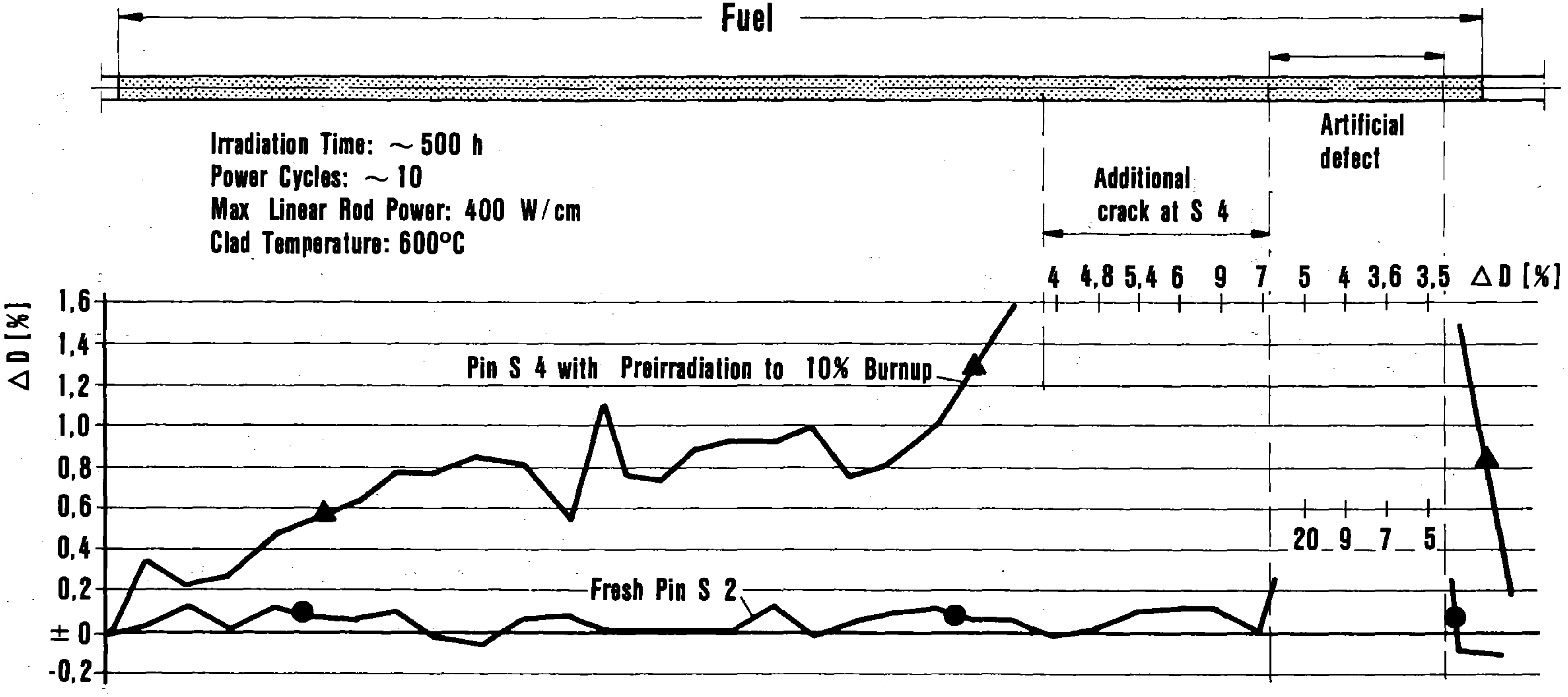
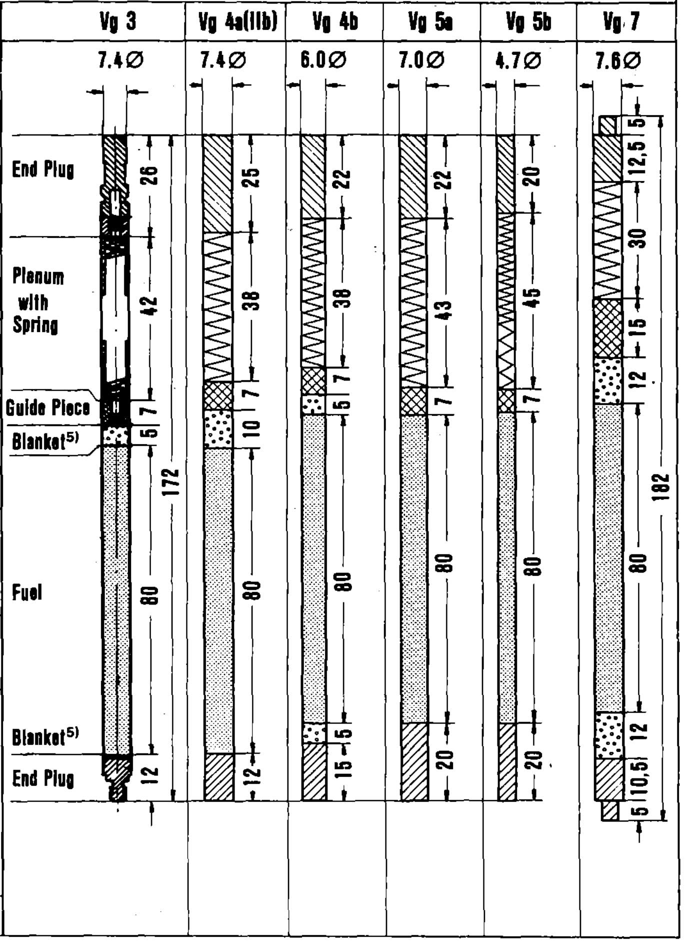


