Forschungszentrum Jülich GmbH
FZJ

FUEL PEBBLES OPERATIONAL EXPERIENCES
IRRADIATION AND POSTIRRADIATION EXAMINATION

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- **Reference fuel ,TRISO coated particles**
- **Irradiation tests in research reactors**
- **PIE, heating tests**

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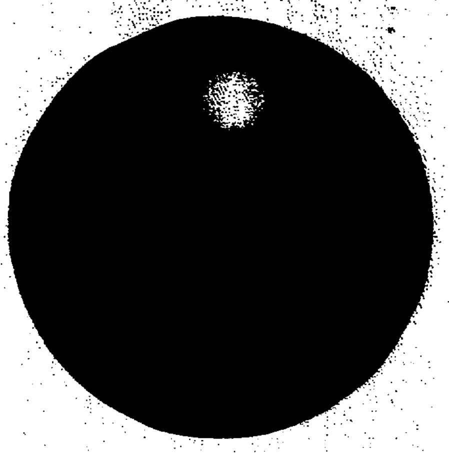
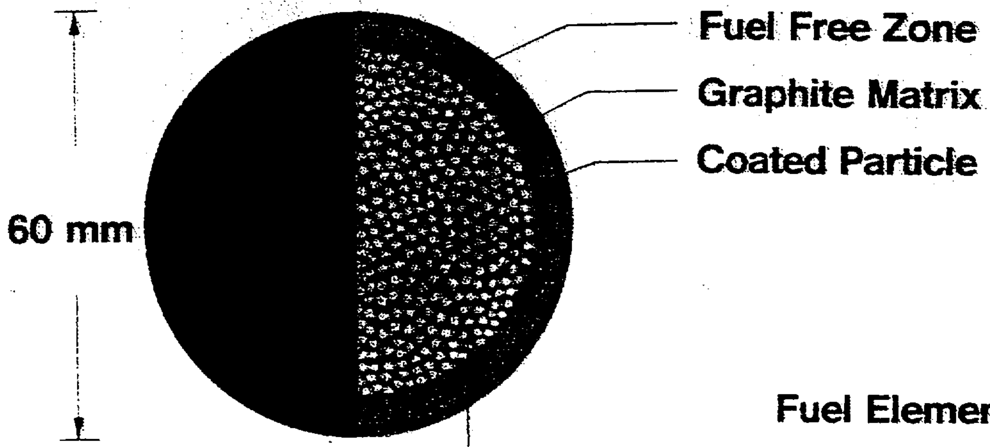
Executive Statements Summary

1. The design of modern HTRs is based on high qualified fuel. This fuel designed in the 1960s and 1970s had been perfected for steam cycle applications in the 1980s and early 1990s enabling the design of small inherently safe modular HTRs with self-limiting temperatures of < 1600 ^{0}C.
2. In the past for normal reactor conditions, irradiation testing has been performed in material test reactors and in the AVR. Parameters such as burn up, operating temperature and fast neutron fluence are varied to assess fuel performance. Continuous monitoring of released fission gas during irradiation tests gave a direct indication of the integrity of fuel coatings.
3. **In the German program, relevant irradiation tests with more than $2x10^5$ particles were performed without a single coated particle failure during irradiation. Statistically, this result corresponds to a 95% confidence level that the coating failure fraction is less than $2x10^{-5}$.**

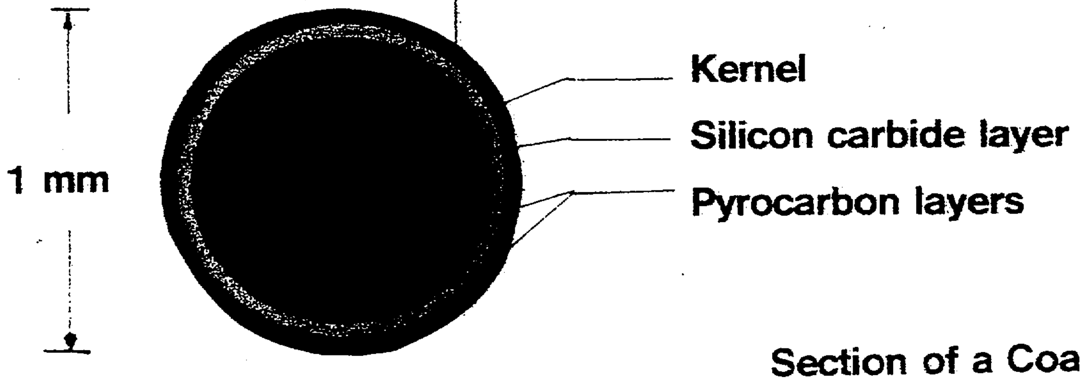
4. Postirradiation examinations had been carried out in the FZJ – Hot Cell Laboratories. One of the most important examination method are the heating tests for simulating accident conditions in special designed and constructed furnaces.(e.g. **KÜFA** *cold finger furnace*) These tests under off-normal conditions has provided fuel performance information as a function of burn up, fast neutron fluence, heating time and temperature up to 2500 ^{0}C.
5. **Kr 85 gas release fractions during accident condition testing up to 1600 ^{0}C were low at $<10^{-6}$, even at 1800 ^{0}C for 50-100 h. With >11% FIMA fuel, release remains at this low level throughout a 350 h test at 1600 ^{0}C . At 1800 ^{0}C, 10^{-3} release fractions are reached as a consequence of diffusion through degraded SiC.**
6. **At 1600 ^{0}C the fuel does not suffer irreversible changes and continues to retain all safety- relevant fission products (e.g. Cs, I, Sr). Ag 110m diffuses at 1200 – 1600 0C through intact SiC, but the amount of the generated silver is low.**
7. Know how transfer with ESCOM representatives is going on by the author. **Additional experiments** should be performed with higher temperatures, longer heating time and with fuel from accelerated tests to establish the performance margins under accident conditions of new designed reactors. This means also to irradiate actual fuel produced for the new ESCOM reactors.

