Metals and Ceramics Division

**INTERIM REPORT ON THE POST IRRADIATION EXAMINATION OF
CAPSULES 2 AND 3 OF THE HFR-B1 EXPERIMENT**

B. F. Myers, editor

Oak Ridge National Laboratory
Oak Ridge, Tennessee

and

G. Pott, W. Schenk, R. Schröder, W. Kühlein, H. J. Bucker, H. Dahmen, K. Landsgesell
and F. Nieveler

Forschungszentrum Jülich GmbH, Jülich
Jülich, Germany

Date Published: September 1994

Prepared for the
U.S. Department of Energy
Office of Advanced Reactor Programs
AF 20 50 10 1

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
and the
FORSCHUNGSZENTRUM JÜLICH GmbH
Jülich, Germany
for the
U.S. Department of Energy
under Contract DE-AC05-84OR21400

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	xii
ABSTRACT	1
1. INTRODUCTION	1
2. OBJECTIVES OF CAPSULES 2 AND 3	1
3. CONFIGURATION OF CAPSULES 2 AND 3	2
4. PIE OF CAPSULES 2 AND 3	2
4.1 PIE TEST PLAN FOR CAPSULES 2 AND 3	2
4.2 DISASSEMBLY OF CAPSULES 2 AND 3	9
4.2.1 Visual Inspection and Photography	9
4.2.2 Capsule 2	9
4.2.3 Capsule 3	9
4.2.4 Gamma Scanning	25
4.2.5 Remaining Tasks	29
4.3 EXAMINATION OF FUEL COMPACTS	29
4.3.1 Visual Inspection and Photography	29
4.3.2 Gamma Scanning	71
4.3.3 Gamma Counting	71
4.3.4 Dimensional and Weight Measurements	82
4.3.5 Remaining Tasks	82
4.4 EXAMINATION OF UNFUELED GRAPHITE BODIES	82
4.4.1 Visual Inspection and Photography	82
4.4.2 Gamma Scanning	82

CONTENTS (Continued)

4.4.3	Gamma Counting of Graphite Sectors	99
4.4.4	Gamma Counting of Small Graphite Components	102
4.4.5	Cesium Distribution Between Fuel Compacts and The Graphite	102
4.4.6	Summary of Inventory Measurements	111
4.4.7	Dimensional Measurements	111
4.5	EXAMINATION OF INERT COMPACTS AND GRAPHITE CYLINDERS	111
4.5.1	Visual Inspection and Photography	116
4.5.2	Dimensional and Weight Measurements	116
4.6	UNBONDED COATED FUEL PARTICLES	116
4.6.1	Visual Inspection and Photography	137
4.6.2	Gamma Counting of Kernels, Coatings and Particles	137
4.6.3	Kernel Retention of Fission Products	169
4.6.4	Cracking of Intact Fuel Particles	169
4.7	HEATING WITH INTERMITTENT WATER-VAPOR INJECTIONS	169
4.7.1	Water-Vapor Injection Tests with Fuel Compacts 2.2.1 and 2.2.2	177
4.7.2	Water-Vapor Injection Tests with Fuel Compacts 3.2.1 and 3.2.2	177
4.7.3	Water-Vapor Injection Tests with UCO Kernels	188
4.8	STATUS OF THE PIE OF CAPSULES 2 AND 3	188
5.	REFERENCES	195

LIST OF FIGURES

Figure	Page
3.1 Cross-sectional view representative of capsules 2 and 3	3
3.2 Perspective view of the contents of capsule 2	4
3.3 Perspective view of the contents of capsule 3	5
4.1 PIE flow chart for capsules 2 and 3	6
4.2 Definition of icons in the PIE flow chart	8
4.3 Modified PIE flow chart with major tasks outlined for capsules 2 and 3	11
4.4 The overview appearances of capsule 2	12
4.5 The overview appearances of the ends of capsule 2	13
4.6 The appearances of capsule 3	14
4.7 View of the end plates of capsule 3	15
4.8 Additional appearances of capsule 3	16
4.9 Further views of the end plates of capsule 3	17
4.10 Detailed views of the end plates of capsule 3 and a heat shield	18
4.11 Selected views of components after opening capsule 2	19
4.12 Selected views of the graphite body in capsule 2	20
4.13 Removal of the end plate, thermocouple protection tubes and adjacent heat shield	21
4.14 Selected views of the graphite body in capsule 3	22
4.15 Selected views of the ends of the graphite body in capsule 3	23
4.16 Views of the inside of the stainless steel capsule 3	24
4.17 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 1	30
4.18 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 1 (enlarged)	30
4.19 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 1	31
4.20 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 1	31

LIST OF FIGURES (continued)

4.21 Gamma scam of the steel capsule for ^{54}Mn focused on fuel hole 1	32
4.22 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 2	33
4.23 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 2 (enlarged)	33
4.24 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 2	35
4.25 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 2	35
4.26 Gamma scam of the steel capsule for ^{54}Mn focused on fuel hole 2	35
4.27 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 3	36
4.28 Gamma scam of the steel capsule for ^{60}Co focused on fuel hole 3 (enlarged)	36
4.29 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 3	37
4.30 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 3	37
4.31 Gamma scam of the steel capsule for ^{54}Mn focused on fuel hole 3	38
4.32 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{144}Ce	39
4.33 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{134}Cs	40
4.34 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{137}Cs	41
4.35 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{106}Ru	42
4.36 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{95}Zr	43
4.37 Gamma scam of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{60}Co	44
4.38 The gamma spectrum of the graphite body from capsule 2	45
4.39 Gamma scan of the gamma scan wires 3.1 and 2.1 for ^{60}Co in capsules 2 and 3	46
4.40 Gamma scan of the gamma scan wires 3.1 and 2.1 for ^{54}Mn in capsules 2 and 3	46
4.41 Gamma scan of the gamma scan wires 3.2 and 2.2 for ^{60}Co in capsules 2 and 3	47
4.42 Gamma scan of the gamma scan wires 3.2 and 2.2 for ^{54}Mn in capsules 2 and 3	47
4.43 Gamma scan of the gamma scan wires 3.3 and 2.3 for ^{60}Co in capsules 2 and 3	48
4.44 Gamma scan of the gamma scan wires 3.3 and 2.3 for ^{54}Mn in capsules 2 and 3	48
4.45 Four views of the fuel compact from position 1 in hole 1 of capsule 2	67

LIST OF FIGURES (continued)

4.46 Four views of the fuel compact from position 2 in hole 1 of capsule 2	68
4.47 Four views of the fuel compact from position 3 in hole 1 of capsule 2	69
4.48 Four views of the fuel compact from position 4 in hole 1 of capsule 2	70
4.49 Four views of the fuel compact from position 1 in hole 1 of capsule 3	72
4.50 Four views of the fuel compact from position 2 in hole 1 of capsule 3	73
4.51 Four views of the fuel compact from position 3 in hole 1 of capsule 3	74
4.52 Four views of the fuel compact from position 4 in hole 1 of capsule 3	75
4.53 View of the loose particles upon opening fuel hole 1 of capsule 3	76
4.54 Gamma scan of the fuel compacts from hole 1 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs	78
4.55 Gamma scan of the fuel compacts from hole 1 of capsules 2 and 3 for ^{106}Ru , ^{95}Zr , and ^{154}Eu	79
4.56 The gamma spectrum of the fuel compact 2.1.1 hole 1 , capsule 2	80
4.57 The cesium inventory of the fuel compacts from fuel holes 1, 2, and 3	86
4.58 Sketch of the measuring facility	89
4.59 The gamma spectrum of graphite sector 2.3	90
4.60 The gamma spectrum of graphite sector 3.3	91
4.61 Gamma scan of graphite sectors from hole 1 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs	93
4.62 Gamma scan of graphite sectors from hole 1 of capsules 2 and 3 for ^{183}Ta , ^{94}Nb , and ^{60}Co	94
4.63 Gamma scan of graphite sectors from hole 2 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs	95
4.64 Gamma scan of graphite sectors from hole 2 of capsules 2 and 3 for ^{183}Ta , ^{94}Nb , and ^{60}Co	96
4.65 Gamma scan of graphite sectors from hole 3 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs	97

LIST OF FIGURES (continued)

4.66 Gamma scan of graphite sectors from hole 3 of capsules 2 and 3 for ^{183}Ta , ^{94}Nb , and ^{60}Co	98
4.67 The activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.1 and 3.1	101
4.68 The activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.2 and 3.2	101
4.69 The activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.3 and 3.3	101
4.70 The inventories (Bq) of the plugs and screws from capsule 2 for ^{144}Ce , ^{137}Cs , ^{134}Cs , and ^{106}Ru	108
4.71 The inventories (Bq) of the plugs and screws from capsule 3 for ^{144}Ce , ^{137}Cs , ^{134}Cs , and ^{106}Ru	108
4.72 The inventories (Bq) of the graphite cylinders and sleeves from capsule 2 for ^{137}Cs , and ^{134}Cs	109
4.73 The inventories (Bq) of the graphite cylinders and sleeves from capsule 3 for ^{137}Cs , and ^{134}Cs	109
4.74 The inventories (Bq) of the particle trays from capsule 2 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru and ^{60}Co	110
4.75 The inventories (Bq) of the particle trays from capsule 2 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru and ^{60}Co	110
4.76 The inventories of ^{137}Cs and ^{134}Cs in the fuel compacts and graphite of capsules 2 and 3	113
4.77 The distribution of ^{137}Cs and ^{134}Cs between fuel compacts and graphite in capsules 2 and 3	113
4.78 Diameter and length measurements on graphite bodies from capsules 2 and 3 before and after irradiation	115
4.79 Three views of the inert compact and associated graphite sleeve from position 2.4.1 of capsule 2	117
4.80 Three views of the inert compact and associated graphite sleeve from position 2.5.1 of capsule 2	118
4.81 Three views of the inert compact and associated graphite sleeve from positions 2.6.1 and 2.6.2 of capsule 2	119
4.82 Three views of the inert compact and associated graphite sleeve from positions 2.6.3 and 2.6.4 of capsule 2	120
4.83 Three views of the graphite cylinders from positions 2.4.2 and 2.4.3 of capsule 2	121

LIST OF FIGURES (continued)

4.84 Three views of the graphite cylinders from positions 2.4.4 and 2.4.5 of capsule 2	122
4.85 Three views of the graphite cylinders from positions 2.5.2 and 2.5.3 of capsule 2	123
4.86 Three views of the graphite cylinders from positions 2.5.4 and 2.5.5 of capsule 2	124
4.87 Four views of the inert compact and associated graphite sleeve from position 3.4.1 of capsule 3	125
4.88 Three views of the inert compact and associated graphite sleeve from position 3.5.1 of capsule 3	126
4.89 Three views of the inert compact and associated graphite sleeve from position 3.6.1 of capsule 3	127
4.90 Three views of the inert compact and associated graphite sleeve from position 3.6.2 of capsule 3	128
4.91 Three views of the inert compact and associated graphite sleeve from position 3.6.3 of capsule 3	129
4.92 Three views of the inert compact and associated graphite sleeve from position 3.6.4 of capsule 3	130
4.93 Three views of the graphite cylinders from positions 3.4.2, 3.4.3, 3.4.4, and 3.4.5 of capsule 3	131
4.94 Three views of the graphite cylinders from positions 3.5.2, 3.5.3, 3.5.4, and 3.5.5 of capsule 3	132
4.95 Components of the particle trays before irradiation	138
4.96 The assembled trays after irradiation	138
4.97 The graphite crucible and niobium encapsulated fuel particles before irradiation	139
4.98 The graphite crucible after irradiation in capsule 2	139
4.99 Views of the opened unbonded particle trays 2-3, 2-4, 2-7, and 2-8 from capsule 2	140
4.100 Views of the opened unbonded particle trays 3-3, 3-4, 3-7, and 3-8 from capsule 3	141
4.101 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays 2-3 and 2-7 in capsule 2	145
4.102 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays 2-4 and 2-8 in capsule 2	146
4.103 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays 3-3 and 3-7 in capsule 3	147

LIST OF FIGURES (continued)

4.104 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays 3-4 and 3-8 in capsule 3	148
4.105 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 2	151
4.106 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 2	152
4.107 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 3	153
4.108 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 3	154
4.109 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 2	157
4.110 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 2	158
4.111 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 3	159
4.112 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 3	160
4.113 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 2	165
4.114 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 2	166
4.115 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 3	167
4.116 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 3	168
4.117 Force and movement conditions under which fissile particles from capsule 2 crack ...	172
4.118 Force and movement conditions under which fertile particles from capsule 2 crack ...	173
4.119 Force and movement conditions under which fissile particles from capsule 3 crack ...	174
4.120 Force and movement conditions under which fertile particles from capsule 3 crack ...	175

LIST OF FIGURES (continued)

4.121 The fractional release and release rate of ^{85}Kr at 800°C from compacts 2.2.1 and 2.2.2 as a function of time and the partial pressure of water vapor	180
4.122 The fractional release and release rate of ^{85}Kr at 800°C from compacts 3.2.1 and 3.2.2 as a function of time and the partial pressure of water vapor	183
4.123 The fractional release and release rate of ^{85}Kr at 800°C from compacts 3.2.1 and 3.2.2 during the second 1 kPa water vapor injection	183
4.124 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor .	189
4.125 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor .	189
4.126 Modified flow chart for capsules 2 and 3 with remaining tasks to be completed or inserted into this report	194

LIST OF TABLES

Table	Page
4.1 Definition of the symbols used on the PIE flow chart	7
4.2 Packing the fluence monitors from capsules 2 and 3	10
4.3 Measurement conditions for the stainless steel capsules 2 and 3.	26
4.4 Measurement conditions for the graphite bodies of capsules 2 and 3	27
4.5 Measurement conditions for the gamma scan wires from capsules 2 and 3	28
4.6 Impulses during gamma scan of gamma scan wire 2.1 from capsule 2	49
4.7 Impulses during gamma scan of gamma scan wire 2.2 from capsule 2	52
4.8 Impulses during gamma scan of gamma scan wire 2.3 from capsule 2	55
4.9 Impulses during gamma scan of gamma scan wire 3.1 from capsule 3	58
4.10 Impulses during gamma scan of gamma scan wire 3.2 from capsule 3	61
4.11 Impulses during gamma scan of gamma scan wire 3.3 from capsule 3	64
4.12 Measurement conditions for the graphite bodies of capsules 2 and 3	77
4.13 Components of the measuring facility	81
4.14 Error analysis	83
4.15 The measured activities (Bq) of selective isotopes of the fuel compacts from capsule 2 ..	84
4.16 The measured activities (Bq) of selective isotopes of the fuel compacts from capsule 3 ..	85
4.17 Dimensional measurements on eight compacts from hole 1 of capsules 2 and 3	87
4.18 Weight measurements of eight compacts from hole 1 of capsules 2 and 3	87
4.19 Measurements conditions for the graphite bodies of capsules 2 and 3	92
4.20 The inventory in the graphite cylindrical sector from capsule 2	100
4.21 The inventory in the graphite cylindrical sector from capsule 3	100
4.22 Error Analysis	103
4.23 Measurement configuration	104

LIST OF TABLES (continued)

4.24 The inventories (Bq) of the plugs and screws from capsule 2 for ^{125}Sb , ^{137}Cs , ^{134}Cs , $^{110\text{m}}\text{Ag}$, and ^{60}Co	105
4.25 The inventories (Bq) of the plugs and screws from capsule 3 for ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru and ^{60}Co	105
4.26 The inventories (Bq) of the graphite cylinders and sleeves from capsule 2 for ^{154}Eu , ^{137}Cs , ^{134}Cs , ^{60}Co , and ^{54}Mn	106
4.27 The inventories (Bq) of the graphite cylinders and sleeves from capsule 3 for ^{154}Eu , ^{137}Cs , ^{134}Cs , ^{133}Ba , ^{60}Co , and ^{54}Mn	106
4.28 The inventories (Bq) of the particle trays from capsule 2 and 3 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru and ^{60}Co	107
4.29 Distribution of cesium between the fuel compacts and the graphite in the fuel element	112
4.30 Summary of inventory measurements on the graphite components of the fuel element ..	114
4.31 Dimensional measurements on cylinders of grade H-451 and H-451I graphite from capsules 2 and 3	133
4.32 Weight measurements on cylinders of grade H-451 and H-451I graphite from capsules 2 and 3	134
4.33 Dimensional measurements on inert compacts and selected graphite annuli from capsules 2 and 3	135
4.34 Weight measurements on inert compacts and selected graphite annuli from capsules 2 and 3	136
4.35 Measurement configuration	142
4.36 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays in capsule 2	143
4.37 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays in capsule 2	143
4.38 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays in capsule 3	144
4.39 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays in capsule 3	144
4.40 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 2	149