Fig. 9: Diameter Increase at Irradiation of Defected Pins

SCHEME I OXIDE PIN PERFORMANCE IN FR 2 CAPSULE EXPERIMENTS

Name of Experiment		FR 2-Vg 3	FR 2 - Vg 4a	FR 2 - Vg 4b	FR 2-Vg5a	FR 2-Vg5b	FR 2-Vg7
Fuel	Material	UO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2
	Pu/U + Pu (%)	0	15	20	19.5	35	15; 30
	Fuel Form	Cyl. Pell./Vibrofuel	Cyl. Pellets	Dish. Pell./Vibrofuel	Cyl. Pellets	Cyl. Pellets	Cyl. Pellets
	Pellet Diameter (mm)	6.25	6.25;6.20	5.10	6.12	3.95	6.40
	Fuel Length (mm)	80	80	80	80	80	80
	Fuel Density (%TD)	88;93/85	85;92	84;90/80	84;87;90;93	86	94
Clad	Material	20/25 CrNiNb	1.4988	1.4988	1.4988	1.4988	1.4970
	Thickness (mm)	0.5	0.5	0.38	0.41	0.30	0.50
Pin	Diameter (mm)	7.4	7.4	6.0	7.04	4.7	7.6
	Length (mm)	172	172	172	172	172	182
Irradiation	Number of Specimens	30	28	35	9	18	12
	Irradiation Vehicle	Na-PbBi-Caps.	Na-PbBi-Caps.	NaK-PbBi-Caps.	NaK-PbBi-Caps.	Na-PbBi-Caps.	NaK-Caps.
	Instrumentation	T_{Na} 1)	T_{Na}	T_{Na}	T_{Na}	T_{Na}	T_{Ha} 2)
	Linear Rod Power (W/cm)	≤750	≤700	≤620	≤575	≤490	450/200
	Max Clad Temperature (C)	≤550	≤600	≤770	≤700	≤450	520/600
	Max Burnup (MWd/kgM)	6 - 68	10 - 90	10 - 120	6/17/47	10/30/90/120	up to ~ 60
Results and Observations	Experimental Status	(1)	(1)	(1)	(1)	(1)	(4)
	Pin Failures	no	no	2 3)	2 4)	no	
	Pin Diameter Increase (%)	0	≤0.3	≤2	≤0.4	≤1.5	
	Fission Gas Release (%)	30 - 70	≤80	≤80	≤60	89 - 93	
	Fuel Relocation	x	x	x	x	x	
	Pu-Segregation		x	x	x	x	
	Fission Product Migration	x	x	x	x	x	
	Internal Clad Corrosion		x	x	x	x	
References		/1/	/2 3/	/4/	/5/	/6/	/7/