SPHERICAL FUEL ELEMENT





Fuel Element



Section of a Coated Particle

IRRADIATION QUALIFICATION OF HTR FUEL ELEMENTS

- TEST FOR DETERMINATION OF PARTICLE DEFECT RATES UNDER CONDITIONES EXCEEDING NORMAL OPERATING CONDITIONS

  800-1200° C

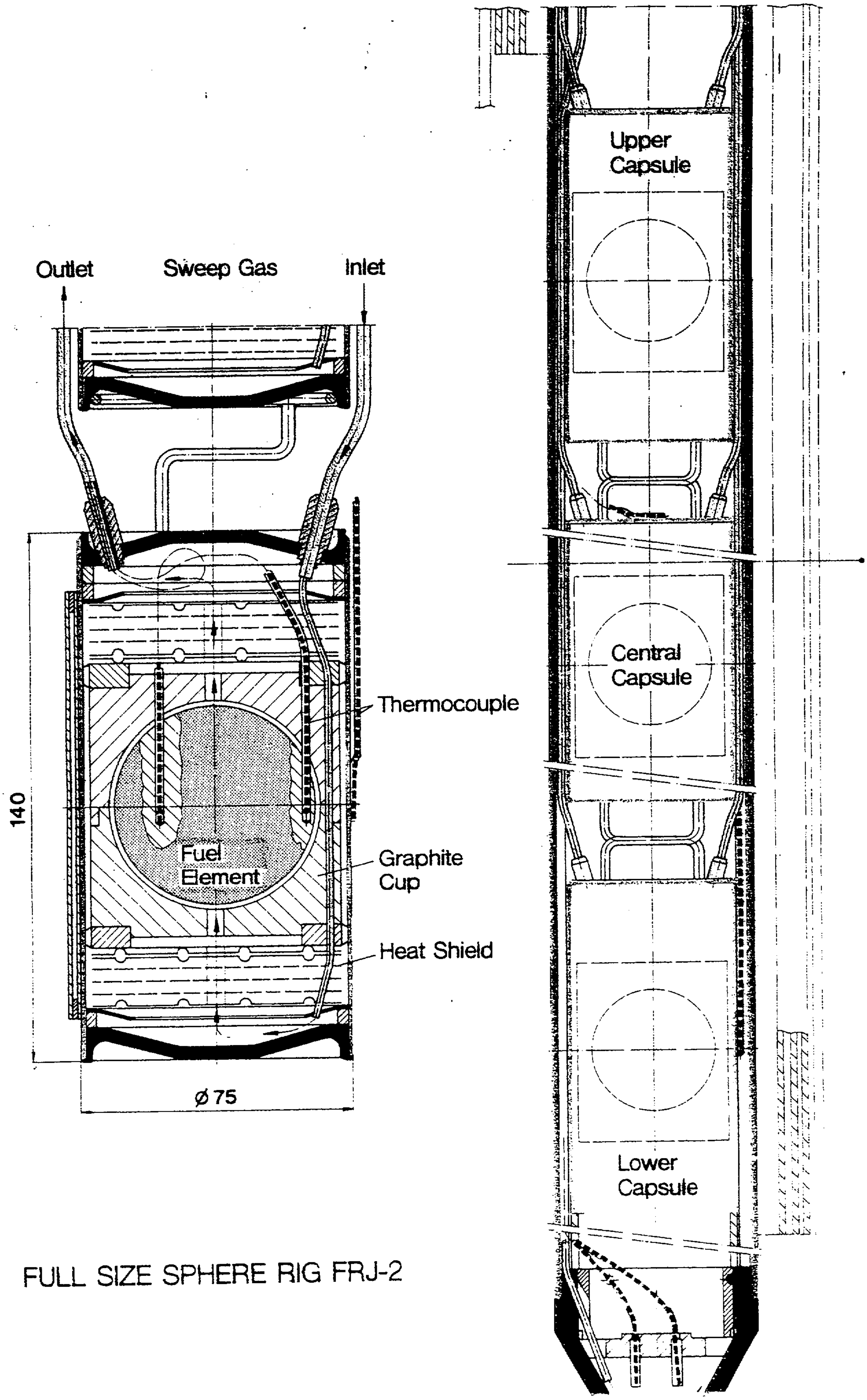
- IRRADIATIONS OF FUEL PARTICLES WITH KNOWN FAILURE FRACTION

  800-1300° C