LIST OF TABLES (continued)

4.41 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 2	149
4.42 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 3	150
4.43 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 3	150
4.44 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 2	155
4.45 Inventory (Bq) of the coatings kernels from fertile particles for selected nuclides from particle trays in capsule 2	155
4.46 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 3	156
4.47 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 3	156
4.48 Inventory (Bq) of bare kernels plus the associated coatings from fissile particles for selected nuclides from particle trays in capsule 2	161
4.49 Inventory (Bq) of bare kernels plus the associated coatings from fertile particles for selected nuclides from particle trays in capsule 2	161
4.50 Inventory (Bq) of bare kernels plus the associated coatings from fissile particles for selected nuclides from particle trays in capsule 3	162
4.51 Inventory (Bq) of bare kernels plus the associated coatings from fertile particles for selected nuclides from particle trays in capsule 3	162
4.52 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 2	163
4.53 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 2	163
4.54 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 3	164
4.55 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 3	164
4.56 Force and movement conditions under which fissile particles from capsule 2 crack	170
4.57 Force and movement conditions under which fertile particles from capsule 2 crack ...	170

LIST OF TABLES (continued)

4.58 Force and movement conditions under which fissile particles from capsule 3 crack	171
4.59 Force and movement conditions under which fertile particles from capsule 3 crack . . .	171
4.60 Technical data for the KORA facility	176
4.61 Property data on the fuel compacts and fuel kernels used in the heating tests with intermitent injections of water vapor	178
4.62 Irradiation conditions, ^{85}Kr inventory at the beginning of test and test conditions for the fuel compacts and fuel kernels used in the heating tests with intermittent injections of water vapor	179
4.63 The fractional release and release rate of ^{85}Kr at 800°C from compacts 2.2.1 and 2.2.2 as a function of time and the partial pressure of water vapor	181
4.64 The fractional release and release rate of ^{85}Kr at 800°C from compacts 3.2.1 and 3.2.2 as a function of time and the partial pressure of water vapor	184
4.65 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor	190
4.66 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor	193

INTERIM REPORT ON THE POST IRRADIATION EXAMINATION OF CAPSULES 2 AND 3 OF THE HFR-B1 EXPERIMENT

B. F. Myers

ABSTRACT

This is an interim report on the post irradiation examination (PIE) of capsules 2 and 3 of the HFR-B1 experiment. The PIE has been conducted by the Forschungszentrum Jülich and is nearing completion. After disassembly of the capsules, the examination focused on capsule components including fuel compacts, inert compacts fired in different media, graphite cylinders of different grades, unbonded coated fuel particles and unfueled graphite; in addition, heating experiments with intermittent injections of water vapor were conducted using fuel compacts and the kernels of uranium oxycarbide. Measurement involved gamma scanning and counting, photography, metallography, dimensional and weight changes, burnup determination and fission product release.

1. INTRODUCTION

Capsules 2 and 3 were part of the HFR-B1 experiment. Experiment HFR-B1 was a cooperative experiment conducted under the *US/FRG Umbrella Agreement for Cooperation in Gas Cooled Reactor Development* at the Joint Research Centre, Petten, The Netherlands. The experiments were designed to provide for measurement of fission gas and metallic fission product release in simulated, prismatic core, fuel elements over the range of MHTGR normal operating conditions and in the presence of significant quantities of water vapor. The irradiation was begun in April 1987 and ended in July 1989, during which 445 effective full power days were accumulated.

Following the irradiation phase of experiment HFR-B1, the fuel elements were sent to the Forschungszentrum, Jülich GmbH (KFA) for postirradiation examination (PIE). The fuel elements were contained in three capsules designated 1, 2, and 3. The PIE of capsules 2 and 3 began in 1991 under the *US/FRG Umbrella Agreement for Cooperation in Gas Cooled Reactor Development*. This agreement was in force in 1991. By 1993, the support for work in gas-cooled reactor research had largely been terminated at the KFA and the *Umbrella Agreement* was no longer regarded as an appropriate basis by the KFA for cooperative work. As a consequence, the PIE of capsule 1 is being conducted under subcontract with the KFA.

2. OBJECTIVES OF CAPSULES 2 AND 3

The main objectives of capsules 2 and 3 were as follows:

1. measurement of the release of fission gas at temperatures near and above the upper limit of HTGR normal operating temperatures (capsule 2),

*Research sponsored by the Forschungszentrum Jülich GmbH, Jülich, Germany and by the Office of Advanced Reactor Programs, Division of HTGRs, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

2. measurement of the effect of hydrolysis on coated fuel particles with exposed uranium oxycarbide (UCO) kernels and on the surrounding fuel compact matrix and graphite (capsule 3),
3. measurement of the irradiation response of grades H-451 and H-451I graphite and of inert compacts fired in alumina and silicon carbide molds and,
4. provision of unbonded, coated fuel particles and of fuel compacts for use in postirradiation tests including the determination of the release of fission products from the kernels.

The most important measurements for capsules 2 and 3 were, however, the on-line fission gas release measurements during the irradiation. The resulting data satisfy objectives 1 and 2 above and provided the basis for the analysis of the effect of high temperatures and water vapor on fission gas release. The other objectives were, to a large degree, independent and supplemental.

3. CONFIGURATION OF CAPSULES 2 AND 3

A capsule consists of a stainless steel container which houses a cylindrical graphite body, heat shields, and fluence detectors, and has sweep gas inlet and outlet lines. The graphite body itself contains seven, full length holes in which are placed fuel compacts, inert compacts, graphite specimens, trays of unbonded particles and three, niobium-encapsulations.¹ A cross sectional view representative of capsules 2 and 3 is shown in Fig. 3.1. Perspective views of capsules 2 and 3 are shown in Figs. 3.2 and 3.3; in these figures, the numbers x.y.z indicate the capsule number (x), the hole number (y) and the axial stacking position (z). The stacking position numbers are ordered with number 1 in the top position. The fuel compacts are in holes 1, 2, and 3; the inert compacts and the graphite specimens are in holes 4, 5, and 6 and trays of unbonded particles are in the unnumbered central hole. Where the letters a and b are appended to the three number identification, there are, in those positions, a fuel compact and graphite sleeve, respectively.

4. PIE OF CAPSULES 2 AND 3

The PIE of capsules 2 and 3 consists essentially of five major tasks: (1) the disassembly of the capsules, and the examination of (2) the fuel compacts, (3) the unfueled graphite bodies, (4) the unbonded coated fuel particles and (5) the inert compacts and graphite specimens.

4.1 PIE TEST PLAN FOR CAPSULES 2 AND 3

The PIE test plan for capsules 2 and 3¹ is represented by the flow chart of Fig. 4.1. The definitions of the symbols used in the flow chart are presented in Table 4.1 and the icons are identified in Fig. 4.2. There are six tasks on the flow chart that were not done. These tasks involved measurements of the coefficient of thermal expansion (CTE) and Young's modulus (YM); the shipping of capsule 1 and encapsulated samples to ORNL; measurements of the gamma scan wires at the Joint Research Centre, Petten, The Netherlands (JRC); and heating of graphite sectors. Furthermore, the heating tests were altered by using only 2 fuel compacts per capsule and 10 unbonded fuel particles from capsule 3. The KFA hot cells did not have the equipment to measure the CTE and YM; the expense of shipping capsule 1 to ORNL and performing the PIE was too great and a subcontract was made with the KFA to conduct the PIE for the available funds. The gamma scan wires were measured at the KFA. The samples on which the KFA was requested to measure the CTE and YM can be readily shipped to the U.S. for measurements if requested. The same applies to the encapsulated samples as the necessary equipment to analyze them is at General Atomics (GA).

Fig. 3.1 Cross-sectional representative of capsules 2 and 3

Fig. 3.2 Perspective view of the contents of capsule 2
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 3.3 Perspective view of the contents of capsule 3
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.1 PIE flow chart for capsules 2 and 3

Table 4.1 Definitions of symbols used on the PIE flow chart

C_n	= capsule n or a component of capsule n
cph	= cutting plane, horizontal (h)
cpv	= cutting plane, vertical (v)
CTE	= coefficient of thermal expansion
DC	= deconsolidation including separation of parts
DM	= measurement of dimensions
FC	= fuel compacts
GC	= gamma counting to determine the quantity of fission products in the addressed component
GS	= gamma scan to determine the relative distribution of fission products along a selected direction of a component
HT	= heating tests
L	= leach
ME	= metallographic examination
m(x)	= maintain separation of components x [where x is identified in the definition of S(nx)] according to the definition in Table 5 of ref. 1
mx C^n	= number of components m from capsule n
PA	= partition measurements
Ph	= photograph
S(nx)	= selection of n components where x is given by c for compacts, g for graphite cylinders, p for particles, and t for tray
VE	= visual examination
WM	= weight measurement
YM	= measurement of Young's modulus
(1 ea)	= measurement to be made on one sample of each type from both C^2 and C^3
(x)	= number of measurements for the quantities defined above

ORNL-DWG 90-2282B

Fig. 4.2 Definition of icons used on the PIE flow chart

The flow chart, modified by deleting the tasks that could not be done at the KFA and by outlining the major tasks, is shown as Fig. 4.3.

4.2 DISASSEMBLY OF CAPSULES 2 AND 3

The three capsules of HFR-B1 were received by the KFA. Capsules 1 and 2 were joined by a cross bar; the cross bar was severed and capsule 1 was placed in storage in anticipation of shipping it the ORNL. The process and operations of disassembly are identified in Figs. 4.3, 4.2 and Table 4.1.

4.2.1 Visual Inspection and Photography²

The stainless steel capsules showed light, spotted red-brown discoloration on the outer surfaces. The overview appearances of capsule 2 are shown in Figs. 4.4 and 4.5 by photographs 468/26; /28; /31; /32; and /35. On capsule 2, the welding joint of the gas tube on the upper end plate is strongly corroded as shown in Fig. 4.5, photograph 468/36. The overview appearances of capsule 3 are shown in Figs. 4.6, 4.7, 4.8, 4.9, and 4.10. Capsule 3 exhibits corrosion on the lower welding joint, the joint for the thermocouple protection tube and on the exit gas tube on the end plate which shows light corrosion developing (see photographs 468/18; /19; /22; /23; /24; and 469/17-25; /31).

4.2.2 Capsule 2²

By circumferential grinding of the capsule at the level of the welding joints, the end plates were removed. The graphite appeared, after removing the heat shields, as shown in Fig. 4.11, photograph 468/40. The heat shields were warped but shiny and appeared as shown by the examples in Fig. 4.11, photographs 468/1 and 468/2. The gamma scan wires were removed and placed in aluminum cans. The thermoelements, shown in Fig. 4.11, photograph 468/4, exhibited no visible damage. Thereafter, the graphite body was removed from the remaining capsule. The visible inspection of the graphite body, as shown in Fig. 4.12, photographs 468/41-43, brought no special feature to light, all markings were well recognized.

To loosen the upper and lower flux monitors on the underside of the end plates (Fig. 4.11, photograph 468/2), the retaining bands were cut by means of a grinding disk. The flux monitors were removed from the encapsulations by grinding on a lathe with a special holding configuration. Thereafter, the capsule content was placed in an aluminum can.

4.2.3 Capsule 3²

The opening of capsule 3 was analogous to the procedure used for capsule 2. The thermoelements were easily pulled and there were no noteworthy features. The end plate, thermocouple protection tubes and adjacent heat shield are shown in Fig. 4.13, photographs 469/33-35. All protection tubes remained intact in the bore holes on the graphite body. The heat shields showed a light discoloration but were otherwise in order. The withdrawal of the gamma scan wires was arranged with more difficulty than in capsule 2. This difficulty may be the result of the oxidation of the niobium protection tubes by the water vapor added in the experiments in capsule 3. By pushing, the graphite bodies slid out to an extent that permitted their removal from the bore holes with forceps. Visual inspection of the graphite bodies found no special features. The bodies are shown in Fig. 4.14, photographs 469/30; /37; /41 and in Fig. 4.15, photographs 469/26-29. The inside of the stainless steel capsule is shown in Fig. 4.16, photographs 469/38-40.

The fluence detectors from capsules 2 and 3 were sent to Petten for evaluation on 12.02.91. The packing and identification of the fluence monitors is shown in Table 4.2. The steel capsules with end plates and heat shields were sent to the KFA hot cell 1 on 11.03.91.

Table 4.2 Packing the fluence monitors from capsules 2 and 3

<u>Can No.</u>	<u>Identification</u>		<u>Capsule No. & Detector Pos.</u>	<u>Remark Content</u>
	<u>upper</u>	<u>lower</u>		
5	xxxxx	o	2, north upper	in order
6	x	x	2, south upper	in order
7	xx	x	2, north lower	broken
8	xx	xx	2, south lower	broken
9	xxx	xx	3, north upper	broken
10	xxx	xxx	3, south upper	broken
11	xxxx	x	3, north lower	in order
12	xxxx	xx	3, south lower	in order

Fig. 4.3 Modified PIE flow chart with major tasks outlined for capsules 2 and 3

HFR-B1
Kapsel 2

468/26

468/28

468/31

Fig. 4.4 The overview appearances of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR B1
Kapsel 2

468135

468132

468136

Fig. 4.5 The overview appearances of the ends of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

468118

468119

Fig. 4.6 The appearances of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

468123

468124

468122

Fig. 4.7 View of the end plates of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

469117

469118

469119

469120

Fig. 4.8 Additional appearances of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.9 Further views of the end plates of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

469123

469122

469121

HFR-B1
Kapsel 3

HFR-B1
Kapsel 3

469124

469125

469131

Fig. 4.10 Detailed views of the end plates of capsule 3 and a heat shield
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

468142

468143

468141

Fig. 4.11 Selected views of components after opening capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

*HFR B1
Kapsel 2*

468140

Oberer Wärmeschild - oben

46812

Oberer Wärmeschild - unten

46811

46814

Fig. 4.12 Selected views of the graphite body in capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

469134

469135

469133

Fig. 4.13 Removal of the end plate, thermocouple protection tubes and adjacent heat shield
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

469130

469137

469141

Fig. 4.14 Selected views of the graphite body in capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

469126

469127

28

29

Fig. 4.15 Selected views of the ends of the graphite body in capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

Stahl Kapsel
innen

469138

39

40

Fig. 4.16 Views of the inside of the stainless steel capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

4.2.4 Gamma Scanning

As a part of the disassembly of the capsules, gamma scans have been made of the steel-encased graphite bodies³, of the graphite bodies after removal from the steel containers⁴ and of the three gamma scan wires⁵ in each capsule.

4.2.4.1 Apparatus

The measuring apparatus is in the Brennstoffzellenlabor (BZL) of the hot cells (HZ). It consists of a measurement bench which is installed horizontally parallel to the cell wall in cell 3. A step motor drives a carriage along the bench. A mechanical counter on the spindle controls the set distance.

A passage in the cell wall between the measuring bench and the outside of the cell serves for the insertion of the collimator with different narrow, high slits, which are aligned at right angles to movement path of the carriage. Gamma rays travel through the collimator to a crystal of pure germanium. The impulses produced in the detector by the gamma quanta are amplified and lead to a gamma scan system which is installed in a personal computer.

4.2.4.2 Measurements

Measurements were made with the three types of sample: the stainless steel capsule and contents, the graphite body and the gamma scan wires. The latter were removed from the niobium tubes in which they were irradiated and placed, for the scans, in steel tubes with a 6mm outer diameter and a wall thickness of 1 mm.