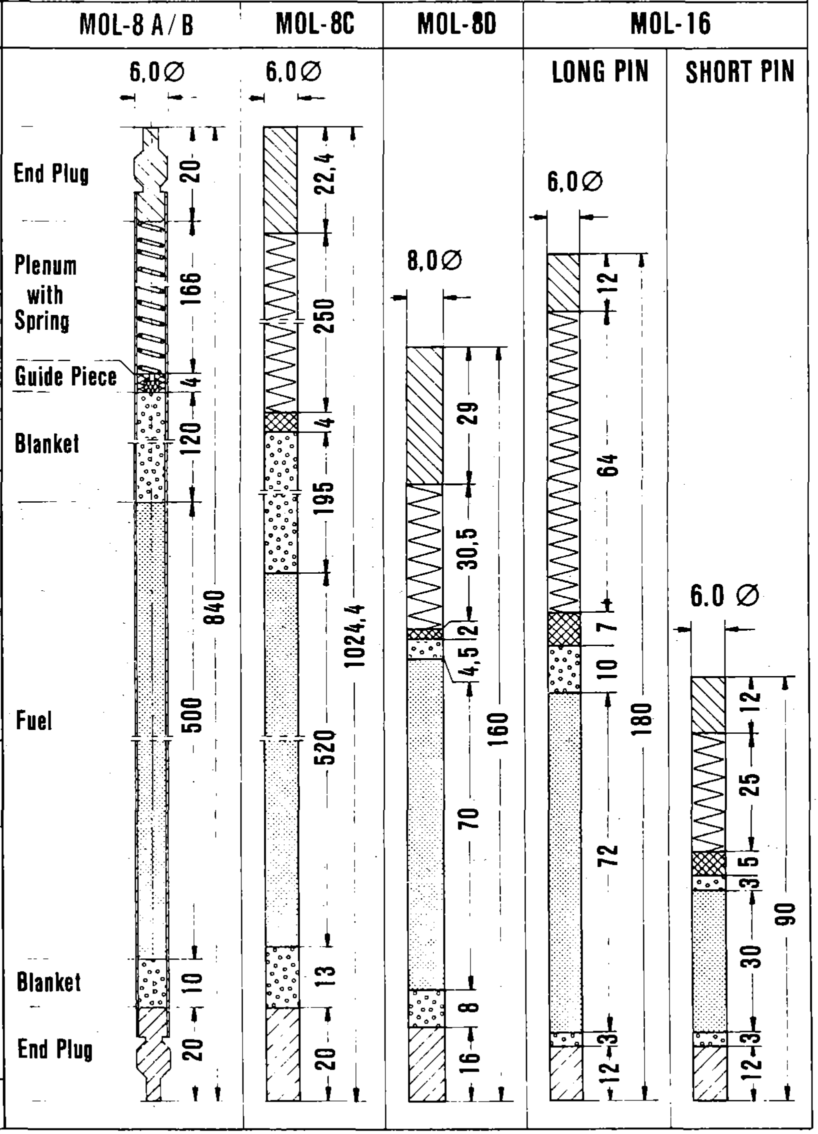


Explanations: 1) T_{Na} ≙ sodium temperature
2) T_{Ha} ≙ clad surface temperature
3) failures in vibropins
4) probably due to coolant disturbances
5) or insulating pellets

Experimental Status: (1) results evaluated
(2) irradiation completed
(3) irradiation in progress
(4) under preparation

SCHEME II. OXIDE PIN PERFORMANCE IN BR 2 CAPSULE EXPERIMENTS

Name of Experiment		MOL-8A/B	MOL-8 C	MOL-8 D	MOL-16
Fuel	Material	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2
	Pu/U + Pu (%)	20	20	20	30
	Fuel Form	Cyl. Pellets	Cyl. Pellets	Annul. Pell.	Pellets
	Pellet Diameter (mm)	5.10	5.19/5.10/4.99	6.90;6.70	5.05
	Fuel Length (mm)	500	520	70	72/30
	Fuel Density (%TD)	85-87	88/91/95	85/92	86
Clad	Material	1.4988	1.4988	1.4988	1.4988
	Thickness (mm)	0.38	0.38	0.45	0.38
Pin	Diameter (mm)	6.0	6.0	8.0	6.0
	Length (mm)	840	1024.4	160	180/90
Irradiation	Number of Specimens	4	10	12	14
	Irradiation Vehicle Instrumentation	FAFNIR-Caps. T_{Ha}[1], P_G[2]	FAFNIR-Caps. T_{Ha}, P_G	FAFNIR T_{Ha}, T_Z[3]	T-Contr. Caps. T_{Ha}
	Linear Rod Power (W/cm)	410-590	350-550	160-400	400
	Max Clad Temperature (C)	$\leqslant 590$	680-720	$\leqslant 400$	530-720
	Max Burnup (MWd/kgM)	60-106	93-118	20-80	40-120
Results and Observations[5]	Experimental Status	(1)	(1)	(1)(2)(3)	(1)(2)(3)
	Pin Failures	1[4]	4[4]	no	1
	Pin Diameter Increase (%)	$\leqslant 0.5$	$\leqslant 1.9$	~ 0	
	Fission Gas Release (%)	$\leqslant 85$	60-80	$\leqslant 50$	
	Fuel Relocation	x	x	x	x
	Pu-Segregation	x	x	x	x
	Fission Product Migration	x	x	x	x
	Internal Clad Corrosion	x	x		x
References		/8 9/	/10 11/	/12/	/13/