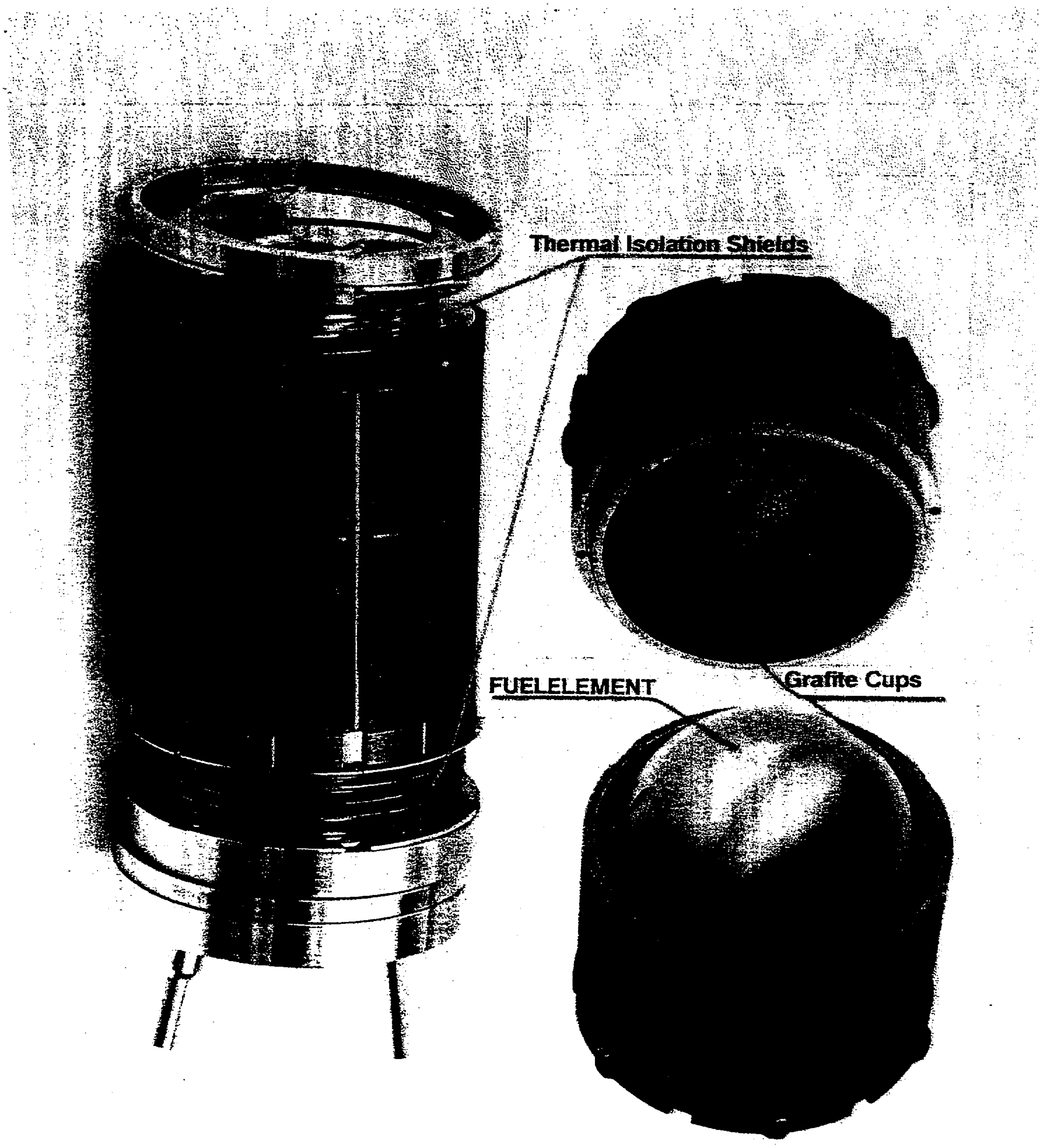
- TEST FOR DETERMINATION OF BURN UP INFLUENCES ON DEFECT RATES

  1000-1200° C

- FUEL ELEMENT REFERENCE TESTS



FULL SIZE SPHERE RIG FRJ-2

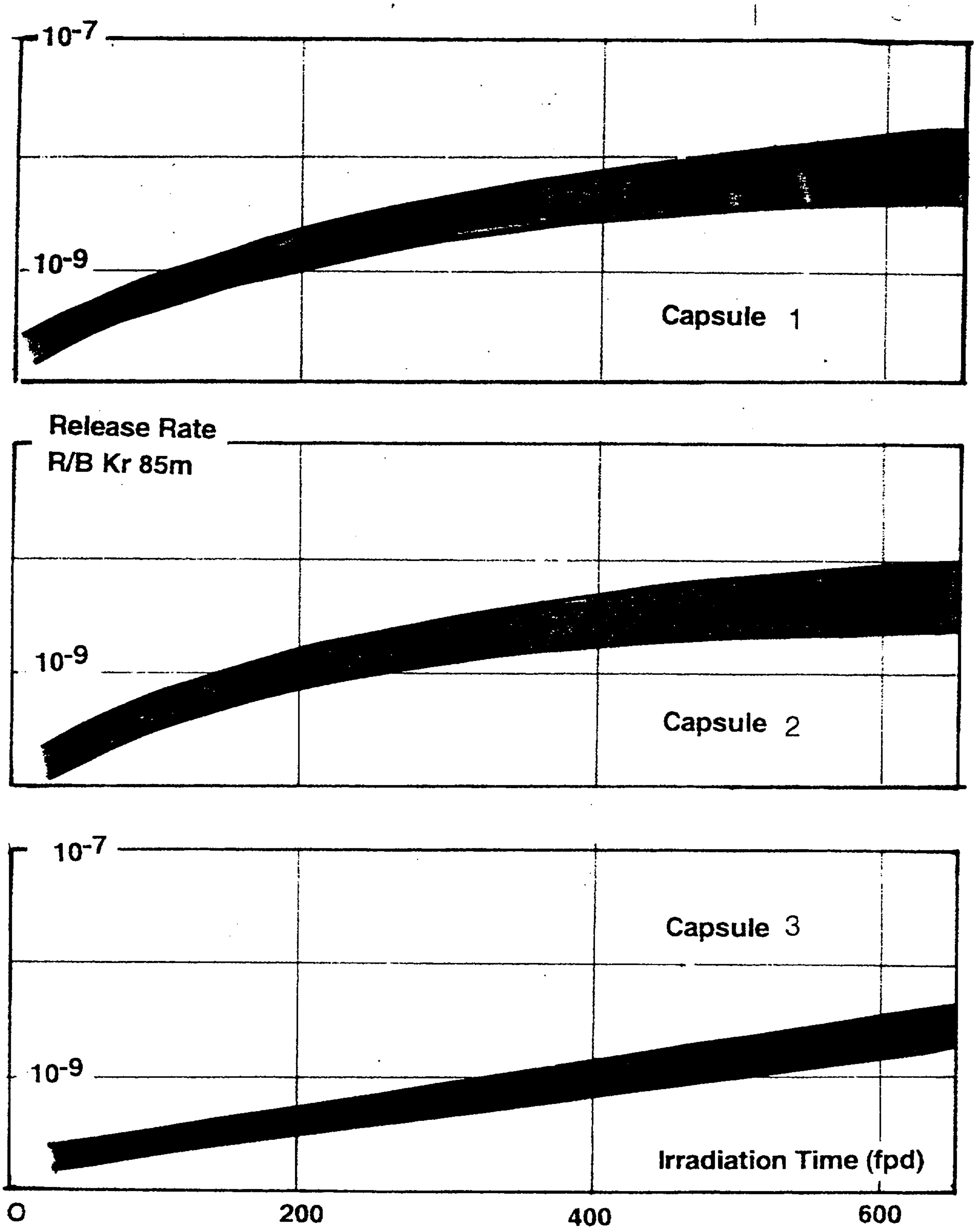


HTR FULL SIZE SPHERE RIG

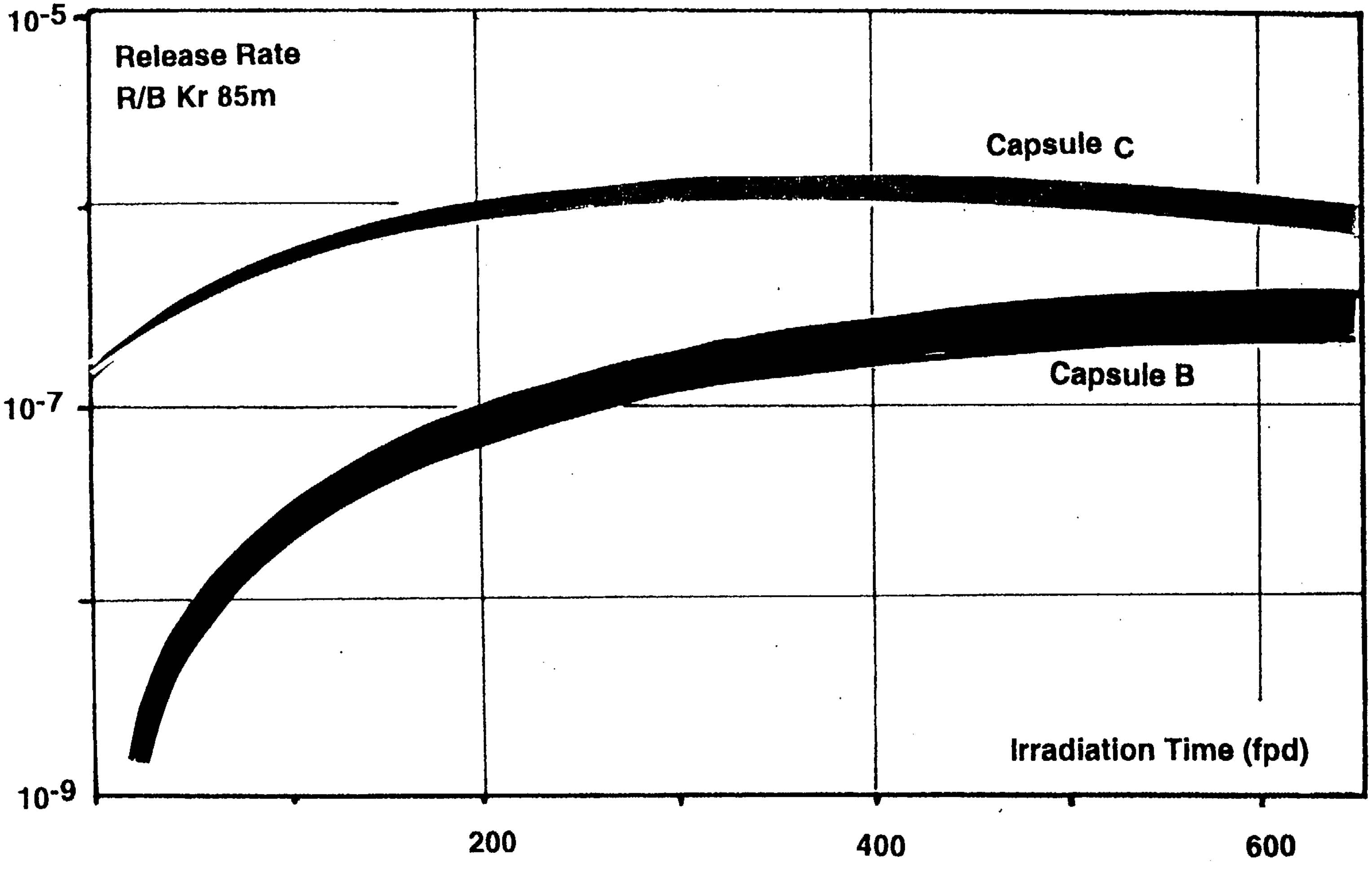
CAPSULE COMPONENTS

Experiment FRJ 2-K15
- Irradiation-Data -

Capsule Nr.		1	2	3
Irradiation time (fpd)		650		
Burn up (% fima)		14,8	16,0	15,2
Fast Neutron Fluence (E > 0,1 MeV x 10^{25}) m^{-2}		0,2	0,3	0,2
Fuel Element Power (kW)	Start	1,9	2,2	2,0
	End	0,6	0,6	0,6
R/B Kr 85m	Start	2 E -10	2 E -10	1 E -10
	End	1,2 E -8	4 E -9	3 E -9
Power / CP (W)		0,23 / 0,06		
Fuel Element Surface Temp. (°C)		800	900 - 1000	800