The samples were laid in the receiving cradle of the carriage and so aligned, in the cases of the stainless steel capsules and the graphite bodies, that a fuel hole was in line with the detector. Then a sample was moved before the collimator slit. In this position, a suitable collimator was chosen and then a gamma spectrum taken. With this spectrum, the energy window, in which the peak of the interesting nuclide occurred, was determined; likewise the measurement time at the measurement point. The stainless steel capsules, the graphite bodies, and the gamma scan wires were measured at each measurement point for 500 s except for gamma scan wire number 1 in capsule 3. In the latter case the measurement time was 300 s; the results were corrected to a measurement time of 500 s.

Thereafter, the beginning of the sample was placed before the collimator opening and the step motor with the chosen step width started. For each step a gamma spectrum was taken. With this, in the energy region of the individual peaks, the net peak areas were determined. To that end, the impulse numbers were summed and the spectrum background, an average value of the impulse number calculated from the three channels, left and right of the photopeak, subtracted. Per sample, three scans were made, in the cases of the stainless steel capsules and the graphite bodies, whereby each of the three fuel holes in turn was aligned to the detector. The peak net areas were stored in the PC and after the end of the scans were transferred to a spreadsheet. Here, the results were back calculated to a common date, 22.1.91. the date of the first measurement in the cases of the stainless steel capsules and the graphite bodies and to 1.3.91 in the case of the gamma scan wires.

The instruments and conditions of the measurements for the stainless steel capsules, for the graphite bodies they contained and the gamma scan wires are given in Tables 4.3, 4.4 and 4.5, respectively.

Table 4.3 Measurement conditions for the stainless steel capsules 2 and 3

Collimator: Length	545 mm
Slit Height	60 mm
Slit Width	0.5 mm
Measurement Distance	930 mm
Step Length	1 mm
Measurement Time at each point	100 s
Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-2300 V
Relative Efficiency	3.5%
Preamplifier	DSG
Main Amplifier	ORTEC Nr. 573
High Voltage Apparatus	Schlumberger 219
Reference Pulser	Canberra 1501
Personal Computer	Compaq Deskpro 386/20
Spread Sheet	Microsoft Excel
Gammascan-System	ORTEC Maestro
Measured Energy Range	2 to 1670 KeV
Energy Windows	⁶⁰ Co 1323 to 1342 KeV
	⁵⁴ Mn 624 to 845 KeV
	¹³⁴ Cs 598 to 612 KeV
	¹³⁷ Cs 654 to 670 KeV

Table 4.4 Measurement conditions for the graphite bodies of capsules 2 and 3

Collimator:	Length	545 mm
	Slit Height	10 mm
	Slit Width	1 mm
	Measurement Distance	930 mm
	Step Length	1 mm
	Measurement Time at each point	500 s
Detector	DSG Typ PGP 1516 SNG-167 planar	
Voltage	-2300 V	
Relative Efficiency	3.5%	
Preamplifier	DSG	
Main Amplifier	ORTEC Nr. 573	
High Voltage Apparatus	Schlumberger 219	
Reference Pulser	Canberra 1501	
Personal Computer	Compaq Deskpro 386/20	
Spread Sheet	Microsoft Excel	
Gammascan-System	ORTEC Maestro	
Measured Energy Range	20 to 1670 KeV	
Energy Windows;	¹⁴⁴ Ce	129 to 140 KeV
	¹³⁴ Cs	598 to 612 KeV
	¹⁰⁶ Ru	616 to 629 KeV
	¹³⁷ Cs	654 to 670 KeV
	⁹⁵ Zr	715 to 732 KeV
	¹⁵⁴ Eu	1267 to 1283 KeV
	⁶⁰ Co	1323 to 1342 KeV

Table 4.5 Measurement conditions for the gamma scan wires from capsules 2 and 3

Collimator:	Length	545 mm
	Slit Height	30 mm
	Slit Width	5 mm
	Measurement Distance	930 mm
	Step Length	1 mm
	Measurement Time at each point	500 s (300 s)
Detector	DSG Typ PGP 1516 SNG-167 planar	
Voltage	-2300 V	
Relative Efficiency	3.5%	
Preamplifier	DSG	
Main Amplifier	ORTEC Nr. 573	
High Voltage Apparatus	Schlumberger 219	
Reference Pulser	Canberra 1501	
Personal Computer	Compaq Deskpro 386/20	
Spread Sheet	Microsoft Excel	
Gammascan-System	ORTEC Maestro	
Measured Energy Range	2 to 1670 KeV	
Energy Windows	⁶⁰ Co	1323 to 1342 KeV
	⁵⁴ Mn	624 to 845 KeV

4.2.4.3 Results

The gamma scans of the stainless steel capsule, having the graphite bodies within, for the nuclides ^{137}Cs , ^{134}Cs , ^{60}Co , and ^{54}Mn are presented in Figs. 4.17 through 4.31. The figures show the relative activity distributions of the three aligned capsules oriented by rotation so that each of the fuel holes with their complement of fuel compacts was, in turn, scanned in the axial direction. The activities (impulses) are referenced to the common date 22.1.91. The capsules are ordered as they were positioned during the irradiation. The activity profiles for ^{60}Co , which have the least scatter, qualitatively match the axial profile of burnup⁶ for the three capsules.

The gamma scans of the fueled graphite bodies for the nuclides ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru , ^{95}Zr , and ^{60}Co are presented in Figs. 4.32 through 4.37. In Fig. 4.37, the relatively large activity in capsule 3 for ^{60}Co results from the gamma scan wire assembly stuck in graphite body 3. The spectrum of the graphite body from capsule 2 is shown in Fig. 4.38.

The gamma scans of the three gamma scan wires, 1, 2, and 3, for the nuclides ^{54}Mn and ^{60}Co are presented in Figs. 4.39 through 4.44. The capsules are ordered in the figures as they were positioned during the irradiation. Measurements for the nuclides ^{51}Cr and ^{58}Co were not successful as the dead time was too long. In tables 4.6 through 4.11, the gamma scan measurements are presented; all measurements have been corrected to the common time of 1.3.91.

4.2.5 Remaining Tasks

Two tasks in the disassembly remain to be done or reported. The leaching of the inside surfaces of the stainless steel capsules remains to be done. The results of gamma counting the graphite caps and plugs from the disassembly are report below in Sect. 6 on the examination of the unfueled graphite bodies.

4.3 EXAMINATION OF FUEL COMPACTS

In each of capsules 2 and 3 there were three fuel holes and in each fuel hole there were four compacts. The examination of these fuel compacts involved visual inspection and photography, gamma counting, dimensional and weight measurements, metallography, fission product distribution between the fuel compacts and the contiguous graphite and deconsolidation. The process and operations of examining the fuel compacts are identified in Figs. 4.3, 4.2 and Table 4.1.

4.3.1 Visual Inspection and Photography²

In each capsule, fuel hole number 1 was opened for inspection and photography of the contents.

4.3.1.1 Capsule 2²

By means of a specially made screw apparatus equipped with a small borehole, the end plate of the fuel hole was opened. A glance into the channel showed that several small broken pieces of the compact lay loosely. By means of a dust filter nozzle, the four fuel compacts which stood loose in the fuel hole were now removed and a white mark made on the upper end. Because the compacts stood loose in the fuel hole, marking the orientation of the upper compact in the channel was waived. Photographs of four views of each fuel compact from fuel hole 1 of the graphite body are shown in Fig. 4.45, photographs 472/24-27, Fig. 4.46, photographs 472/28-31, Fig. 4.47, photographs 472/32-35 and Fig. 4.48, photographs 473/1-4.

Abb. 1a

HFR-B1 Stahlkapseln
Brennstoffkanal 1 zum Detektor
Co 60 (1333 keV)

Fig. 4.17 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 1
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 1b

HFR-B1 Stahlkapseln
Brennstoffkanal 1 zum Detektor
Co 60 (1333 keV)

Fig. 4.18 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 1 (enlarged)
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.19 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 1
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.20 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 1
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 1e

HFR-B1 Stahlkapseln
Brennstoffkanal 1 zum Detektor
Mn 54 (835 keV)

Fig. 4.21 Gamma scan of the steel capsule for ^{54}Mn focused on fuel hole 1
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 2a

HFR-B1 Stahlkapseln
Brennstoffkanal 2 zum Detektor
Co 60 (1333 keV)

Fig. 4.22 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 2b

HFR-B1 Stahlkapseln
Brennstoffkanal 2 zum Detektor
Co 60 (1333 keV)

Fig. 4.23 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 2 (enlarged)
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 2c

HFR-B1 Stahlkapseln
Brennstoffkanal 2 zum Detektor
Cs134 (605 keV)

Fig. 4.24 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 2d

HFR-B1 Stahlkapseln
Brennstoffkanal 2 zum Detektor
Cs 137 (662 keV)

Fig. 4.25 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 2e

HFR-B1 Stahlkapseln
Brennstoffkanal 2 zum Detektor
Mn 54 (835 keV)

Fig. 4.26 Gamma scan of the steel capsule for ^{54}Mn focused on fuel hole 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 3a

HFR-B1 Stahlkapseln
Brennstoffkanal 3 zum Detektor
Co 60 (1333 keV)

Fig. 4.27 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 3
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 3a

HFR-B1 Stahlkapseln
Brennstoffkanal 3 zum Detektor
Co 60 (1333 keV)

Fig. 4.28 Gamma scan of the steel capsule for ^{60}Co focused on fuel hole 3 (enlarged)
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 3c

HFR-B1 Stahlkapseln
Brennstoffkanal 3 zum Detektor
Cs134 (605 keV)

Fig. 4.29 Gamma scam of the steel capsule for ^{134}Cs focused on fuel hole 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 3d

HFR-B1 Stahlkapseln
Brennstoffkanal 3 zum Detektor
Cs137 (662 keV)

Fig. 4.30 Gamma scam of the steel capsule for ^{137}Cs focused on fuel hole 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 3e

HFR-B1 Stahlkapseln
Brennstoffkanal 3 zum Detektor
Mn 54 (835 keV)

Fig. 4.31 Gamma scan of the steel capsule for ^{54}Mn focused on fuel hole 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.32 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{144}Ce
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.33 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{134}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.34 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{137}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.35 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{106}Ru
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.36 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{95}Zr
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.37 Gamma scan of graphite bodies 2 and 3 focused on fuel holes 1, 2, and 3 for ^{60}Co
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.38 The gamma spectrum of the graphite body from capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.39 Gamma scan of the gamma scan wires 3.1 and 2.1 for ^{60}Co in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.40 Gamma scan of the gamma scan wires 3.1 and 2.1 for ^{54}Mn in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.41 Gamma scan of the gamma scan wires 3.2 and 2.2 for ^{60}Co in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.42 Gamma scan of the gamma scan wires 3.2 and 2.2 for ^{54}Mn in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.43 Gamma scan of the gamma scan wires 3.3 and 2.3 for ^{60}Co in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.44 Gamma scan of the gamma scan wires 3.3 and 2.3 for ^{54}Mn in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.6 Impulses during gamma scan of gamma scan wire 2.1 from capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement date: 18.3.91
Measurement time: 500 s/point
Data corrected to: 1.3.91

Step size: 1 mm
Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
0	45	57	23	8663	76799
1	6	2	24	9256	76744
2	0	47	25	9123	76506
3	0	33	26	9618	76908
4	64	142	27	0009	77330
5	40	539	28	9353	77137
6	371	3100	29	8222	76348
7	991	9589	30	9655	77474
8	2180	18728	31	9625	76948
9	3131	28757	32	9654	76841
10	4009	38172	33	10346	77207
11	6094	47143	34	9663	76787
12	6402	56228	35	9248	77249
13	7220	65017	36	8779	77288
14	7896	71231	37	8710	76814
15	8966	74328	38	9305	77467
16	9037	74773	39	9507	76640
17	10316	74252	40	9469	77291
18	8968	76461	41	9447	77246
19	8516	76696	42	8210	76782
20	9959	76357	43	10061	76149
21	9768	76696	44	9400	76981
22	9740	76866	45	9532	77286

^(a) $I(t)$ = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.6 (Continued)

Measurement date: 18.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
46	9527	77051	69	9288	78199
47	10285	76685	70	9626	77234
48	8611	77288	71	9958	77377
49	9086	76898	72	8786	77796
50	9575	77094	73	9693	77912
51	8817	77551	74	9471	77677
52	8817	77551	75	10602	77666
53	10431	76741	76	9816	77603
54	9752	76383	77	9380	77811
55	9635	76705	78	10071	78360
56	9355	76850	79	9701	77391
57	9538	76981	80	9722	77633
58	9507	77384	81	10066	77461
59	9763	77172	82	10691	77902
60	9611	77381	83	9779	77630
61	9608	76936	84	9872	77534
62	9559	77315	85	10874	77541
63	10294	77666	86	9733	76670
64	9410	77590	87	9628	75772
65	9367	77955	88	9391	75175
66	9769	77961	89	9169	76144
67	9168	78652	90	9135	75082
68	10242	77909	91	9529	75633

Table 4.6 (Continued)

Measurement date: 18.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn:I(t)}^{(s)}$	$^{60}\text{Co:I(t)}^{(s)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(s)}$	$^{60}\text{Co:I(t)}^{(s)}$
92	9091	74794	101	132	985
93	8813	70645	102	114	77
94	8062	63568	103	0	39
95	7074	54006	104	51	61
96	5814	44284	105	22	37
97	4155	34099	106	57	50
98	2775	23733	107	0	36
99	1726	13844	108	0	49
100	482	5680	109	0	31

Table 4.7 Impulses during gamma scan of gamma scan wire 2.2 from capsule 2

Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement date: 19.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
0	16	44	23	11298	79718
1	0	49	24	11522	79047
2	0	46	25	11850	79675
3	106	70	26	10684	79501
4	51	134	27	10817	79409
5	68	565	28	11244	79576
6	326	3250	29	10967	79208
7	1080	9664	30	11634	79625
8	2021	19878	31	11033	79700
9	3382	29854	32	10723	79866
10	5999	40115	33	11436	78581
11	5774	50933	34	11457	79467
12	8540	61480	35	10197	78985
13	9441	69756	36	10598	79001
14	10470	75033	37	11229	79321
15	11101	76967	38	11235	79620
16	10552	77100	39	10742	78992
17	11136	76695	40	10907	79557
18	10503	77198	41	11030	79602
19	9731	76915	42	10859	79059
20	10602	78196	43	11226	79233
21	10157	78785	44	10516	79301
22	10801	79308	45	11678	79322

^(a) $I(t)$ = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.7 (Continued)

Measurement date: 19.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
46	10844	79024	69	10201	79191
47	10542	79861	70	11540	78784
48	11122	79532	71	11521	78795
49	10874	79173	72	11223	78540
50	11311	79369	73	11264	78998
51	10972	80321	74	11210	79198
52	11147	79485	75	10522	78842
53	11894	78803	76	10122	79122
54	11044	79354	77	10833	78719
55	11523	79714	78	10977	79476
56	10487	79155	79	11325	78916
57	11061	79496	80	11171	78904
58	11403	79550	81	11350	78754
59	11723	79490	82	11135	78431
60	11650	79738	83	10910	79113
61	11620	79382	84	11156	78466
62	11444	79129	85	11298	78640
63	11060	79449	86	11053	78987
64	10829	79060	87	11621	78414
65	11189	78933	88	9975	78451
66	11584	78927	89	10450	76830
67	11083	78623	90	10311	76581
68	11694	78683	91	10413	74664

Table 4.7 (Continued)

Measurement date: 19.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
92	10170	70262	101	0	72
93	8505	61930	102	21	50
94	6744	51323	103	12	70
95	5371	43097	104	2	38
96	3933	32297	105	40	34
97	2595	22727	106	52	18
98	1983	13142	107	91	21
99	599	5325	108	0	53
100	20	915	109	0	40