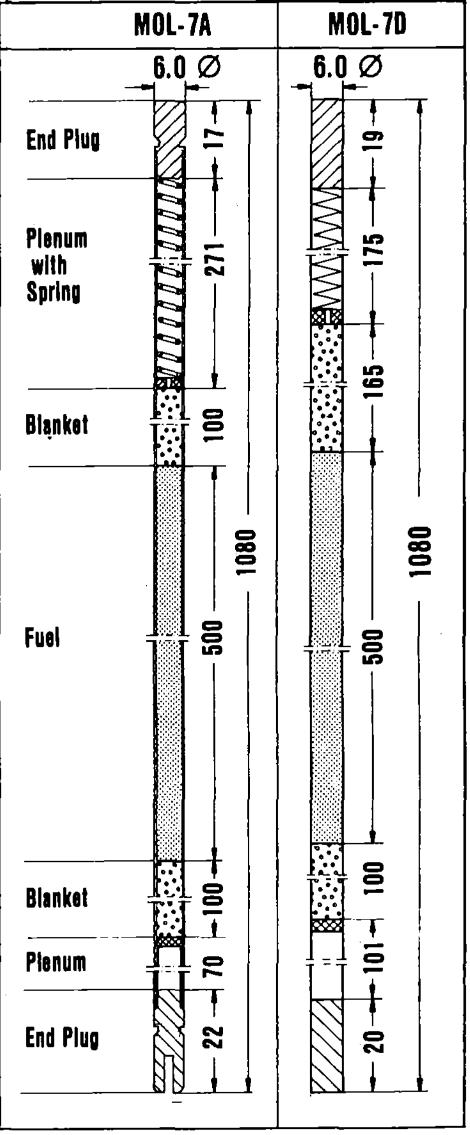


Explantions: 1) $T_{Ha} \triangleq$ clad surface temperature
2) $P_G \triangleq$ gas pressure in plenum
3) $T_Z \triangleq$ fuel central temperature
4) due to coolant disturbances
5) refers only to exper. status (1)

Experimental Status: (1) results evaluated
(2) irradiation completed
(3) irradiation in progress
(4) under preparation

SCHEME III. OXIDE PIN PERFORMANCE IN BR 2 BUNDLE EXPERIMENTS

Name of Experiment		MOL-7A	MOL-7D
Fuel	Material	UO_2-PuO_2	UO_2-PuO_2
	Pu / U + Pu (%)	20	30
	Fuel Form	Cyl. Pellets	Cyl. Pellets
	Pellet Diameter (mm)	5.01	5.05
	Fuel Length (mm)	500	500
	Fuel Density (%TD)	88	87
Clad	Material	SS,3 types	1.4988
	Thickness (mm)	0,38	0.40
Pin	Diameter (mm)	6.0	6.0
	Length (mm)	1080	1080
Bundle	Number of Pins	7	19
	Pitch / Diameter Ratio	1.32	1.32
	Spacing	Spark eroded grids	Helical fins
Irradiation	Linear Rod Power (W / cm)	560	450
	Max Clad Temperature (C)	630	590
	Max Burnup (MWd / kgM)	45	95
Results and Observations	Experimental Status	(1)	(2)
	Pin Failures	$1^{1)}$	no
	Pin Diameter Increase (%)	~ 0,1%	
	Fission Gas Release (%)	70-80	
	Fuel Relocation	x	
	Pu-Segregation	x	
	Fission Product Migration	x	
	Internal Clad Corrosion	x	
References		/14 15/	/16/