Experiment FRJ 2-K15 - Fission Gas Release



— 1 Failed particle

HTR REFERENCE TEST , FISSION GAS RELEASE
(HFR-K6)

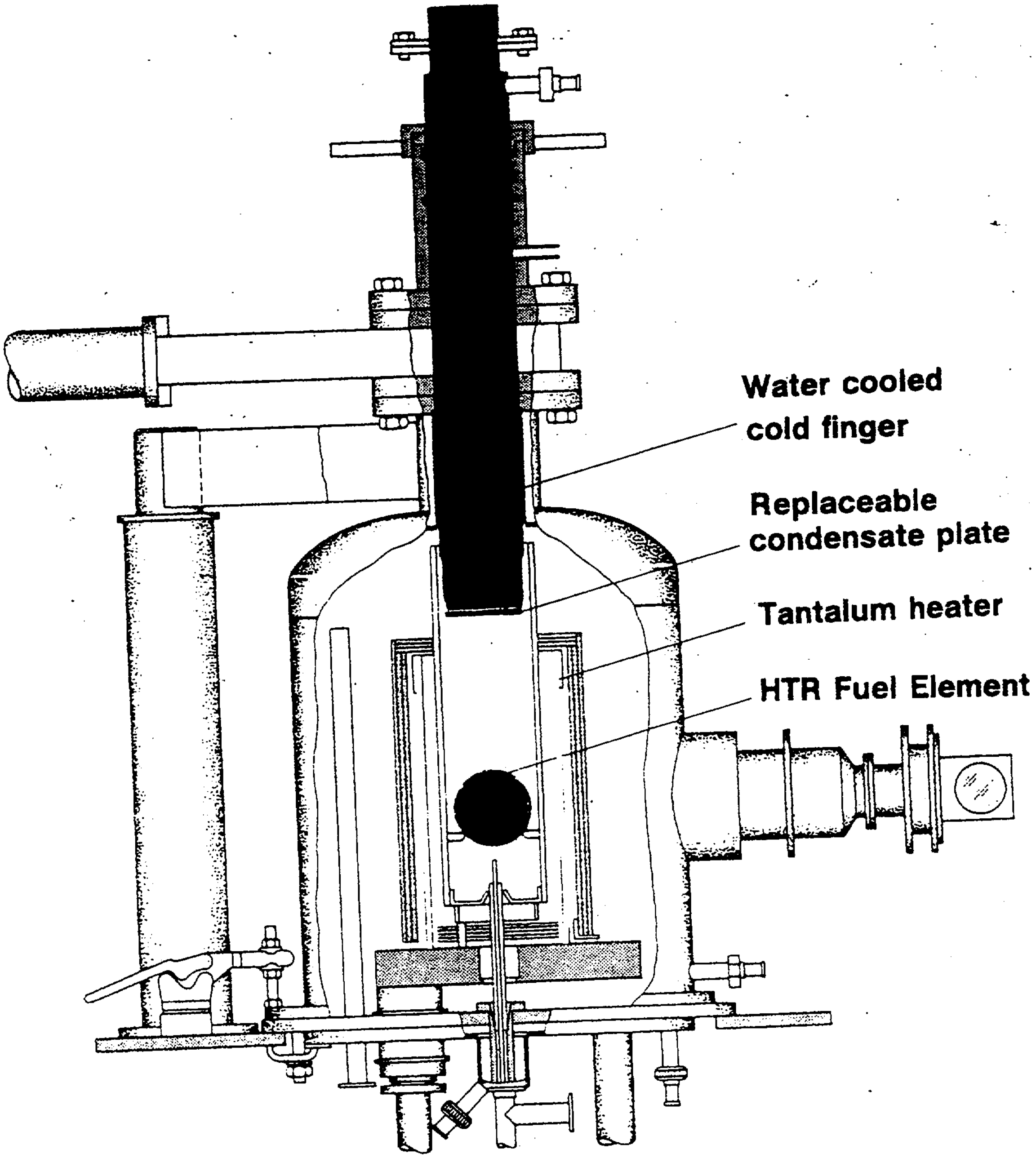
KFA-HZ-3/94

Experiment	Specimens per capsule	Number of particles	Irrad. time (efpd)	Temp. centre (°C)	Burnup (% FIMA)	Fluence (10^{25} m^{-2} E>16 fJ)	In-pile Release R/B ^{85m}Kr
HFR-P4	36 small sph.	58800	351	940-1075	9.6-14.9	5.5-8.0	8E-8 - 9E-8
SL-P1	12 small sph.	19600	330	800	8.6-11.3	5.0-6.7	1E-6
HFR-K3	4 fuel sph.	65600	359	920-1220	7.5-10.6	4.0-5.9	1E-7 - 3E-7
FRJ2-K13	4 fuel sph.	65600	396	1120-1150	7.5-8.0	0.2	2E-9 - 2E-8
FRF2-K15	3 fuel sph.	28800	533	970-1150	14.1-15.3	0.1-0.2	3E-9 - 1E-6
FRJ2-P27	3 compacts	22020	232	1080-1320	7.6-8.0	1.3-1.7	1E-7 - 1E-5
HFR-K5	4 fuel sph.	58400	359	cycled	6.7-9.1	4.0-5.9	1E-7 - 3E-7
HFR-K6	4 fuel sph.	58400	359	cycled	7.2-9.7	4.0-5.9	1E-7 - 3E-7