Table 4.8 Impulses during gamma scan of gamma scan wire 2.3 from capsule 2

Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement date: 20.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
0	0	68	23	10816	77856
1	5	60	24	10564	77880
2	5	85	25	10937	78548
3	0	71	26	10546	78158
4	0	74	27	9456	77944
5	27	176	28	11050	78822
6	32	513	29	11138	78159
7	256	2631	30	10290	78254
8	1131	8554	31	10597	79298
9	2105	18305	32	9861	78327
10	3873	28498	33	9978	77968
11	4451	38722	34	10902	78013
12	6907	48898	35	9899	77717
13	7300	58945	36	10092	78318
14	8778	67894	37	10811	78488
15	9253	738377	38	10518	77838
16	10276	74987	39	11098	78541
17	11024	70209	40	10353	79006
18	9710	75856	41	10427	78807
19	10328	76049	42	10617	78220
20	9588	76233	43	11169	77859
21	9805	76267	44	11143	78204
22	9871	76446	45	11101	78473

^(a) $I(t)$ = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.8 (Continued)

Measurement date: 20.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
46	10315	78600	69	10278	79564
47	10184	78732	70	10516	79373
48	10007	78218	71	10252	78809
49	11158	79322	72	11268	79295
50	10945	78985	73	9953	79161
51	10444	78527	74	11649	78876
52	10212	78718	75	10980	79720
53	10997	78051	76	10851	78952
54	10371	78566	77	10114	79363
55	10544	78438	78	11353	79219
56	11024	78150	79	11660	78969
57	10384	78081	80	11339	79144
58	10463	78618	81	10403	79378
59	10344	77854	82	11260	78861
60	10877	78513	83	10409	78841
61	11502	78768	84	10484	79083
62	10661	79091	85	10799	78703
63	10750	79247	86	10583	79134
64	11013	78750	87	10902	79054
65	11059	79414	88	10695	78807
66	10903	78552	89	10981	77724
67	10349	79141	90	10477	77489
68	10744	78936	91	10283	76605

Table 4.8 (Continued)

Measurement date: 20.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
92	9742	74699	101	140	380
93	9868	69201	102	50	112
94	8552	59204	103	35	24
95	6535	49214	104	85	50
96	4887	39469	105	0	45
97	4140	29737	106	41	40
98	2671	19907	107	30	60
99	1235	10600	108	54	76
100	132	3545	109	0	39

Table 4.9 Impulses during gamma scan of gamma scan wire 3.1 from capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany
Measurement date: 6.3.91 Step size: 1 mm
Measurement time: 500 s/point Collimator: 5 x 30 mm
Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
0	27	65	23	6406	56564
1	32	45	24	5715	56528
2	45	28	25	6622	57031
3	35	67	26	6603	56556
4	54	72	27	6622	56482
5	66	267	28	6087	57005
6	170	1461	29	6268	57922
7	604	5279	30	6552	57750
8	888	12020	31	6457	57745
9	2011	19629	32	5507	57431
10	2192	25987	33	6530	57354
11	3432	32982	34	6815	58711
12	3331	39113	35	6628	57519
13	5267	45960	36	6809	57891
14	5776	50937	37	5316	58875
15	5042	53806	38	6734	58814
16	5665	53487	39	6860	59162
17	5239	53261	40	6434	58287
18	5302	54975	41	6746	59315
19	5639	55093	42	6305	59044
20	6205	55771	43	5739	59873
21	6839	56044	44	6976	59636
22	5212	56031	45	6587	60388

^(a) $I(t)$ = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.9 (Continued)

Measurement date: 6.3.91
 Measurement time: 500 s/point
 Data corrected to: 1.3.91

Step size: 1 mm
 Collimator: 5 x 30 mm

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
46	6772	59847	69	8459	65941
47	6503	60974	70	7147	65740
48	7230	60400	71	7035	66659
49	6367	60698	72	7549	66330
50	8085	60800	73	7385	66616
51	7200	60773	74	6730	67923
52	6364	61644	75	8027	67311
53	7246	61869	76	7446	67080
54	8126	62663	77	7686	67104
55	7500	61780	78	7731	67663
56	7108	62195	79	8465	68000
57	7655	62823	80	8194	69205
58	7414	62474	81	8008	68611
59	7435	63003	82	7074	68874
60	6642	63189	83	8178	69038
61	6458	63975	84	6852	69291
62	6549	63565	85	8165	69110
63	7285	64112	86	8650	69331
64	7840	63839	87	9303	68095
65	7185	65232	88	7616	68440
66	7716	64395	89	8321	69085
67	7703	64774	90	7901	69040
68	7909	64714	91	7957	68669

Table 4.9 (Continued)

Measurement date: 6.3.91 Step size: 1 mm
 Measurement time: 500 s/point Collimator: 5 x 30 mm
 Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
92	8275	65327	101	42	132
93	6654	59441	102	5	57
94	5526	50653	103	54	28
95	5028	41882	104	0	33
96	4000	32506	105	0	22
97	3339	23777	106	0	50
98	1343	14362	107	56	17
99	553	6405	108	3	45
100	145	1479	109	0	42

Table 4.10 Impulses during gamma scan of gamma scan wire 3.2 from capsule 3

Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement date: 7.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
0	9	9	23	7166	56489
1	25	15	24	6774	56998
2	39	38	25	6720	57206
3	19	72	26	7439	56706
4	59	68	27	6876	57419
5	66	263	28	7671	57266
6	229	1458	29	7212	57696
7	452	5315	30	7829	57806
8	1193	11997	31	7346	57897
9	2170	19193	32	7389	58208
10	2609	26244	33	7033	58149
11	4175	33739	34	7100	58050
12	4724	40702	35	7127	58072
13	5957	47753	36	7256	57969
14	5847	52070	37	7625	58293
15	6545	55516	38	8078	59052
16	6446	55839	39	7636	59820
17	7184	55778	40	8599	58503
18	6660	56325	41	7395	60225
19	6283	55507	42	7894	59915
20	6402	56075	43	8491	60039
21	7094	56489	44	7941	59967
22	7246	56312	45	7872	60450

^(a) I(t) = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.10 (Continued)

Measurement date: 7.3.91 Step size: 1 mm
 Measurement time: 500 s/point Collimator: 5 x 30 mm
 Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn}:I(t)^{(s)}$	$^{60}\text{Co}:I(t)^{(s)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(s)}$	$^{60}\text{Co}:I(t)^{(s)}$
46	8351	60300	69	8137	65805
47	8134	60156	70	8743	65679
48	7405	61284	71	8749	66810
49	8184	61180	72	8769	67006
50	8939	61984	73	8160	67150
51	8324	61137	74	9074	67345
52	8994	62141	75	8717	68090
53	8124	61574	76	8463	67634
54	8174	62335	77	9114	68290
55	8494	62378	78	9225	67375
56	8329	62578	79	9055	66941
57	8262	62111	80	8750	67109
58	8468	63097	81	8557	67528
59	8853	62856	82	8654	67298
60	9171	63331	83	9002	68082
61	8768	64131	84	8608	68828
62	8578	64148	85	8751	69871
63	8745	64187	86	9324	70645
64	8915	65274	87	8582	71772
65	8785	64917	88	9630	72742
66	8331	65642	89	9634	73141
67	8412	65130	90	9730	73014
68	8185	65798	91	9315	72123

Table 4.10 (Continued)

Measurement date: 7.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
92	7939	68669	101	20	106
93	7414	62353	102	39	50
94	7167	52631	103	23	12
95	5428	42968	104	89	12
96	4125	33269	105	0	6
97	2906	23556	106	10	6
98	1720	14193	107	0	27
99	726	6202	108	0	17
100	93	1394	109	80	40

Table 4.11 Impulses during gamma scan of gamma scan wire 3.3 from capsule 3

Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement date: 8.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$	Distance (mm)	$^{54}\text{Mn}:I(t)^{(a)}$	$^{60}\text{Co}:I(t)^{(a)}$
0	43	51	23	6676	56751
1	0	13	24	7543	57360
2	0	40	25	6902	56850
3	0	01	26	7445	57151
4	75	40	27	6423	57285
5	0	196	28	7215	57236
6	0	802	29	6994	57015
7	281	3497	30	7176	57414
8	868	9124	31	7029	57439
9	2030	16496	32	6915	57623
10	2715	23903	33	7358	57468
11	3219	30865	34	6552	57270
12	4005	38290	35	7691	58345
13	5303	45498	36	6495	56769
14	5364	51281	37	7203	57534
15	6645	55363	38	6890	57862
16	5733	55888	39	6867	58029
17	6390	55955	40	6505	57994
18	6681	56291	41	7896	58465
19	6330	56025	42	7873	59101
20	6251	56436	43	7062	58696
21	7001	56343	44	7447	59013
22	6616	57017	45	7300	59451

^(a) $I(t)$ = impulses/500s at 835 KeV for ^{54}Mn and 1333 KeV for ^{60}Co

Table 4.11 (Continued)

Measurement date: 8.3.91 Step size: 1 mm
 Measurement time: 500 s/point Collimator: 5 x 30 mm
 Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(a)}$	$^{60}\text{Co:I(t)}^{(a)}$
46	7519	59902	69	7641	64704
47	7672	59660	70	8389	65098
48	7319	59698	71	8498	65271
49	7282	59667	72	8273	65391
50	7388	60257	73	8217	66611
51	7944	60610	74	8877	65988
52			75	8350	66519
53	7788	61022	76	8067	65911
54	8071	61539	77	8447	65816
55	7165	61481	78	8660	65567
56	8204	62154	79	8486	65712
57	7969	61777	80	7817	65307
58	7762	62755	81	7710	66069
59	8365	62440	82	8506	65828
60	8029	63079	83	7912	66869
61	7435	62414	84	8480	67783
62	7705	63593	85	9035	68240
63	8074	63743	86	9226	69530
64	7786	63802	87	9318	70638
65	7996	63309	88	8724	70394
66	7870	64364	89	8968	71209
67	8220	64623	90	8712	71406
68	7605	64266	91	9509	70694

Table 4.11 (Continued)

Measurement date: 8.3.91

Step size: 1 mm

Measurement time: 500 s/point

Collimator: 5 x 30 mm

Data corrected to: 1.3.91

Distance (mm)	$^{54}\text{Mn:I(t)}^{(s)}$	$^{60}\text{Co:I(t)}^{(s)}$	Distance (mm)	$^{54}\text{Mn:I(t)}^{(s)}$	$^{60}\text{Co:I(t)}^{(s)}$
92	8609	68999	101	37	160
93	7990	62553	102	0	52
94	6839	53586	103	0	18
95	6100	44072	104	30	36
96	4458	34563	105	0	66
97	3060	25319	106	21	21
98	2185	16083	107	0	6
99	1167	7706	108	0	19
100	177	2128	109	13	13

HFR-B1
Kapsel 2

K 2.1.1

472 / 24

472 / 25

472 / 26

472 / 27

Fig. 4.45 Four views of the fuel compact from position 1 in hole 1 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1Kapsel 2

K2.1.2

472/28

472/29

472/30

472/31

Fig. 4.46 Four views of the fuel compact from position 2 in hole 1 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2
K 2.1.3

472/32

472/33

472/34

472/35

Fig. 4.47 Four views of the fuel compact from position 3 in hole 1 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2
K.2.1.4

47311

47312

47313

47314

Fig. 4.48 Four views of the fuel compact from position 4 in hole 1 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

4.3.1.2 Capsule 3²

Here, the screw cap could be easily twisted off. On the top of the uppermost compact, there lay about ten individual particles which, to be sure, were broken from the compact surface. Removing the loose coated particles to a filter by suction allowed one to see that the compacts lay loose in the borehole and could rotate. On this basis, also here a marking of the north side was waived. However, a white mark was put on top of all four compacts. The three other compacts were lightly held in the borehole and could be pressed out however from the underside of the fuel hole. Photographs of four views of each fuel compact from fuel hole 1 of the graphite body are shown in Fig. 4.49, photographs 470/29-32, Fig. 4.50, photographs 471/38-41, Fig. 4.51, photographs 471/0-2, and 471/42 and Fig. 4.52, photographs 471/3-6. The loose particles observed upon opening capsule 3 are shown in Fig. 4.53, photograph 480/18.

4.3.2 Gamma Scanning

The fuel compacts were gamma scanned⁴ after removal of them from the graphite bodies. The apparatus and the measurements are essentially described in paragraphs 4.2.4.1 and 4.2.4.2. The instruments and conditions of the measurements for the fuel compacts are presented in Table 4.12.

The gamma scans of the fuel compacts from hole 1 of capsules 2 and 3 are shown in Figs. 4.54 and 4.55 for the nuclides ¹⁴⁴Ce, ¹³⁴Cs, ¹³⁷Cs, ¹⁰⁶Ru, ⁹⁵Zr and ¹⁵⁴Eu. The spectrum for fuel compact 2.1.1 of hole 1 in capsule 2 is shown in Fig. 4.56.

4.3.3 Gamma Counting

The inventory of selected fission products was determined⁷ from measurement of the gamma radiation on all 24 fuel compacts from graphite bodies 2 and 3. The fuel compacts were designated according to their position during the irradiation. The first number designates the capsule, the second, the fuel hole, and the third the position of the compact in the fuel hole numbered from top to bottom.

4.3.3.1 Apparatus

The measuring apparatus is located in the Brennstoffzellenlabor of the hot cells. It consists of a rotatable specimen table in the cell, a double collimator [doppelkonuskollimator] in the cell wall and a planar germanium detector in the service area. The nuclear electronics, a multichannel analyzer, a PC with gamma analysis and evaluation software are located in the service area. The components of the apparatus are identified in Table 4.13.

4.3.3.2 Measurements

The fuel compacts were packed in aluminum cans of 20 mm diameter and 0.3 mm wall thickness, and stood on a slowly rotating turntable during the measurements.⁷ The gamma radiation encountered the germanium detector in passing through the shuttered double collimator (doppelkonuskollimator). The impulse produced in the detector was amplified and collected as a spectrum in the multichannel analyzer. The spectrum was transferred to a PC and evaluated therewith.

HFR-B1
K.3.1.1

470129

470130

470132

470131

Fig. 4.49 Four views of the fuel compact from position 1 in hole 1 of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
K.3.1.2

471138

471139

471140

471141

Fig. 4.50 Four views of the fuel compact from position 2 in hole 1 of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1

K.3.1.3

471142

47110

47111

47112

fig. 4.51 front views of the fuel compact from position 3 in hole 1 of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

47113
K.3.1.4

47113

47114

47115

47116

Fig. 4.52 Four views of the fuel compact from position 4 in hole 1 of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR B1
Kapsel 3

Brennstoff
Kanal 1

470118

Fig. 4.53 View of the loose particles upon opening fuel hole 1 of capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.12 Measurement conditions for the graphite bodies of capsules 2 and 3

Collimator: Length	545 mm
Slit Height	30 mm
Slit Width	0.5 mm
Measurement Distance	930 mm
Step Length	1 mm
Measurement Time at each point	1000 s
Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-2300 V
Relative Efficiency	3.5%
Preamplifier	DSG
Main Amplifier	ORTEC Nr. 573
High Voltage Apparatus	Schlumberger 219
Reference Pulser	Canberra 1501
Personal Computer	Compaq Deskpro 386/20
Spread Sheet	Microsoft Excel
Gammascan-System	ORTEC Maestro
Measured Energy Range	20 to 1670 KeV
Energy Windows:	
^{144}Ce	129 to 140 KeV
^{134}Cs	598 to 612 KeV
^{106}Ru	616 to 629 KeV
^{137}Cs	654 to 670 KeV
^{95}Zr	715 to 732 KeV
^{154}Eu	1267 to 1283 KeV
^{60}Co	1323 to 1342 KeV

Fig. 4.54 Gamma scan of the fuel compacts from hole 1 of capsules 2 and 3 for ^{144}Ce , ^{134}Cs , and ^{137}Cs Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.55 Gamma scan of the fuel compacts from hole 1 of capsules 2 and 3 for ^{106}Ru , ^{95}Zr , and ^{154}Eu Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.56 The gamma spectrum of the fuel compact 2.1.1 hole 1, capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.13 Components of the measuring facility

Turning apparatus:	5 rotations/min
Double collimator:	
smallest slit	0.8 mm
opening angle	3°
measurement distance (narrow collimator - turn table center)	209 mm
Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-2300 V
Relative Efficiency	3.5%
Preamplifier	DSG 51 P
Main Amplifier	ORTEC Nr. 573
High Voltage Apparatus	Schlumberger 219
Reference Pulser	Canberra 1501
Multichannel analyzer	Canberra 35 plus
Personal Computer	Compaq Deskpro 386/20
Gamma analysis and evaluation system	Canberra Spectran F

The measurement configuration was calibrated with an AVR fuel element whose ^{137}Cs inventory had been determined by comparison with a standard from the firm Buchler. This fuel element likewise was measured in an aluminum can with 0.3 mm wall thickness. The different self absorption of the calibrated fuel element and of the fuel compacts was taken into account in the calibration function of the evaluation software.