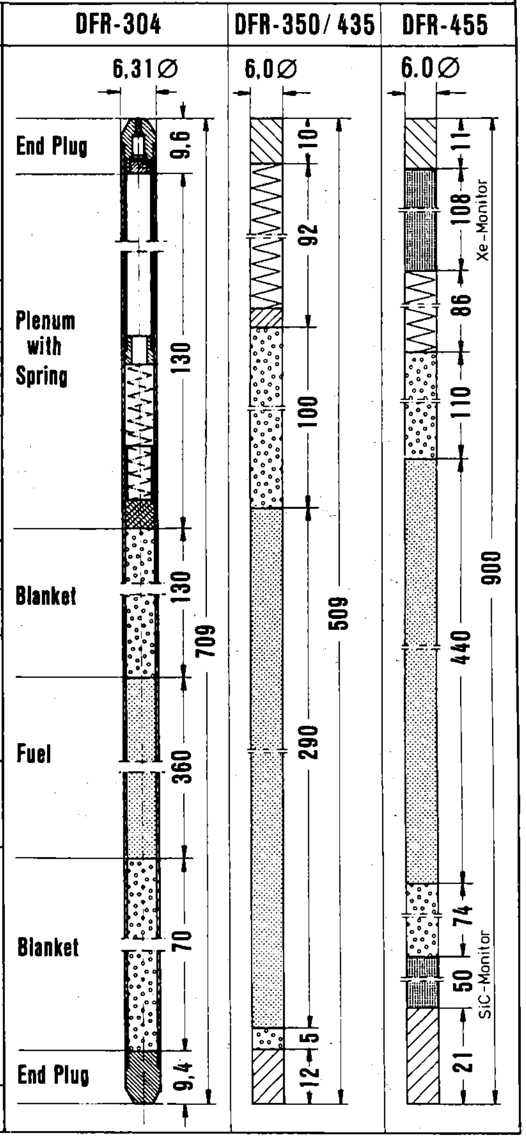


Explanations: 1) probably fabricational defect

Experimental Status: (1) results evaluated
(2) irradiation completed
(3) irradiation in progress
(4) under preparation

SCHEME IV. OXIDE PIN PERFORMANCE IN DFR PIN AND BUNDLE EXPERIMENTS

Name of Experiment		DFR-304	DFR-350	DFR-435	DFR-455
Fuel	Material	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2
	Pu / U + Pu (%)	20	20	20	30
	Fuel Form	Cyl. Pellets	Dished Pellets	Dished Pellets	Dished Pellets
	Pellet Diameter (mm)	5.40	5.04	5.04	5.09
	Fuel Length (mm)	360	290	290	440
	Fuel Density (%TD)	89	90	89	85 – 90
Clad Material		1.4988	1.4961 / 1.4988	1.4988	1.4970 / 81 / 88
Pin	Diameter (mm)	6.31	6.00	6.00	6.00
	Length (mm)	709	509	509	900
Bundle	Number of Pins		77		60
	Pitch / Diameter Ratio		1.22		1.32
	Spacing		Grid		Grid
Irradiation Vehicle		Trefoil		Trefoil	
Irradiation	Number of Specimens	3	23[1]	8[2]	60
	Linear Rod Power (W / cm)	500	450	390	470-500
	Max Clad Temperature (C)	700	630	⩽650	630
	Max Burnup (MWd / kgM)	56	53	65 - 90	50
Results and Observations	Experimental Status	(1)	(1)	(1)	(2)
	Pin Failures	no	no	5[3]	5[4]
	Pin Diameter Increase (%)	0.5 – 0.6	0.5 – 1.1	⩽1.5	0.3 – 0.8
	Fission Gas Release (%)	~ 90	61 – 95	~ 95	x
	Fuel Relocation	x	x	x	x
	Pu-Segregation	x	x	x	x
	Fission Product Migration	x	x	x	x
	Internal Clad Corrosion	x	x	x	x
References		/ 17 18 /	/ 19 20 21 /	/ 22 /	/ 23 /