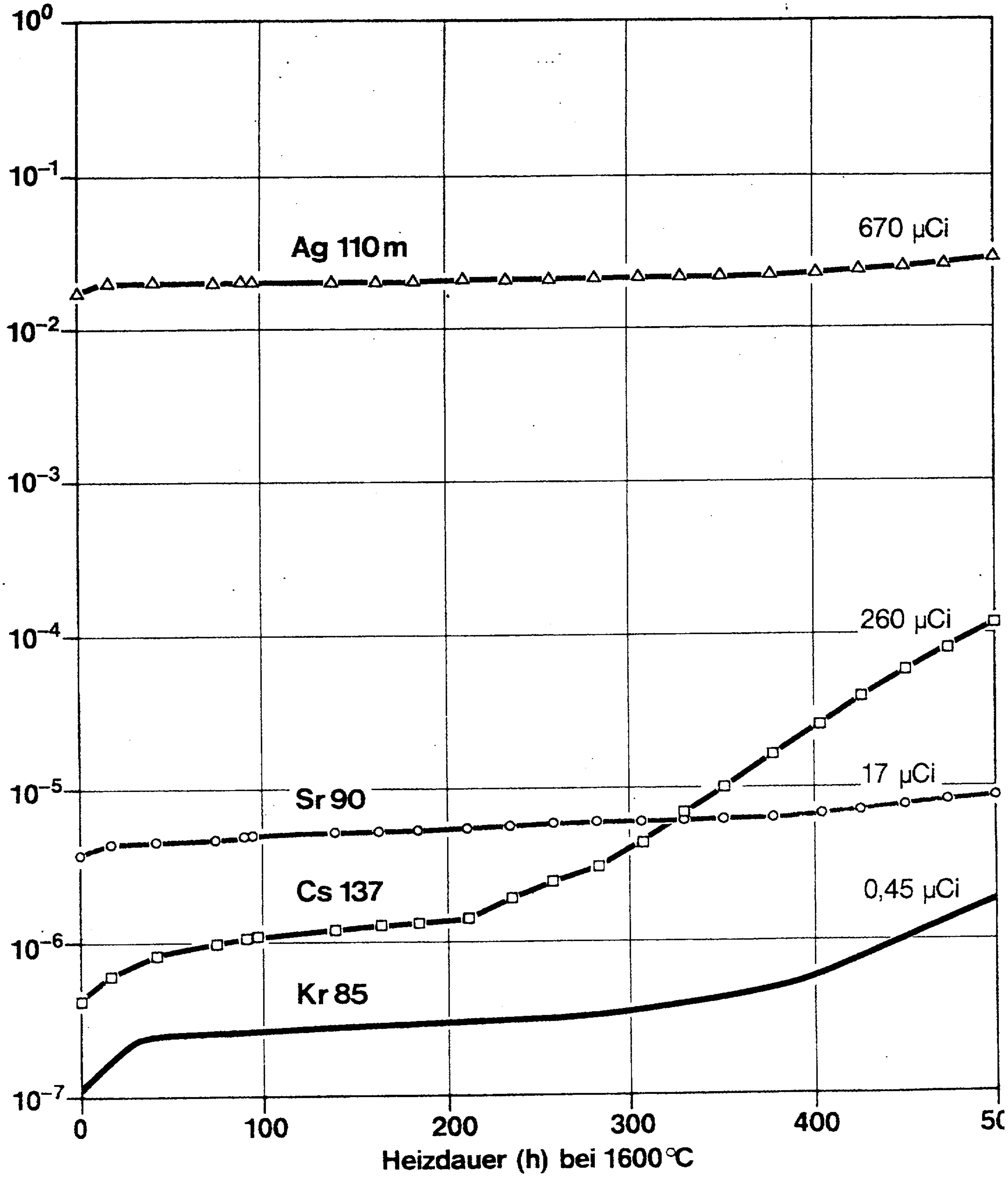
Parameters and results from irradiation tests with modern UO_2 TRISO fuel