The results of an error analysis for the inventory is presented in Table 4.14.

4.3.3.3 Results

The fission product inventory was determined for all fuel compacts from graphite bodies 2 and 3. The results were back corrected to the common time 10.07.89, the reactor shutdown time. The results are presented in Tables 4.15 and 4.16. The ^{137}Cs and ^{134}Cs values are graphically given in Fig. 4.57.

4.3.4 Dimensional and Weight Measurements²

Since the compacts all had a very rough surface and the edges of the cylinders were very easily broken, the dimensional measurements were taken with a measuring microscope having a micrometer stage. This meant that the measurement could not be made to the desired accuracy² of 0.1 mm. The results are presented in Table 4.17

The compacts were weighed with a Mettler balance. The specified accuracy² of 0.1 mg was not attainable under the hot cell conditions. The results are presented in Table 4.18.

4.3.5 Remaining Tasks

The remaining tasks are the determination of the partition coefficient (i.e., the distribution of fission products between the fuel compact matrix material and the contiguous graphite), metallography and deconsolidation of two fuel compacts.

4.4 EXAMINATION OF UNFUELED GRAPHITE BODIES

The unfueled graphite bodies were prepared by removing, from the fueled graphite bodies¹ of capsules 2 and 3 (see Fig. 3.2 and in reference 9 Figs. 1 and 2), per capsule, 12 fuel compacts (see Sects. 4.3.1.1 and 4.3.1.2) from the fuel holes, 10 trays of unbonded particles, and 3 graphite crucibles of niobium-encapsulated particles from the central hole¹ of each capsule, 6 graphite cylinders and the 6 surrounding graphite sleeves, and 8 fuel-free compacts. The 7 holes from which these specimens were removed each had a graphite screw at the top and a graphite plug at the bottom as shown, for example, in Fig. 3.2.

4.4.1 Visual Inspection and Photography²

The unfueled graphite bodies were inspected but not photographed. The external appearance of the graphite bodies are, however, shown in Fig. 4.11, photographs 468/41-43 for capsule 2 and in Fig. 4.14, photographs 469/30; 37; 41 for capsule 3.

4.4.2 Gamma Scanning

To prepare the unfueled graphite bodies for gamma scanning as well as gamma counting (see Sect. 4.4.3), the two graphite bodies were each cut into 120° cylindrical sectors in the process of which the cut was vertically through the centers of the simulated coolant holes (see Fig. 3.2). Thereafter, these cylindrical sectors were cut in half to provide 6 cylindrical sector halves per capsule.

Table 4.14 Error analysis

The determination of the activity at the end of the irradiation is calculated with the equation:

$$A = F \cdot (\exp\{\lambda \cdot t_d\}) / (\gamma \cdot t_m \cdot e \cdot \kappa)$$

where F = net peak area

where λ = decay constant

t_d = decay time

γ = gamma yield

t_m = counting time

e = detector efficiency

κ = self absorption correction factor

As the essential sources of error were taken:

$\Delta F \sim 0.4\%$ the error in the peak area determination for the Spectran F

$\Delta t_m \sim 1\%$ error in the total time correction

$\Delta e \sim 5\%$ error of the calibration including the calibration standard

$\Delta \kappa \sim 3\%$ error in the determination of the self absorption of the calibration standard and of the fuel compacts

the total error is $\leq 10\%$

Table 4.15 The measured activities (Bq) of selective isotopes of the fuel compacts from capsule 2

Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Compact x.y.z represents capsule x, fuel hole y and compact z (z = 1 at top of stack)

	J	K	L	M	N	O	P	Q	R
1	The measured activities of fuel compacts in capsule 2								
2									
3		Activity (Bq)					Activity (Bq)		
4	Isotope	Compact 2.1.1	Compact 2.1.2	Compact 2.1.3	Compact 2.1.4		Sum in 2.1		
5									
6	144Ce	7.00E+10	6.65E+10	6.45E+10	6.83E+10		2.69E+11		
7	134Cs	8.57E+09	8.48E+09	8.57E+09	8.48E+09		3.41E+10		
8	137Cs	5.44E+09	5.46E+09	5.50E+09	5.44E+09		2.18E+10		
9	154Eu	2.33E+08	2.40E+08	2.28E+08	2.49E+08		9.50E+08		
10	106Ru	2.18E+10	2.16E+10	2.20E+10	2.09E+10		8.63E+10		
11	125Sb	3.87E+08	3.87E+08	4.57E+08	3.97E+08		1.63E+09		
12									
13		Activity (Bq)					Activity (Bq)		Activity (Bq)
14	Isotope	Compact 2.2.1	Compact 2.2.2	Compact 2.2.3	Compact 2.2.4		SUM in 2.2		Sum in 2
15									
16	144Ce	6.88E+10	6.97E+10	7.06E+10	6.61E+10		2.75E+11		8.14E+11
17	134Cs	8.85E+09	8.91E+09	8.76E+09	8.93E+09		3.55E+10		1.04E+11
18	137Cs	5.53E+09	5.59E+09	5.48E+09	5.72E+09		2.23E+10		6.61E+10
19	154Eu	2.50E+08	2.42E+08	2.30E+08	2.39E+08		9.61E+08		2.89E+09
20	106Ru	2.19E+10	2.24E+10	2.17E+10	2.17E+10		8.77E+10		2.61E+11
21	125Sb	3.87E+08	4.02E+08	3.97E+08	4.27E+08		1.61E+09		4.84E+09
22									
23		Activity (Bq)					Activity (Bq)		
24	Isotope	Compact 2.3.1	Compact 2.3.2	Compact 2.3.3	Compact 2.3.4		Sum in 2.3		
25									
26	144Ce	6.74E+10	6.69E+10	6.71E+10	6.85E+10		2.70E+11		
27	134Cs	8.65E+09	8.68E+09	8.64E+09	8.57E+09		3.45E+10		
28	137Cs	5.46E+09	5.49E+09	5.46E+09	5.50E+09		2.19E+10		
29	154Eu	2.39E+08	2.51E+08	2.26E+08	2.58E+08		9.74E+08		
30	106Ru	2.18E+10	2.20E+10	2.12E+10	2.17E+10		8.67E+10		
31	125Sb	3.77E+08	3.87E+08	4.07E+08	4.27E+08		1.60E+09		

Table 4.16 The measured activities (Bq) of selective isotopes of the fuel compacts from capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany
Compact x.y.z represents capsule x, fuel hole y and compact z (z = 1 at top of stack)

	J	K	L	M	N	O	P	Q	R
32	The measured activities of fuel compacts in capsule 3								
33									
34		Activity (Bq)					Activity (Bq)		
35	Isotope	Compact 3.1.1	Compact3.1.2	Compact3.1.3	Compact3.1.4		Sum in 3.1		
36									
37	144Ce	5.95E+10	5.76E+10	5.83E+10	5.22E+10		2.28E+11		
38	134Cs	6.61E+09	5.87E+09	5.20E+09	4.78E+09		2.25E+10		
39	137Cs	4.96E+09	4.71E+09	4.52E+09	4.37E+09		1.86E+10		
40	154Eu	2.00E+08	1.73E+08	1.54E+08	1.29E+08		6.56E+08		
41	106Ru	1.60E+10	1.46E+10	1.35E+10	1.28E+10		5.69E+10		
42	125Sb	3.67E+08	3.57E+08	2.88E+08	3.28E+08		1.34E+09		
43									
44		Activity (Bq)					Activity (Bq)		Activity (Bq)
45	Isotope	Compact 3.2.1	Compact 3.2.2	Compact 3.2.3	Compact 3.2.4		Sum in 3.2		Sum in 3
46									
47	144Ce	5.91E+10	5.73E+10	5.23E+10	5.48E+10		2.24E+11		6.63E+11
48	134Cs	6.89E+09	6.10E+09	5.46E+09	4.93E+09		2.34E+10		6.80E+10
49	137Cs	5.04E+09	4.86E+09	4.57E+09	4.43E+09		1.89E+10		5.57E+10
50	154Eu	2.10E+08	1.89E+08	1.82E+08	1.39E+08		7.20E+08		2.04E+09
51	106Ru	1.69E+10	1.60E+10	1.47E+10	1.25E+10		6.01E+10		1.73E+11
52	125Sb	4.27E+08	3.08E+08	2.48E+08	2.68E+08		1.25E+09		3.89E+09
53									
54		Activity (Bq)					Activity (Bq)		
55	Isotope	Compact 3.3.1	Compact3.3.2	Compact 3.3.3	Compact3.3.4		Sum in 3.3		
56									
57	144Ce	5.72E+10	5.21E+10	5.36E+10	4.88E+10		2.12E+11		
58	134Cs	6.50E+09	5.78E+09	5.09E+09	4.76E+09		2.21E+10		
59	137Cs	4.86E+09	4.63E+09	4.41E+09	4.36E+09		1.83E+10		
60	154Eu	1.92E+08	1.63E+08	1.69E+08	1.38E+08		6.62E+08		
61	106Ru	1.60E+10	1.45E+10	1.33E+10	1.23E+10		5.61E+10		
62	125Sb	3.40E+08	3.87E+08	2.78E+08	2.98E+08		1.30E+09

Fig. 4.57 The cesium inventory of the fuel compacts from fuel holes 1, 2, and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany
Compact x.y.z represents capsule x, fuel hole y and compact z (z = 1 at top of stack)

Table 4.17 Dimensional measurements on eight compacts from hole 1 of capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Capsule Position	Compact No.	Length (mm)		Δ Length		Diameter (mm)		Δ Diameter	
		before	after	(mm)	%	before	after	(mm)	%
2.1.1	7161-019-01-48	19.12	19.00	0.12	0.6	12.46	12.40	0.06	0.5
2.1.2	149	19.05	19.00	0.05	0.3	12.45	12.35	0.10	0.8
2.1.3	164	19.06	18.90	0.16	0.8	12.45	12.30	0.15	1.2
2.1.4	14	18.99	18.85	0.14	0.7	12.47	12.35	0.12	1.0
3.1.1	138	19.06	18.85	0.21	1.1	12.44	12.35	0.09	0.7
3.1.2	35	19.05	18.90	0.15	0.8	12.46	12.35	0.11	0.9
3.1.3	145	19.02	18.90	0.12	0.6	12.45	12.35	0.10	0.8
3.1.4	97	19.02	18.90	0.12	0.6	12.46	12.40	0.06	0.5

Table 4.18 Weight measurements of eight compacts from hole 1 of capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Capsule Position	Compact No.	Weight (g)		Δ Weight	%
		before	after		
2.1.1	7161-019-01-48	3.5772	3.535	0.0422	1.18
2.1.2	149	3.5704	3.532	0.0384	1.07
2.1.3	164	3.5630	3.537	0.0260	0.73
2.1.4	14	3.5604	3.555	0.0050	0.15
3.1.1	138	3.5695	3.519	0.0505	1.41
3.1.2	35	3.5731	3.529	0.0441	1.23
3.1.3	145	3.5701	3.532	0.0381	1.07
3.1.4	97	3.5687	3.546	0.0227	0.64

4.4.2.1 Apparatus

The description of the apparatus has already been given in Sect. 4.2.4.1.

4.4.2.2 Measurement

Two cylindrical sector halves were laid in the receiving cradle of the carriage with a cut surface of the sectors against the cradle; see Fig. 4.58. Then the sectors were moved before the collimator slit. In this position, a suitable collimator was chosen and then a gamma spectrum taken. With this spectrum, the energy window, in which the peak of the interesting nuclide occurred, was determined; likewise the measurement time at the measurement point.

Thereafter, the beginning of the first sector was placed before the collimator opening and the step motor with the chosen step width started. For each step a gamma spectrum was taken. Illustrative gamma spectra for graphite sectors 2.3 and 3.3 are shown in Figs. 4.59 and 4.60, respectively. With these, in the energy region of the individual peaks, the net peak areas were determined. To that end, the impulse numbers were summed and the spectrum background, an average value of the impulse number calculated from the three channels, left and right of the photopeak, subtracted. The peak net areas were stored in the PC and after the end of the scans were transferred to a spreadsheet.

The scans were performed between 2.9.92 and 11.9.91. Because of the short measurement time, the results were not back calculated to a common time.

The instruments and conditions of the measurements for the cylindrical sectors are given in Table 4.19.

4.4.2.3 Results

The results are presented in Figs. 4.61 through 4.66. They show the relative distribution of the fission products ^{144}Ce , ^{137}Cs , and ^{134}Cs as well as the activities of ^{183}Ta , ^{94}Nb , and ^{60}Co at the measurement time. The results from capsule 2 and 3 are shown in a comparative mode; the upper graph in each figure represents capsule 2 for halves from the same sector, sectors being designated as 1, 2, or 3 and the lower graph in each figure represents capsule 3 for halves from the same sector. The indentation in the middle of the scan profile marks the contiguous boundaries of the sector halves. Note that on the figures, the German designation for the cylindrical sector halves is "Graphitsegments"; also, note that the screws and plugs are in the fuel holes except for sector 2.1.

Gamma scans of the graphite bodies with the fuel compacts removed were obtained for the nuclides ^{144}Ce , ^{134}Cs , ^{137}Cs , ^{60}Co , ^{94}Nb , and ^{182}Ta . These scans illustrate that the cesium activity in the graphite body of capsule 2 is about 3 times larger than that in the graphite body of capsule 3. By contrast, the inverse occurs with the concentrations of ^{60}Co , ^{94}Nb , and ^{182}Ta ; their activities in the graphite body of capsule 3 are about 3 times larger than those in the graphite body of capsule 2. These relations are likely to be the result of the frequent injections of water vapor into capsule 3; capsule 2 experienced no water vapor injection. The factorial differences in burnup and temperature in capsules 2 and 3 are small compared to the factorial differences in activities cited.