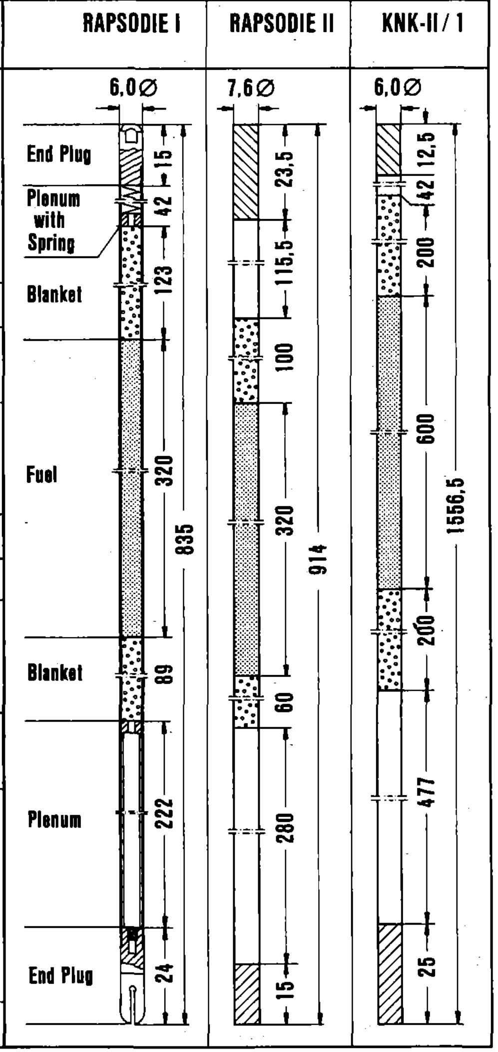


Explanations: 1) 23 pins of German origin
2) trefoil load changed
3) operated above scheduled lifetime
4) due to fuel impurities

Experimental Status: (1) results evaluated
(2) irradiation completed
(3) irradiation in progress
(4) under preparation

SCHEME V OXIDE PIN PERFORMANCE IN RAPSODIE AND KNK II BUNDLE EXPERIMENTS

Name of Experiment		RAPSODIE I Monitor	RAPSODIE I	RAPSODIE II Monitor	RAPSODIE II	KNK II / 1
Fuel	Material	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2
	Pu / U + Pu (%)	30	30	30	30	30
	Fuel Form	Dished Pellets	Dished Pellets	Dished Pellets	Dished Pellets	Dished Pellets
	Pellet Diameter (mm)	5.06 – 5.12	5.09	6.41	6.41	5.09
	Fuel Length (mm)	320	320	320	320	600
	Fuel Density (%TD)	85	87	86.5	86.5	86.5
Clad Material		1.4970 / 1.4988	1.4970 / 1.4988	1.4970	1.4970	1.4970 / 81 / 88
Pin	Diameter (mm)	6.0	6.0	7.6	7.6	6.0
	Length (mm)	840	835	914	914	1556.5
Bundle	Number of Pins		2x34		19	7x211
	Pitch / Diameter Ratio		1.27		1.16	1.32
	Spacing		Grid		Spiral Wire	Grid
Irradiation Vehicle		Monitor-Capsule		Monitor-Capsule		
Irradiation	Number of Specimens	5	68	3	19	1477
	Linear Rod Power (W / cm)	460	480	480	480	435
	Max Clad Temperature (C)	615	615	650	650	620
	Max Burnup (MWd / kgM)	66	95	100	109	65
Results	Experimental Status	(1)	(1)	(3)	(3)	(3)
	Pin Failures	no	no	no	no	
	Pin Diameter Increase (%)	0.4 – 0.8	81 – 96			
	Fission Gas Release (%)					
	Fuel Relocation	x	x			
	Pu-Segregation	x	x			
	Fission Product Migration	x	x			
	Internal Clad Corrosion	x	x			
References		/ 24 /	/ 25 26 /			/ 27 /



Experimental Status: (1) results evaluated (3) irradiation in progress
(2) irradiation completed (4) under preparation