Post Irradiation Examinations for HTR Fuel Elements

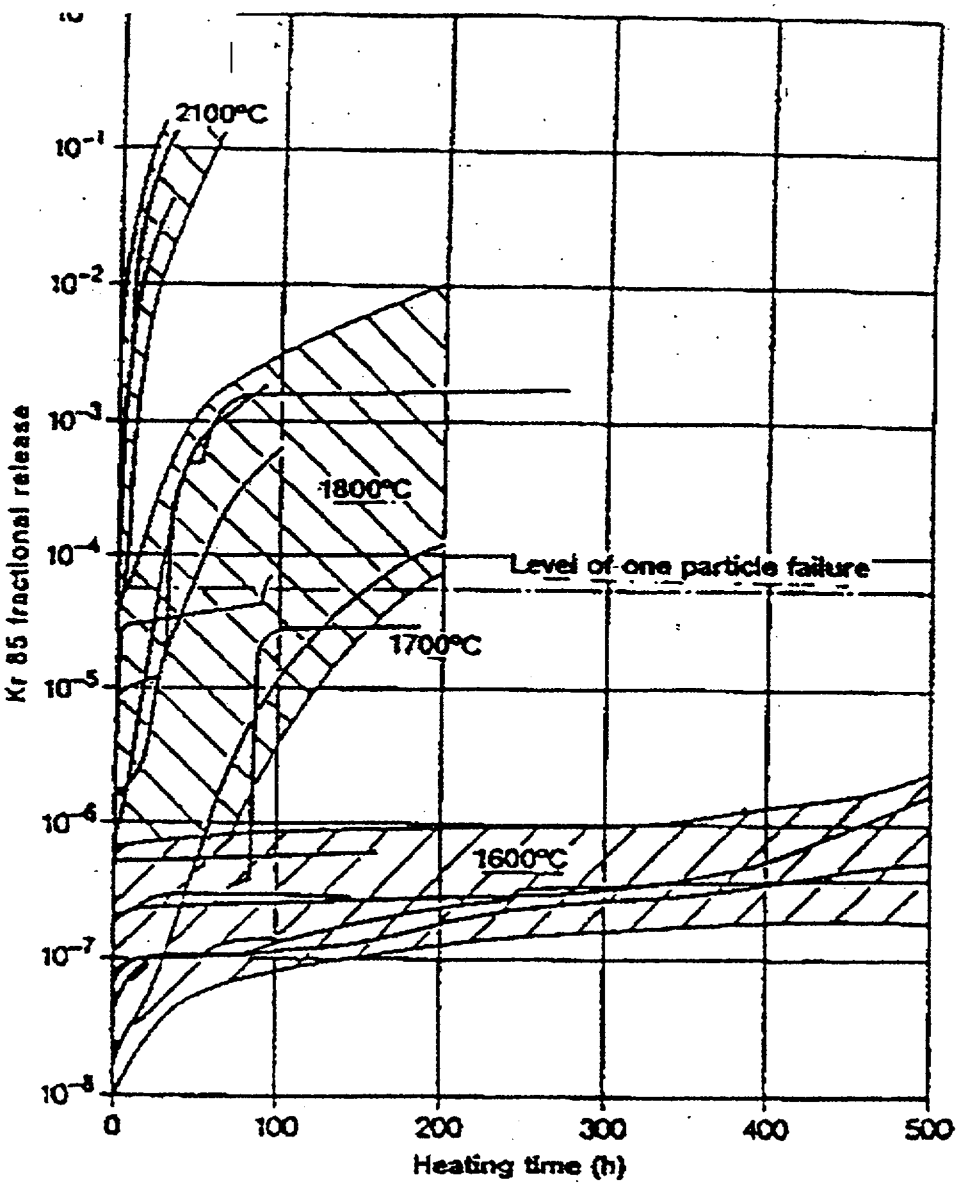
- Neutron Radiographie (Irradiation Device)
- Gamma Scan (Flux Distribution)
- Examination of Neutron Fluence Monitors
  (Fast Fluence, Burn up)
- Dismantling of Rig and Capsules
- Inspection, Photodocumentation
- Dimensional Measurements of Fuel Ball
- Burn up Measurement (Comparison with Calculation)
- Gamma Spectrometrie - Fission Product Distribution
  (Fuel element, Components)
- Corrosiontest
- Compressive Strength (generally not necessary)
- Ceramographie / REM
- Accident-Simulation-Tests
  (Corrosion, High Temperature >1600°C)



Heating furnace used in accident simulation tests with irradiated HTR fuel elements