A general postulate accounting for the activity differences is the following. Water vapor oxidizes the binder of the graphite body thus reducing the retentivity of the graphite for fission products. For example, the diffusion coefficient of cesium increases with increasing graphite oxidation.¹⁰ Thus ^{133}Cs and ^{137}Cs spend less time moving through the oxidized graphite and have lower activities in the graphite. In transit, less time is available for activation of ^{133}Cs to ^{134}Cs . Consequently, the ratio of

Fig. 4.58 Sketch of the measuring facility
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.59 The gamma spectrum of graphite sector 2.3 at the axial location 15 mm above the bottom of the graphite sector on 12.9.91
Source: Forschungszentrum Jülich GmbH, Jülich, German

Fig. 4.60 The gamma spectrum of graphite sector 3.3 at the axial location 15 mm above the bottom of the graphite sector on 30.8.91
Source: Forschungszentrum Jülich GmbH, Jülich, German

Table 4.19 Measurement conditions for the graphite bodies of capsules 2 and 3

Collimator: Length	545 mm
Slit Height	30 mm
Slit Width	5 mm
Measurement Distance	930 mm
Step Length	1 mm
Measurement Time at each point	500 s
Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-2300 V
Relative Efficiency	3.5%
Preamplifier	DSG 51 P
Main Amplifier	ORTEC Nr. 573
High Voltage Apparatus	Schlumberger 219
Reference Pulser	Canberra 1501
Personal Computer	Compaq Deskpro 386/20
Spread Sheet	Microsoft Excel
Gammascan-System	ORTEC Maestro
Measured Energy Range	20 to 1670 KeV
Energy Windows:	
¹⁴⁴ Ce	127 to 139 KeV
¹³⁴ Cs	598 to 612 KeV
¹⁰⁶ Ru	616 to 622 KeV
¹³⁷ Cs	654 to 670 KeV
⁹⁵ Nb	696 to 711 KeV
¹⁸¹ Ta	1116 to 1128 KeV
⁶⁰ Co	1324 to 1339 KeV

Fig. 4.61 Gamma scan of graphite sectors from hole 1 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.62 Gamma scan of graphite sectors from hole 1 of capsules 2 and 3 for ^{183}Ta , ^{94}Nb , and ^{60}Co
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Abb. 4a

Abb. 7a

Fig. 4.63 Gamma scan of graphite sectors from hole 2 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.64 Gamma scan of graphite sectors from hole 2 of capsules 2 and 3 for ^{183}Ta , ^{94}Nb , and ^{60}Co
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1

Abb. 5a

HFR-B1

Abb 8a

Fig. 4.65 Gamma scan of graphite sectors from hole 3 of capsules 2 and 3 for ^{144}Ce , ^{137}Cs , and ^{134}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1

Abb. 5b

HFR-B1

Abb. 8b

Fig. 4.66 Gamma scan of graphite sectors from hole 3 of capsules 2 and 3 for ^{182}Ta , ^{94}Nb , and ^{60}Co
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

$^{134}\text{Cs}/^{137}\text{Cs}$ is expected to be less in the oxidized graphite of capsule 3 than in the unoxidized graphite of capsule 2. These deductions are consistent with the gamma scan results. The water vapor can also attack the metal components in such a way that the reaction products become mobile and then move into the graphite; this would happen to a greater extent in capsule 3 than in capsule 2; this is observed for reaction products involving ^{60}Co , ^{94}Nb , and ^{182}Ta .

The gamma scans also illustrate that the cesium activity in the graphite from capsule 2 is far greater than the cerium activity. This reflects the known, greater retentivity of cerium than of cesium, in this instance, by the fuel (UCO) in particles with exposed kernels. The reduced cesium to cerium activity ratio in the graphite from capsule 3 as compared to capsule 2 is thought to result from a combination of factors involving the relative effects of water vapor in inducing the release of cerium and cesium from the fuel and the reduced retentivity or increased diffusivity of cerium and cesium on the graphite surfaces. Note that the release of cerium from UCO fuel is much smaller than that of cesium in the absence of water vapor but comparable to that of cesium in the presence of water vapor. The diffusivity in graphite of cerium is smaller than that of cesium in the absence of water vapor; comparative data are not available under conditions involving water vapor.

4.4.3 Gamma Counting of Graphite Sectors

4.4.3.1 Apparatus

The apparatus is the same as described in Sect. 4.3.3.1. The components of the apparatus are identified in Table 4.13.

4.4.3.2 Measurements

The cylindrical sector halves with plugs in the bottom and screws in the top of the fuel holes stood during the measurements on a slowly rotating table. The gamma radiation passed through a double collimator and encountered the germanium planar detector. The impulses produced in the detector were processed as before (see Sect. 4.3.3.2).

The calibration of the measurement facility was made with an AVR fuel element whose ^{137}Cs inventory had been determined with a standard from the Buchler firm. For the determination of the self absorption in the sectors, a graphic cylinder with the same cross sectional surface was taken as the basis.

4.4.3.3 Results

The results are presented in Tables 4.20 and 4.21. In addition, the inventories of ^{137}Cs and ^{134}Cs are graphically displayed in Figs. 4.67, 4.68, and 4.69. In Tables 4.20 and 4.21, the identification of the sector halves are indicated by the sequence x.y.p where x is the capsule number, y, is the fuel hole number and p, when included in the sequence, is the original position of the sector half being o for the upper half and u for the lower half. As in Tables 4.20 and 4.21, there are identified six sectors halves and three sectors per capsule. Figs. 4.67, 4.68, and 4.69 reflect these identifications as the inventories (Bq) are given for the six sector halves for both capsules.

As the gamma scans indicated (see Sect. 4.4.2.3), the cesium activities in capsule 2 are significantly larger than those in capsule 3. As determined from Figs. 4.67, 4.68, and 4.69, the mean ratio of ^{137}Cs in capsule 2 to that in capsule 3 is 3.0 and that of ^{134}Cs is 3.8. Furthermore, the mean ratio of ^{137}Cs for the upper sector halves in capsule 2 to that in capsule 3 is 3.3 whereas the mean ratio of ^{137}Cs for the lower sector halves in capsule 2 to that in capsule 3 is 2.6. The ratios of the ^{137}Cs inventories in the upper as opposed to the lower halves of the sectors are significantly different as the standard

Table 4.20 The inventory in the graphite cylindrical sector from capsule 2.
The activity (Bq) has been corrected to reactor shutdown.
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Segment Nr.	Co 60	Cs 134	Cs 137	Nb 94	Ta 182
2.1o	4,18E+06	7,98E+08	4,34E+08		
2.1u	1,92E+08	8,65E+08	4,64E+08	4,27E+05	5,71E+09
2.1	1,96E+08	1,66E+09	8,98E+08	4,27E+05	5,71E+09
2.2o	7,03E+07	8,05E+08	4,31E+08	1,58E+05	2,48E+09
2.2u	1,22E+08	7,68E+08	4,26E+08	2,66E+05	3,77E+09
2.2	1,92E+08	1,57E+09	8,57E+08	4,24E+05	6,25E+09
2.3o	4,07E+06	7,35E+08	4,09E+08		
2.3u	1,15E+08	8,00E+08	4,37E+08	2,66E+05	2,69E+09
2.3	1,19E+08	1,54E+09	8,46E+08	2,66E+05	2,69E+09
Graf.-Körper 2	5,08E+08	4,77E+09	2,60E+09	1,12E+06	1,47E+10

Table 4.21 The inventory in the graphite cylindrical sector from capsule 3.
The activity (Bq) has been corrected to reactor shutdown.
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Segment Nr.	Co 60	Cs 134	Cs 137	Nb 94	Ta 182
3.1o	1,95E+08	2,10E+08	1,34E+08	4,58E+05	6,47E+09
3.1u	5,58E+08	2,41E+08	1,77E+08	1,26E+06	2,12E+10
3.1	7,53E+08	4,51E+08	3,11E+08	1,71E+06	2,77E+10
3.2o	2,18E+08	2,19E+08	1,37E+08	5,07E+05	9,27E+09
3.2u	5,54E+08	2,28E+08	1,70E+08	1,33E+06	2,06E+10
3.2	7,72E+08	4,47E+08	3,07E+08	1,84E+06	2,99E+10
3.3o	1,84E+08	1,93E+08	1,26E+08	4,50E+05	7,54E+09
3.3u	5,44E+08	2,06E+08	1,61E+08	1,24E+06	2,07E+10
3.3	7,28E+08	3,99E+08	2,87E+08	1,69E+06	2,82E+10
Graf.-Körper 3	2,25E+09	1,30E+09	9,05E+08	5,24E+06	8,58E+10

Fig. 4.67 The Activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.1 and 3.1
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.68 The Activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.2 and 3.2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.69 The Activities of ^{137}Cs and ^{134}Cs in the graphite sectors 2.3 and 3.3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

deviation in both cases is only 2%. Such a difference is not found for ^{134}Cs where the corresponding ratios are 3.8 and 3.7, respectively. In the latter cases, the standard deviations are as large as 7%.

The results of an error analysis for the inventory is given in Table 4.22

4.4.4 Gamma Counting of Smaller Graphite Components

The plugs and screws, individual graphite cylinders and sleeves and individual particle trays were gamma counted.

4.4.4.1 Measurement

The smaller graphite components were measured for average activity levels outside the hot cells on a measurement plate. The plugs, screws, the graphite cylinders and sleeves as well as the particle trays were measured in aluminum cans with a 0.3 mm wall thickness. The detector was housed in a lead device in order to shield against background radiation. The measurement distance was 30, 50, or 80 cm and the measurement time was between 5000 and 20000 s depending on the activity of the sample. See Table 4.23 for the other conditions of the measurements.

The calibration measurement was done with an ^{154}Eu standard, preparation number BV938, from the firm Amersham Buchler. Its activity on 1.12.89 amounted to $407.1 \text{ kBq} \pm 3\%$.

For every measured object, a gamma spectrum was taken with the Canberra 35 plus multichannel analyzer and the results evaluated in a PDP micro 11 computer with the analysis software Spectran F. These results were transferred to a PC and with the help of the spreadsheet program Excel, the self absorption was taken into account.

4.4.4.2 Results

In terms of the activity (Bq) of selected isotopes, the inventories for the graphite plugs and screws are given in Tables 4.24 and 4.25 for capsules 2 and 3, respectively, for the graphite cylinders and sleeves are given in Tables 4.26 and 4.27 for capsules 2 and 3, respectively, and for the particle trays are given in Table 4.28 for capsules 2 and 3. The graphical presentations of these data are given in Fig. 4.70 and 4.71 for the plugs and screws for capsules 2 and 3 respectively, in Figs. 4.72 and 4.73 for the graphite cylinders and sleeves from capsules 2 and 3, respectively and in Figs. 4.74 and 4.75 for the particle trays from capsules 2 and 3, respectively. The isotopes measured vary for different graphite components and capsules; see Tables 4.24 through 4.28

4.4.5 Cesium Distribution Between Fuel Compacts and the Graphite

An overview of the distribution of ^{137}Cs and ^{134}Cs between the fuel compacts and the graphite in the fuel element was prepared. In this determination, the contents of the central hole were not considered, i.e., the particle trays with contained fuel particles and the graphite crucible containing the niobium-encapsulated fuel particles. The activities of the graphite cylinders and sleeves from the coolant holes which were not gamma counted were calculated using the average values for those that were. As was evident from the totality of measured activities, as shown below, the graphite sectors contained between 97 and 98% of the cesium isotopes found among graphite components; therefore, the omissions and approximations just stated did not introduce a significant error into the determination of cesium distribution.

Table 4.22 Error Analysis
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

As the essential sources of error were taken:

$\Delta F \sim 2.0\%$ the error in the peak area determination for the Spectran F

$\Delta t_m \sim 1\%$ error in the total time correction

$\Delta e \sim 5\%$ error of the calibration including the calibration standard

$\Delta \kappa \sim 8\%$ error in the determination of the self absorption of the calibration standard and of the graphite sectors

The maximum error is $\leq 16\%$ This analysis is valid for ^{137}Cs ; the results for the other nuclides can involve greater errors.

Table 4.23 Measurement configuration
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement distance:	80, 50, 30 cm
Measurement time:	5000 s to 20000 s
Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-3000 V
Relative Efficiency	3.5%
Preamplifier	DSG 51 P
Main Amplifier	Canberra Model 2011
High Voltage Apparatus	Ortec Model 459
Multichannel analyzer	Canberra 35 plus
Computer	PDP-Micro 11
Gamma analysis and evaluation system	Canberra Spectran F

Table 4.24 The inventories (Bq) of the plugs and screw caps from capsule 2 for ^{125}Sb , ^{137}Cs , ^{134}Cs , $^{110\text{m}}\text{Ag}$, and ^{60}Co . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

	Co 60	Cs 134	Cs 137	Ag 110m	Sb 125	Ce 144	Ru 106
2.1 Cap	2,52E+05	3,20E+07	1,67E+07	1,10E+06	4,86E+05		
2.2 Cap	2,43E+05	3,17E+07	1,66E+07	1,17E+06	3,94E+05		
2.3 Cap	2,31E+05	2,90E+07	1,51E+07	1,16E+06	3,24E+05		
2.4 Cap	5,96E+05	4,06E+06	2,06E+06				
2.5 Cap	2,84E+05	4,37E+06	2,20E+06				
2.6 Cap	1,97E+05	4,29E+06	2,16E+06				
2.7 Cap	3,39E+05	3,81E+06	1,93E+06				
2.1 Plug	3,00E+05	2,94E+07	1,60E+07	1,20E+06	8,21E+05		
2.2 Plug	2,74E+05	3,38E+07	1,86E+07	1,63E+06	5,57E+05		
2.3 Plug	2,28E+05	2,41E+07	1,33E+07	9,47E+05	5,33E+05		
2.4 Plug	3,33E+05	9,28E+05	4,76E+05				
2.5 Plug	9,16E+05	9,88E+05	5,05E+05				
2.6 Plug	3,88E+05	1,19E+06	6,18E+05				
2.7 Plug	2,62E+05	5,84E+05	3,04E+05				

Table 4.25 The inventories (Bq) of the plugs and screw caps from capsule 3 for ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru , and ^{60}Co . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

	Co 60	Cs 134	Cs 137	Ag 110m	Sb 125	Ce 144	Ru 106
3.1 Cap	3,61E+05	9,99E+06	6,19E+06			1,08E+07	2,17E+06
3.2 Cap	3,20E+05	9,57E+06	5,66E+06			2,72E+06	
3.3 Cap	3,09E+05	8,87E+06	5,36E+06			4,58E+06	
3.4 Cap	2,43E+05	9,41E+04	6,23E+04			1,32E+04	
3.5 Cap	3,03E+05	9,25E+05	5,19E+05			6,59E+04	
3.6 Cap	4,51E+05	7,19E+05	4,08E+05				
3.7 Cap	2,38E+05	4,14E+05	2,32E+05				
3.1 Plug	1,45E+05	8,84E+06	7,67E+06			2,77E+07	9,81E+06
3.2 Plug	1,69E+05	1,08E+07	9,25E+06			3,98E+07	1,30E+07
3.3 Plug	2,43E+05	1,22E+07	1,07E+07			4,27E+07	1,41E+07
3.4 Plug	1,70E+05	8,29E+05	4,65E+05				
3.5 Plug	2,66E+05	8,47E+04	5,26E+04				
3.6 Plug	2,84E+05	8,55E+04	5,24E+04				
3.7 Plug	4,56E+05	8,06E+04	5,34E+04				

Table 4.26 The inventories (Bq) of selected graphite cylinders, inert compacts and sleeves from capsule 2 for ^{154}Eu , ^{137}Cs , ^{134}Cs , ^{60}Co and ^{54}Mn . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

	Co 60	Cs 134	Cs 137	Eu 154	Mn 54	Ba 133
2.4.1 a	3,56E+06	6,12E+06	3,21E+06		2,34E+05	
2.4.1 b	6,98E+05	3,42E+06	1,76E+06		4,58E+04	
2.4.2	3,03E+05	7,30E+06	3,79E+06			
2.4.5	4,79E+06	7,18E+06	3,67E+06			
2.5.1 a	5,11E+06	6,43E+06	3,34E+06		4,36E+05	
2.5.1 b	8,75E+05	3,64E+06	1,86E+06		8,67E+04	
2.5.2	2,35E+05	5,55E+06	2,79E+06			
2.5.5	5,40E+06	1,19E+07	6,10E+06			
2.6.1 b	3,65E+05	3,81E+06	1,94E+06			
2.6.2 a	2,51E+06	1,03E+07	5,37E+06	1,51E+05	1,59E+05	
2.6.2 b	1,03E+06	6,13E+06	3,20E+06			
2.6.3 b	6,08E+05	5,66E+06	2,93E+06			
2.6.4 a	2,84E+06	7,64E+06	3,93E+06	1,74E+05	1,13E+05	
2.6.4 b	4,78E+05	4,04E+06	2,11E+06			

Table 4.27 The inventories (Bq) of selected graphite cylinders, inert compacts and sleeves from capsule 3 for ^{154}Eu , ^{137}Cs , ^{134}Cs , ^{133}Ba , ^{60}Co and ^{54}Mn . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