SCHEME VI OXIDE PIN PERFORMANCE AT START UP AND TRANSIENT OPERATION CONDITIONS

Name of Experiment		FR 2 - LOOP 2	FR 2 - LOOP 3	FR 2-LOOP 5	MOL-10	HFR-DUELL	HFR-KAKADU
Special Feature of the Experiment		Fuel restructuring at start-up and short -term irradiation		Fuel-clad mechanical interaction at power cycling		Start-up and operational power ramping	
Fuel	Material	UO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2	UO_2-PuO_2
	Pu / U + Pu (%)	0	11.5	6/ 18	15	30	30
	Fuel Form	Cyl. / Dish.Pell. Vibrofuel	Cyl. Pellets	Cyl.Pellets	Cyl.Pellets	Dish.Pellets	Dish.Pellets
	Pellet Diameter (mm)	9.90/ 9.75	8.30/ 8.50	6.15	5.21	5.09	5.09
	Fuel Length (mm)	140/ 150	140	40	40	150	600
	Fuel Density (%TD)	85/ 88/ 90/ 93	83/ 90	85/ 95	90.6/ 91.2	86.5	86.5
Clad	Material	1.4988	1.4988	Incoloy 800	1.4970/ 88	1.4970	1.4970
	Thickness (mm)	1.0	0.7	0.40	0.36	0.38	0.38
Pin	Diameter (mm)	12.0	10.0	7.0	6.0	6.0	6.0
	Length (mm)	188.5	177.4	86.5/ 98.5	100	453	1556.5
Irradiation	Number of Specimens	43	34	10	2	8	3
	Irradiation Vehicle	He-Loop	He-Loop	He-Loop	VADIA-Caps.	DUELL-Caps.	KAKADU-Caps.
	Instrumentation	$T_{He}^{1)}$, $T_{Ha}^{2)}$, $T_Z^{3)}$	T_{He}, T_{Ha}	T_{He}, T_{Ha}	T_{Ha}, $D_p^{4)}$	T_{Ha}, D_p	T_{Ha}, D_p
	Linear Rod Power (W/cm)	500/ 750/ 1000	500-1000	440-520	300-500	$\leqslant 450$	$\leqslant 500$
	Max Clad Temperature (C)	500-620	500	500-740	500-600	500	650
	Max Burnup (MWd/ kgM)	10 min/ 2h/ 24h*)	8h-27d*)	3-16	~ 75		
Results and Observations	Experimental Status	(1)	(1)	(1)	(1)(2)	(3)(4)	(4)
	Pin Failures	0	0	0	0		
	Pin Diameter Increase (%)	(no)	(no)	x	0.25		
	Fission Gas Release (%)						
	Fuel Relocation	x	x	x			
	Pu -Segregation						
	Fission Product Migration	x	x	x			
	Internal Clad Corrosion						
References		/ 28/	/ 29/	/ 30/	/ 31/		

Explanations: *) irradiation time

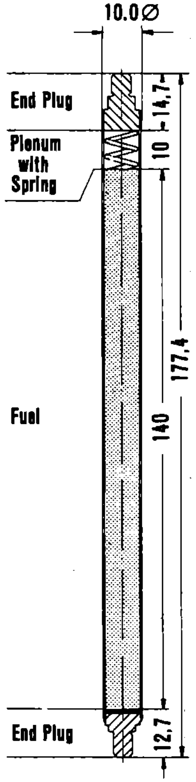
1) T_{He} ≙ helium temperature 3) T_Z ≙ fuel central temperature

2) T_{Ha} ≙ clad surface temperature 4) D_p ≙ pin diameter

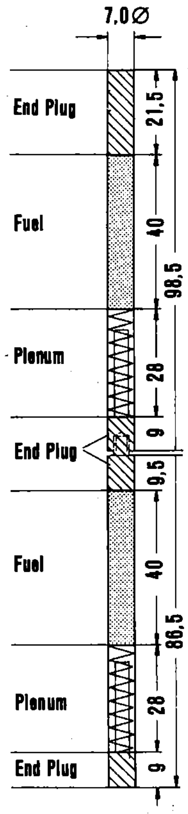
Experimental Status: (1) results evaluated (3) irradiation in progress