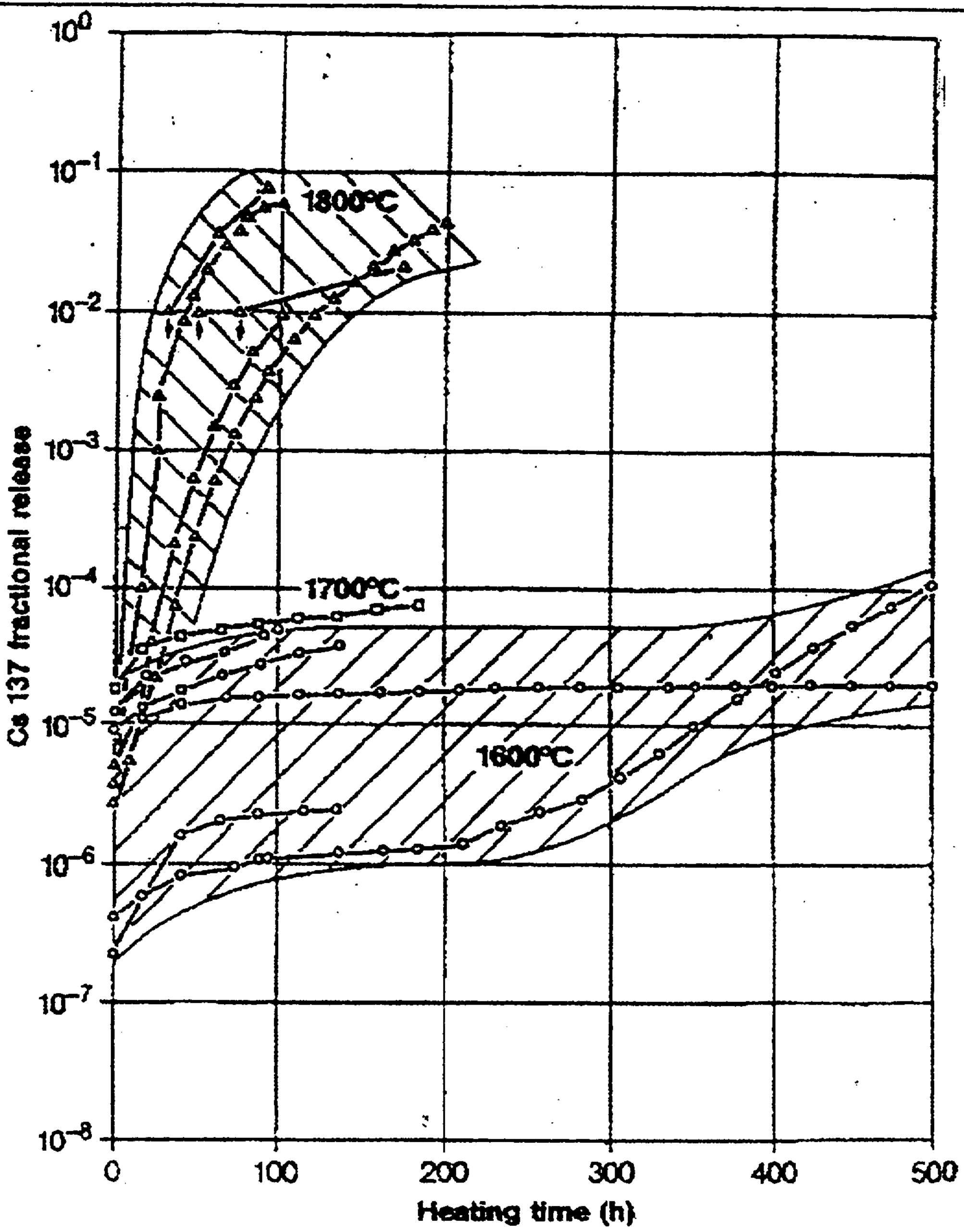


Spaltproduktfreisetzung aus einem BE mit UO_2-TRISO Partikeln (HFR-K3/1) bei 1600 °C



Krypton release during tests with irradiated spherical fuel elements at 1600 to 2100°C.

Accident condition performance of German fuel



Caesium release from heated spheres as a function of heating times up to 500 hours.

Accident condition performance of German fuel

Results of accident simulation tests with irradiated fuel elements containing UO_2 Triso

Fuel Element	Burnup %FIMA	Fast Fluence $10^{25} m^{-2}$ E>0.1 MeV	Heating test		Number of failed particles **		Fractional release				
			Temp (°C)	Time (h)	manuf.	heating	^{85}Kr	^{90}Sr	^{110m}Ag	^{134}Cs	^{137}Cs
AVR 71/22	3.5	0.9	1600	500	no	no	4.0E-7	5.3E-6	9.0E-4	6.9E-5	2.0E-5
HFR-K3/1	7.7	3.9	1600	500	no	no	1.8E-6	1.8E-7	2.7E-2	1.3E-4	1.1E-4
FRJ2-K13/2	8.0	0.1	1600	138 (160)	no	no	6.4E-7	3.3E-7	2.8E-3	1.0E-4	3.9E-5
AVR 82/20	8.6	2.4	1600	100	no	no	1.5E-7	3.8E-6	4.4E-3	1.2E-4	6.2E-5
AVR 82/9	8.9	2.5	1600	500	no	no	5.3E-7	8.3E-5	1.9E-2	5.9E-4	7.6E-4
AVR 89/13	9.1	2.6	1620 *	~10	no	no	2.0E-7	***	8.3E-4	1.3E-5	1.1E-5
			1620 *	~10		no	1.3E-9	***	1.5E-2	1.6E-6	1.4E-6
AVR 85/18	9.2	2.6	1620 *	~10	no	no	1.4E-7	***	6.5E-3	1.0E-5	1.3E-5
AVR 90/5	9.2	2.7	1620 *	~10	no	no	1.9E-7	***	1.1E-3	7.7E-6	9.0E-6
			1620 *	~10		no	6.6E-9	***	9.0E-4	3.5E-6	3.3E-6
AVR 90/2	9.3	2.7	1620 *	~10	1	2	1.0E-4	***	3.7E-2	5.0E-5	4.6E-5
AVR 90/20	9.8	2.9	1620 *	~10	2	3	2.4E-4	***	7.6E-2	5.6E-6	6.5E-6
AVR 91/31	9.0	2.6	1700 *	~10	2	18	1.2E-3	***	6.2E-1	3.7E-3	2.4E-3
AVR 74/11	6.2	1.6	1700	184.5	1	no	3.0E-5	7.2E-6	4.8E-2	8.4E-5	7.6E-5
FRJ2-K13/4	7.6	0.1	1600	138	no	no	3.0E-7	2.0E-8	4.5E-4	5.7E-6	2.5E-6
			1800	100		2	7.2E-5	1.4E-3	5.3E-1	9.7E-3	9.9E-3
AVR 88/33	8.5	2.3	1600	50	no	no	1.0E-7	8.4E-6	1.2E-3	1.1E-4	1.2E-4
			1800	20		~4	1.8E-4	2.3E-4	2.1E-1	4.4E-4	4.6E-4
AVR 88/15	8.7	2.4	1600	50		no	6.3E-8	***	9.1E-3	8.8E-6	1.2E-5
			1800	50	1	~6	2.9E-4	1.1E-2	8.1E-1	1.3E-2	1.4E-2
AVR 76/18	7.1	1.9	1800	200	no	~3	1.2E-4	6.6E-2	6.2E-1	5.3E-2	4.5E-2
AVR 88/41	7.6	2.0	1800	24	no	no	2.4E-7	1.2E-4	7.7E-2	1.4E-4	1.5E-4
HFR-K3/3	10.2	6.0	1800	100	no	~12	6.5E-4	1.5E-3	6.7E-1	6.4E-2	5.9E-2

* simulating calculated core heatup curve   ** out of 16400 particles   *** not measured