	Co 60	Cs 134	Cs 137	Eu 154	Mn 54	Ba 133
3.4.1a	1,73E+06	9,35E+05	6,66E+05	2,34E+04	1,17E+05	
3.4.1b	4,88E+05	5,69E+05	3,88E+05			
3.4.2	2,66E+05	7,44E+05	4,98E+05			
3.4.4	4,21E+06	1,83E+06	1,14E+06	2,72E+04		
3.5.1 a	1,68E+06	8,24E+05	5,77E+05	2,17E+04	1,12E+05	
3.5.1 b	4,81E+05	4,81E+05	3,20E+05			
3.5.2	3,49E+05	1,32E+06	8,00E+05			
3.5.4	3,94E+06	7,98E+05	5,36E+05	2,10E+04		
3.6.1 b	6,50E+05	1,01E+06	5,95E+05			
3.6.2 a	1,26E+06	2,33E+06	1,45E+06	1,68E+05	1,18E+05	8,38E+03
3.6.2 b	4,53E+05	9,71E+05	6,01E+05			
3.6.3 b	6,78E+05	7,44E+05	4,83E+05			
3.6.4 a	1,59E+06	1,07E+06	7,33E+05	1,72E+05	7,67E+04	7,55E+03
3.6.4 b	4,88E+05	4,04E+05	2,69E+05			

Table 4.28 The inventories (Bq) of the particle trays from capsules 2 and 3 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru , and ^{60}Co . Coated particles not included. Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Tray Nr.	Co 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106
2-3	6,53E+06	1,78E+05	7,05E+06	3,84E+06	7,40E+04	1,66E+06
2-4		1,21E+05	5,10E+06	2,66E+06		
2-7		1,31E+05	5,18E+06	2,70E+06		
2-8		1,18E+05	5,59E+06	2,87E+06		
3-3	2,75E+04	9,89E+04	4,92E+05	2,96E+05		
3-4		1,73E+05	4,72E+05	2,87E+05		
3-7	2,63E+04	9,45E+04	4,27E+05	2,72E+05		
3-8		7,33E+04	3,59E+05	2,31E+05

Fig. 4.70 The inventories (Bq) of the plugs and screw caps from capsule 2 for ^{144}Ce , ^{137}Cs , ^{134}Cs , and ^{106}Ru . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.71 The inventories (Bq) of the plugs and screw caps from capsule 3 for ^{144}Ce , ^{137}Cs , ^{134}Cs , and ^{106}Ru . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.72 The inventories (Bq) of the graphite cylinders and sleeves from capsule 2 for ^{137}Cs , and ^{134}Cs
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.73 The inventories (Bq) of the graphite cylinders and sleeves from capsule 3 for ^{137}Cs , and ^{134}Cs ,
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.74 The inventories (Bq) of the particle trays from capsule 2 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru , and ^{60}Co . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.75 The inventories (Bq) of the particle trays from capsule 3 for ^{154}Eu , ^{144}Ce , ^{137}Cs , ^{134}Cs , ^{106}Ru , and ^{60}Co . Source: Forschungszentrum Jülich GmbH, Jülich, Germany

The results of the overview calculations are shown in Table 4.29 and Figs. 4.76 and 4.77. The fraction of cesium in the graphite is small. For ^{134}Cs , the fractions for capsules 2 and 3 are 0.045 and 0.019, respectively; for ^{137}Cs , the fractions for capsules 2 and 3 are 0.039 and 0.016, respectively. The ratios of the fractional cesium content in the graphite to that in the graphite plus fuel compacts is about 2.4 for both capsules 2 and 3. This ratio is comparable to the ratio of the impluses measured for capsules 2 and 3, respectively during the gamma scan of the graphite sectors as evident from Figs. 4.61, 4.63 and 4.65. These observations are in accord with the postulate presented in Sect. 4.4.2.3.

Capsule 3 but not capsule 2 was subjected to intermittent injections of water vapor. The lower cesium content in capsule 3 is attributable to the effects of graphite hydrolysis. The diffusivity of cesium is greater in hydrolyzed than unhydrolyzed graphite¹⁰. Therefore, the transport of cesium through the graphite in capsule 3 is faster than in capsule 2 and less cesium is expected to be found in capsule 3. To maintain a mass balance, more cesium in capsule 3 than in capsule 2 would be expected to be adsorbed on the respective stainless steel capsule containers.

Note that in Table 4.29, activity (Bq) data in the first data row have been taken from Tables 4.20 and 4.21 for capsules 2 and 3, respectively. Activity (Bq) data in the fifth data row have been taken from Tables 4.15 and 4.16 for capsules 2 and 3, respectively

4.4.6 Summary of Inventory Measurements

A summary is provided in Table 4.30 of the inventory measurements of the graphite parts of the fuel element as depicted in Figs. 3.2 and 3.3. The fuel element can be thought of as a graphite cylinder with 7 vertical holes containing a variety of components. The inventories were measured on the graphite body, the screw caps at the top and the plugs at the bottom of each hole, and the contents of each hole selectively.

4.4.7 Dimensional Measurements⁷

Dimensional measurements on graphite bodies from capsules 2 and 3, both before and after irradiation, are presented in Fig. 4.78. The preirradiation measurements were taken from the *Design and Safety Report*⁸ (Figs. 16 and 17 of this report). The axial orientation of the fuel bodies in the capsule during irradiation are indicated by the words "oben" (top) and "unter" (bottom) and not by the pictorial orientation.

The measurements were made with a vernier micrometer. The reading accuracy amounted to ± 0.005 mm. The diameter was determined at two locations 90° apart for each axial portion of constant diameter of which there are four (see Fig. 4.78). The length for graphite body 2 was determined at two locations 180° apart and for graphite body 3, at four locations 90° apart for each axial portion of constant diameter of which there are four (see Fig. 4.78).

4.5 EXAMINATION OF INERT COMPACTS AND GRAPHITE CYLINDERS

The three, normally, coolant holes in the graphite body of each capsule contained a complement of 6 inert compacts each within a graphite sleeve and 8 graphite cylinders. The inert compacts were fired in either SiC or Al powder; the SiC powder was expected to lead to increased compact strength. The sleeves surrounding the compacts were intended to bridge the diameter of the hole. The graphite cylinders were either of grade H-451 or H-451I; the differences in dimensional change, coefficient of thermal expansion and Young's modulus were to be assessed. Unfortunately, the KFA was unable to measure the coefficient of thermal expansion or Young's modulus in their hot cells. The graphite samples are, however, available for testing elsewhere.

Table 4.29 Distribution of cesium activity (Bq) between the fuel compacts and the graphite in the fuel element Source: Forschungszentrum Jülich GmbH, Jülich, Germany

	Capsule 2		Capsule 3	
	Cs 134	Cs 137	Cs 134	Cs 137
Graphite sectors with plugs and screws in fuel holes	4.77E+09	2.60E+09	1.30E+09	9.05E+08
Plugs and screw for holes 4 to 7	2.02E+07	1.03E+07	3.23E+06	1.85E+06
Graphite cylinders and sleeves	1.39E+08	7.17E+07	2.21E+07	1.42E+07
Total for graphite	4.93E+09	2.68E+09	1.33E+09	9.21E+08
Fuel compacts	1.04E+11	6.61E+10	6.80E+10	5.57E+10
Graphite/(graphite + compact)	4.53%	3.90%	1.91%	1.63%

Fig. 4.76 The inventories of ^{137}Cs and ^{134}Cs in the fuel compacts and graphite of capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.77 The distribution of ^{137}Cs and ^{134}Cs between fuel compacts and graphite in capsules 2 and 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.30 Summary of inventory measurements on the graphite components of the fuel element

<u>Component</u>	<u>Tables</u>	<u>Figures</u>
Graphite cylindrical sectors	4.20, 4.21	4.67, 4.68, 4.69
Fuel compacts in holes 1, 2, 3	4.15, 4.16	4.57
Screw caps and plugs in holes 1, 2, 3, 4, 5, 6, and 7	4.24, 4.25	4.70, 4.71
Selected graphite cylinders, inert compoacts and graphite sleeves in holes 4, 5, and 6	4.26, 4.27	4.72, 4.73
particle trays in hole 7; particles not included	4.28	4.74, 4.75

Fig.16 Outer dimensions of graphite body, cell 2

Fig.17 Outer dimensions of graphite body, cell 3

Fig. 4.78 Diameter and length measurements on graphite bodies from capsules 2 and 3 before and after irradiation Source: Forschungszentrum Jülich GmbH, Jülich, Germany

4.5.1 Visual Inspection and Photography²

The opening of the coolant holes was not difficult. All contents could easily be removed. No remarkable features were observed. Photographs were taken; the position of the inert compact or graphite cylinder is identified on each photograph and the physical location is given in Fig. 3.2 for capsule 2 and on Fig. 3.3 for capsule 3.

The photographs of the inert compacts with the associated graphite sleeves from capsule 2 are presented in Fig. 4.79, photographs 473/5-7, Fig. 4.80, photographs 273/20-22, Fig. 4.81, photographs 473/23,28,29, and Fig. 4.82, photographs 473/24-26. The photographs of the graphite cylinders are presented in Fig. 4.83, photographs 473/8-10, Fig. 4.84, photographs 473/11-13, Fig. 4.85, photographs 273/14-16, and Fig. 4.86, photographs 273/17-19.

The photographs of the inert compacts with the associated graphite sleeves (only for the sleeves from positions 3.4.1 and 3.5.1) from capsule 3 are presented in Fig. 4.87, photographs 471/7-10, Fig. 4.88, photographs 471/24,26,27, Fig. 4.89, photographs 472/6,8,11, and Fig. 4.90, photographs 472/7,9,10, Fig. 4.91, photographs 472/12,15,18, and Fig. 4.92, photographs 472/13,16,17. The photographs of the graphite cylinders are presented in Fig. 4.93, photographs 472/1-4, Fig. 4.94, photographs 471/22,23,25,28.

4.5.2 Dimensional and Weight Measurements^{2,11}

The dimensions and weights of the graphite cylinders are presented in Tables 4.31 and 4.32. Measurements were made on all eight graphite cylinders per compact. These cylinders, four per stack, were placed in holes 4 and 5 in capsules 2 and 3; see Figs. 3.2 and 3.3.

The dimensions and weights of the inert compacts and selected sleeves are presented in Tables 4.33 and 4.34. For a given capsule position, say x.y.z, for which both the inert compact and the associated sleeve were measured, the capsule position was further distinguished by using x.y.z.a for the inert compact and x.y.z.b for the sleeve.

Measurements were made on 5 of the 6 inert compacts per capsule. In only one of the 5 were measurements made on both the inert compact and the associated graphite sleeve; in all other cases, measurements were made only on the inert compacts. The inert compacts and associated graphite sleeves for hole 5 in both capsule 2 and capsule 3 were not measured.

4.6 UNBONDED COATED FUEL PARTICLES

Unbonded coated fuel particles, in two configurations,¹ were placed in the central hole, hole 7, in both capsules 2 and 3. One configuration involved 10 covered graphite trays per capsule, half of which each contained 110 fissile and the other half, 50 fertile coated fuel particles. The other configuration involved niobium encapsulated particles contained in a graphite crucible. The latter particles were one of three types: designed-to-fail fissile particles, intact fissile particles and particles with exposed kernels generated by laser drilling. The analysis of the particles from trays was conducted; for lack of equipment, analysis of the niobium encapsulated particles was not conducted.

HFR-B1
Kapsel 2

K 2.4.1

47315

47316

47317

Fig. 4.79 Three views of the inert compact and associated graphite sleeve
from position 2.4.1 of capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

K 2.5.1

273120

273121

273122

Fig. 4.80 Three views of the inert compact and associated graphite sleeve
from position 2.5.1 of capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

K 2.6.1 +
2.6.2
473123

473128

473129

Fig. 4.81 Three views of the inert compact and associated graphite sleeve from positions 2.6.1 and 2.6.2 of capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

473124
K 2.6.3+
2.6.4

473125

473126

Fig. 4.82 Three views of the inert compact and associated graphite sleeve from positions 2.6.3 and 2.6.4 of capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

K2.4.2+
2.4.3

47318

47319

473110

Fig. 4.83 Three views of the graphite cylinders from positions 2.4.2 and 2.4.3 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

K2.4.4 +
2.4.5

473111

473112

473113

Fig. 4.84 Three views of the graphite cylinders from positions 2.4.4 and 2.4.5 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

K 2.5.2 +
2.5.3
273114

273115

273116

Fig. 4.85 Three views of the graphite cylinders from positions 2.5.2 and 2.5.3 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 2

*K 2.5.4 +
2.5.5
273117*

273118

273119

Fig. 4.86 Three views of the graphite cylinders from positions 2.5.4 and 2.5.5 of capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

3.4.1

47117

47118

47119

471110

Fig. 4.87 Four views of the inert compact and associated graphite sleeve from position 3.4.1 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1

K.3.5.1

471124

471126

471127

Fig. 4.88 Three views of the inert compact and associated graphite sleeve from position 3.5.1 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.89 Three views of the inert compact position 3.6.1 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

K 3.6.2

472 / 7

472 / 9

472 / 10

Fig. 4.90 Three views of the inert compact position 3.6.2 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

K 3.6.3

472 / 12

472 / 15

472 / 18

Fig. 4.91 Three views of the inert compact position 3.6.3 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1
Kapsel 3

K 3.6.4

472 / 13

472 / 16

472 / 17

Fig. 4.92 Three views of the inert compact position 3.6.4 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

111101
Kapsel 3

K3.4.2 +
3.4.3

472/1

K.3.4.4 +
3.4.5

472/2

K3.4.2-5

472/3

K3.4.2-5

472/4

Fig. 4.93 Three views of the graphite cylinders from positions 3.4.2, 3.4.3, 3.4.4 and 3.4.5 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1

K.3.5.2-5

Seite 1
471125

K.3.5.2-5

Seite 2
471128

K3.5.4+5

471122

K3.5.2+3

471123

Fig. 4.94 Three views of the graphite cylinders from positions 3.5.2, 3.5.3, 3.5.4 and 3.5.5 of capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.31 Dimensional measurements on cylinders of grades H-451 and H451I graphite^(a)
from capsules 2 and 3. Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement apparatus: Micrometer state^(b)
Measurement accuracy: ± 0.05 mm^(b)

Measurement apparatus: Leitz Wegaufnehmer^(c)
Measurement accuracy: ± 0.01 mm^(c)

Capsule Position ^(d)	Cylinder No.	Length (mm)		Δ Length		Diameter (mm)		Δ Diameter	
		before	after	(mm)	(%)	before	after	(mm)	(%)
2.4.2	1	14.00	13.79	0.21	0.03	14.99	14.82	0.17	0.03
2.4.3	2	13.97	13.8	0.17	1.2	14.99	14.80	0.19	1.3
2.4.4	11	13.96	13.77	0.19	0.03	14.99	14.70	0.29	0.04
2.4.5	12	13.96	13.7	0.26	1.9	14.99	14.70	0.29	1.9
2.5.2	4	14.00	13.8	0.20	1.4	14.99	14.80	0.19	1.3
2.5.3	3	14.00	13.74	0.26	0.04	14.99	14.79	0.20	0.03
2.5.4	13	13.84	13.65	0.19	0.03	14.99	14.68	0.31	0.05
2.5.5	14	13.94	13.7	0.24	1.7	14.97	14.80	0.17	1.1
3.4.2	5	14.02	14.0	0.02	0.14	14.99	15.0	-0.01	-0.07
3.4.3	6	13.97	13.92	0.05	0.01	14.99	14.91	0.08	0.01
3.4.4	15	13.91	13.9	0.01	0.07	14.99	14.9	0.09	0.60
3.4.5	16	13.99	13.84	0.15	0.02	14.99	14.87	0.12	0.02
3.5.2	7	14.02	13.9	0.12	0.86	14.99	14.9	0.09	0.60
3.5.4	17	13.95	13.9	0.05	0.36	14.99	14.9	0.09	0.60
3.5.3	8	14.02	13.91	0.11	0.02	14.99	14.89	0.10	0.01
3.5.5	18	13.94	13.80	0.15	0.02	14.99	14.87	0.12	0.02

^(a) Grade H-451 graphite cylinders are numbered 1 through 8. Grade H-451I graphite cylinders are numbered 11 through 18.

^(b) These apply to cylinder numbers 2, 4, 5, 7, and 12, 14, 15, 17.