(2) irradiation completed (4) under preparation

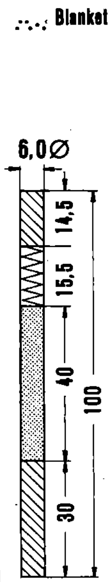
FR2-LOOP3



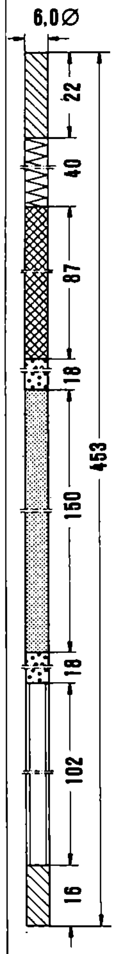
FR2-LOOP5: 2 SPECIMENS



MOL-10

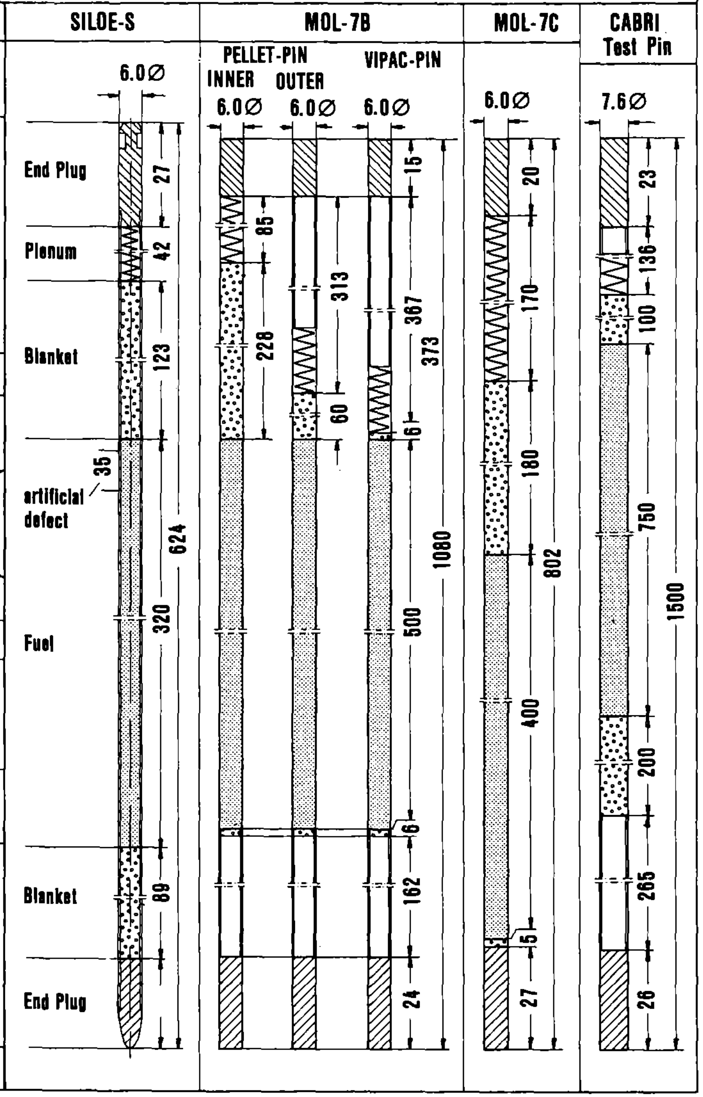


HFR-DUELL



SCHEME VII OXIDE PIN PERFORMANCE UNDER ABNORMAL CONDITIONS

Name of Experiment		SILOE-S	MOL-7B	MOL-7C	VIC-1	CABRI
Special Feature of the Experiment		Failed pin behaviour	Hot channel conditions	Coolant blockage	Power transients and coolant disturbances	
Fuel	Material	UO_2-PuO_2	UO_2-PuO_2	UO_2	UO_2-PuO_2	UO_2/UO_2-PuO_2
	Pu / U + Pu (%)	30	30	0	30	0/ 16.85
	Fuel Form	Dished Pellets	Dished Pellets, Vibrofuel	Dished Pellets	Dish. Pellets	Cyl. / Annul. Pell.
	Pellet Diameter (mm)	5.09	5.12	5.09	5.09	6.4/ 1.2
	Fuel Length (mm)	320	500	400	600	750
	Fuel Density (%TD)	87	86.8	90	86.5	86.5/ 90/ 93
Clad Material		1.4970	1.4970/ 1.4988	1.4970	1.4970	AISI 316
Pin	Diameter (mm)	6.0	6.0	6.0	6.0	7.60
	Length (mm)	609	1080	802	1556.5	1500
Bundle	Number of pins		18	30 (+7 Dummy)		
	Pitch / Diameter Ratio		1.33	1.32		
	Spacing		Grid, 2 types	Grid		
Irradiation Vehicle		Thermopump		Na-Loop	Na-Loop	Na-Loop
Irradiation	Number of Specimens	4	18	3x30	2	31+13
	Linear Rod Power (W / cm)	450	580	380-400	300-450$^{2)}$	$\sim 450^{2)}$
	Max Clad Temperature (C)	630	720	580	650$^{2)}$	$\sim 580^{2)}$
	Max Burnup (MWd / kgM)	$< 10^{1)}$	80	$\leqslant 2.5$	15^2	$\sim 20;\ \sim 60^{2)}$
Results and Observations	Experimental Status	(1)(2)(4)	(2)	(1)(2)(4)	(4)	(3)(4)
	Pin Failures	(artificial)	17	(at blockage)		
	Pin Diameter Increase (%)	$\leqslant 27$	x	Limited failure propagation after blockage		
	Fission Gas Release (%)	x				
	Fuel Relocation	x	x			
	Pu-Segregation	x				
	Fission Product Migration	x	x			
	Internal Clad Corrosion		x			
References		/ 32 /	/ 33 34 /	/ 35 /		/ 36 /



Explanations: 1) after preirradiation in Rapsodie
2) at steady state preirradiation

Experimental Status: (1) results evaluated (3) irradiation in progress
(2) irradiation completed (4) under preparation

SCHEME VIII Synopsis of the Design and Irradiation Parameters