^(c) These apply to cylinder numbers 1, 3, 6, 8, and 11, 13, 16, 18.

^(d) The capsule position is identified by x.y.z where x is the capsule number, y, the hole number, and z the stack number. See also Figs. 3.2 and 3.3.

Table 4.32. Weight measurements on cylinders of grades H-451 and H451I graphite^(a) from capsules 2 and 3. Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Weighing apparatus: Mettler PT 320 SE^(b)
 Weighing accuracy: ± 0.05 mm^(b)

Weighing apparatus: Mettler PM 400^(c)
 Weighing accuracy: ± 0.02 mg^(c)

Capsule Position ^(d)	Compact No.	Weight (g)		Δ Weight (g)	%
		before	after		
2.4.2	1	4.272	4.271	0.001	0.0
2.4.3	2	4.2274	4.227	0.0004	-
2.4.4	11	4.386	4.384	0.002	0.0
2.4.5	12	4.3753	4.372	0.003	0.08
2.5.2	4	4.2410	4.240	0.001	0.02
2.5.3	3	4.266	4.265	0.001	0.0
2.5.4	13	4.351	4.350	0.001	0.0
2.5.5	14	4.2981	4.297	0.001	0.02
3.4.2	5	4.2686	4.264	0.005	0.1
3.4.3	6	4.214	4.211	0.003	0.0
3.4.4	15	4.3759	4.372	0.004	0.1
3.4.5	16	4.344	4.339	0.005	0.0
3.5.2	7	4.2686	4.265	0.004	0.1
3.5.3	8	4.162	4.158	0.004	0.0
3.5.4	17	4.3981	4.392	0.006	0.1
3.5.5	18	4.363	4.356	0.007	0.0

^(a) Grade H-451 graphite cylinders are numbered 1 through 8. Grade H-451I graphite cylinders are numbered 11 through 18.

^(b) These apply to cylinder numbers 2, 4, 5, 7 and 12, 14, 15, 17.

^(c) These apply to cylinder numbers 1, 3, 6, 8 and 11, 13, 16, and 18.

^(d) The capsule position is identified by x.y.z where x is the capsule number, y the hole number, and z the stack number. See also Figs. 3.2 and 3.3.

Table 4.33. Dimensional measurements on inert compacts and selected graphite annuli from capsules 2 and 3. Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Measurement apparatus: Micrometer state^(a)
 Measurement accuracy: $\pm 0.05 \text{ mm}^{(a)}$

Measurement apparatus: Leitz Wegaufnehmer^(b)
 Measurement accuracy: $\pm 0.01 \text{ mm}^{(b)}$

Capsule Position ^(c)	Length (mm)		Δ Length (mm) (%)	Diameter (mm)		Δ Diameter (mm) (%)
	before	after		before	after	
2.4.1a	-	19.3	-	-	12.35	-
2.4.1b	-	18.8	-	-	15.70	-
2.6.1	-	19.22	-	-	12.34	-
2.6.2	-	19.3	-	-	12.30	-
2.6.3	-	18.11	-	-	12.32	-
2.6.4	-	19.2	-	-	12.30	-
3.4.1a		19.3		-	12.4	-
3.4.1b		19.0		-	15.7	-
3.6.1	-	19.31	-	-	12.37	-
3.6.2	-	19.25	-	-	12.3	-
3.6.3	-	19.21	-	-	12.35	-
3.6.4	-	19.30	-	-	12.4	-

^(a) These apply² to inert compacts number 2.4.1a, 2.6.2, 2.6.4, 3.6.2, and 3.6.4.

^(b) These apply¹¹ to inert compacts number 2.6.1, 2.6.3, 3.6.1, and 3.6.3.

^(c) The capsule position is identified by x.y.z where x is the capsule number, y, the hole number, and z the stack number. The capsule position is identified by x.y.z.a or x.y.z.b for the compact and annulus, respectively, when both compact and annulus are measured; otherwise x.y.z represents the compact only. See also Figs. 3.2 and 3.3.

Table 4.34. Weight measurements on inert compacts and selected graphite annuli from capsules 2 and 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Weighing apparatus: Mettler PT 320 SE^(a)
 Weighing accuracy: ± 0.05 mm^(a)

Weighing apparatus: Mettler PM 400^(b)
 Weighing accuracy: ± 0.2 mg^(b)

Capsule Position ^(c)	Weight (g)		Δ Weight	
	before	after	(g)	%
2.4.1a	-	3.229	-	-
2.4.1b	-	2.142	-	-
2.6.1	-	3.327	-	-
2.6.2	-	3.338	-	-
2.6.3	-	3.324	-	-
2.6.4	-	3.313	-	-
3.4.1a	-	3.219	-	-
3.4.1b	-	2.154	-	-
3.6.1	-	3.338	-	-
3.6.2	-	3.326	-	-
3.6.3	-	3.325	-	-
3.6.4	-	3.327	-	-

^(a) These apply² to inert compacts number 2.4.1a, 2.6.2, 2.6.4, 3.6.2, and 3.6.4.

^(b) These apply¹¹ to inert compacts number 2.6.1, 2.6.3, 3.6.1, and 3.6.3.

^(c) The capsule position is identified by x.y.z where x is the capsule number, y, the hole number, and z the stack number. The capsule position is identified by x.y.z.a or x.y.z.b for the compact and annulus, respectively, when both compact and annulus are measured; otherwise x.y.z represents the compact only. See also Figs. 3.2 and 3.3.

4.6.1 Visual Inspection and Photography¹²

A particle tray, cover and screw, before adding coated fuel particles and irradiating, are shown in Fig. 4.95. Ten trays from capsule 2 after irradiation are shown in Fig. 4.96. Similarly, the graphite crucible and the niobium encapsulated fuel particles are shown in Fig. 4.97 before irradiation. The crucible after irradiation in capsule 2 is shown in Fig. 4.98. Particle trays 2-3, 2-4, 2-7, 2-8, and 3-3, 3-4, 3-7, 3-8 were opened. Photographs are shown in Figs. 4.99 and 4.100.

4.6.2 Gamma Counting of Kernels, Coatings and Particles¹³

A total of 40 particles from capsules 2 and 3 were gamma counted individually, and after separating the kernels and coatings of each particle, these constituents were individually counted. From these measurements the kernel release of fission products in intact particles was determined. The separation of the kernels and coatings was made by cracking the particles in an apparatus with which the force upon cracking could be measured.

4.6.2.1 Measurement

The particles as well as the kernels and coatings were measured using a measurement plate located in the hall of the hot cells. The measurement configuration and conditions are given in Table 4.3.5.

Twenty particles were taken from the trays in each capsule; five from each of the trays 2-3, 2-4, 2-7, 2-8, and 3-3, 3-4, 3-7, 3-8. Trays 2-3, 2-7, 3-3 and 3-7 each contained 110 UCO fissile particles and trays 2-4, 2-8, 3-4 and 3-8 each contained 50 ThO₂ fertile particles. Five particles were chosen from each tray.

4.6.2.2 Results

The activities of the intact particles are presented in Tables 4.36, 4.37, 4.38, and 4.39 and plotted in Figs. 4.101, 4.102, 4.103, and 4.104 for the individual fissile and fertile particles from capsules 2 and 3 and for the isotopes ¹⁵⁴Eu, ¹⁴⁴Ce, ¹³⁷Cs, ¹³⁴Cs, ¹²⁵Sb, ¹⁰⁶Ru, and ⁶⁰Co.

The activities of the individual kernels from cracked particles are presented in Tables 4.40, 4.41, 4.42, and 4.43 and plotted in Figs. 4.105, 4.106, 4.107, and 4.108 for particles from capsules 2 and 3 and for isotopes ¹⁵⁴Eu, ¹⁴⁴Ce, ¹³⁷Cs, ¹³⁴Cs, ¹²⁵Sb, and ¹⁰⁶Ru.

The activities of the coatings from cracked particles are presented in Tables 4.44, 4.45, 4.46, and 4.47 and plotted in Figs. 4.109, 4.110, 4.111, and 4.112 for particles from capsules 2 and 3 and for isotopes ¹⁵⁴Eu, ¹⁴⁴Ce, ¹³⁷Cs, ¹³⁴Cs, ¹²⁵Sb, ¹⁰⁶Ru, and ⁶⁰Co.

The sums of the activities of the kernels and the associated coatings are given in Tables 4.48, 4.49, 4.50 and 4.51.

The percent retention of fission products in the kernels of intact fissile and fertile particles from capsules 2 and 3 are given in Tables 4.52, 4.53, 4.54, and 4.55 and shown in Figs. 4.113, 4.114, 4.115, and 4.116.

N85012-1

Fig. 4.95 Component of the particle trays before irradiation
Source : General Atomics Company, San Diego, California

Fig. 4.96 The assembled trays after irradiation
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.97 The graphite crucible and niobium encapsulated fuel particles before irradiation
Source: General Atomics Company, San Diego, California

Fig. 4.98 The graphite crucible after irradiation in capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

2-3

2-4

2-7

2-8

Fig. 4.99 Views of the opened unbonded particle trays 2-3, 2-4, 2-7, and 2-8 from capsule 2
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

3-3

3-4

3-7

3-8

Fig. 4.100 Views of the opened unbonded particle trays 3-3, 3-4, 3-7, and 3-8 from capsule 3
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.35 Measurement Configuration
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Detector	DSG Typ PGP 1516 SNG-167 planar
Voltage	-3000 V
Preamplifier	DSG 51 P
Main Amplifier	Canberra Model 2011
High Voltage Apparatus	Ortec Model 459
Multichannel analyzer	Canberra 35 plus
Computer	Compaq 386/20
Gamma analysis and evaluation system	Canberra Spectran F
Spread sheet	Microsoft Excel
Calibration standard	¹⁵² Eu; preparation no. BV 938 from the firm Amersham Buchler Activity on 1.12.89: 407.1 kBq ± 3%

Table 4.36 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partikel Nr.	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 125
2-3/1	4,57E+07	1,67E+05	7,06E+06	4,14E+06	1,62E+05	1,81E+07	1,86E+05
2-3/2	5,07E+07	2,24E+05	7,80E+06	4,62E+06	2,20E+05	2,08E+07	2,12E+05
2-3/3	4,71E+07	1,96E+05	7,71E+06	4,54E+06	1,89E+05	1,96E+07	2,14E+05
2-3/4	5,61E+07	3,07E+05	7,89E+06	4,67E+06	1,85E+05	2,01E+07	2,36E+05
2-3/5	5,61E+07	2,08E+05	8,08E+06	4,76E+06	1,98E+05	2,12E+07	2,07E+05
2-7/1	4,89E+07	8,59E+04	7,52E+06	4,53E+06	1,90E+05	1,93E+07	2,17E+05
2-7/2	4,89E+07	7,93E+04	7,66E+06	4,54E+06	2,00E+05	1,94E+07	1,56E+05
2-7/3	4,40E+07	1,56E+05	6,82E+06	4,06E+06	1,66E+05	1,79E+07	2,12E+05
2-7/4	4,53E+07	1,70E+05	6,78E+06	4,02E+06	1,65E+05	1,72E+07	1,92E+05
2-7/5	3,95E+07	9,33E+04	6,03E+06	3,61E+06	1,52E+05	1,61E+07	1,70E+05

Table 4.37 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partikel Nr.	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 125
2-4/1	1,71E+07	1,88E+05	1,25E+06	1,27E+06	3,13E+04	9,63E+05	1,95E+05
2-4/2	1,77E+07	1,92E+05	1,25E+06	1,27E+06	2,90E+04	9,26E+05	2,01E+05
2-4/3	1,88E+07	1,07E+05	1,33E+06	1,32E+06	2,47E+04	9,49E+05	2,16E+05
2-4/4	1,88E+07	1,51E+05	1,26E+06	1,28E+06	2,76E+04	8,93E+05	1,97E+05
2-4/5	1,93E+07	1,29E+05	1,36E+06	1,37E+06	2,39E+04	1,08E+06	2,13E+05
2-8/1	1,91E+07	4,91E+04	1,33E+06	1,34E+06	2,39E+04	1,02E+06	2,11E+05
2-8/2	1,93E+07	5,21E+04	1,31E+06	1,32E+06	2,29E+04	9,86E+05	2,14E+05
2-8/3	1,75E+07	7,84E+04	1,26E+06	1,27E+06	2,38E+04	1,03E+06	2,03E+05
2-8/4	1,98E+07	3,61E+04	1,30E+06	1,31E+06	1,91E+04	9,72E+05	2,06E+05
2-8/5	1,71E+07	8,54E+04	1,23E+06	1,25E+06	2,56E+04	8,93E+05	1,91E+05

Table 4.38 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partikel Nr.	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 125
3-3/1	4,75E+07	1,28E+05	5,94E+06	4,20E+06	1,54E+05	1,54E+07	1,88E+05
3-3/2	4,62E+07	2,71E+05	5,85E+06	4,09E+06	1,69E+05	1,50E+07	1,86E+05
3-3/3	4,46E+07	9,55E+04	5,89E+06	4,16E+06	1,67E+05	1,50E+07	1,90E+05
3-3/4	4,93E+07	1,18E+05	6,03E+06	4,24E+06	1,69E+05	1,55E+07	1,74E+05
3-3/5	4,24E+07	3,74E+04	5,76E+06	4,03E+06	1,45E+05	1,41E+07	1,86E+05
3-7/1	3,28E+07	7,32E+04	4,01E+06	3,05E+06	1,18E+05	1,08E+07	1,34E+05
3-7/2	4,48E+07	1,19E+05	5,11E+06	3,90E+06	1,45E+05	1,35E+07	1,76E+05
3-7/3	3,70E+07	8,50E+04	4,15E+06	3,16E+06	1,01E+05	1,11E+07	1,33E+05
3-7/4	4,44E+07	1,35E+05	5,20E+06	3,95E+06	1,38E+05	1,40E+07	1,85E+05
3-7/5	4,53E+07	7,89E+04	5,11E+06	3,87E+06	1,31E+05	1,35E+07	1,71E+05

Table 4.39 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partikel Nr.	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 125
3-4/1	1,50E+07	1,32E+05	7,94E+05	9,80E+05	2,26E+04	6,34E+05	1,60E+05
3-4/2	1,50E+07	1,19E+05	8,49E+05	1,04E+06		7,45E+05	1,63E+05
3-4/3	1,28E+07	6,27E+04	7,84E+05	9,85E+05		7,55E+05	1,64E+05
3-4/4	1,34E+07	9,16E+04	7,94E+05	9,71E+05	1,36E+04	6,90E+05	1,48E+05
3-4/5	1,33E+07	7,14E+04	7,57E+05	9,43E+05	1,77E+04	6,34E+05	1,52E+05
3-8/1	1,18E+07	1,78E+05	6,39E+05	8,51E+05		6,57E+05	1,40E+05
3-8/2	1,12E+07	7,81E+04	5,98E+05	7,96E+05		6,14E+05	1,31E+05
3-8/3	1,15E+07	4,73E+04	6,36E+05	8,54E+05		6,42E+05	1,46E+05
3-8/4	1,19E+07	8,40E+04	6,48E+05	8,69E+05		6,35E+05	1,45E+05
3-8/5	1,16E+07	1,05E+05	6,54E+05	8,81E+05		6,92E+05	1,43E+05

Fig. 4.101 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays 2-3 and 2-7 in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.102 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays 2-4 and 2-8 in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.103 Inventory (Bq) of individual fissile particles for selected nuclides from particle trays 3-3 and 3-7 in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.104 Inventory (Bq) of individual fertile particles for selected nuclides from particle trays 3-4 and 3-8 in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.40 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-3/1	4,45E+7		6,74E+6	3,98E+6	1,87E+5	1,78E+7	2,02E+5
2-3/2	2,60E+7		3,84E+6	2,27E+6	1,05E+5	1,00E+7	1,06E+5
2-3/3	4,91E+7		7,47E+6	4,39E+6	1,77E+5	1,91E+7	1,99E+5
2-3/4	4,94E+7		7,66E+6	4,53E+6	1,97E+5	1,97E+7	2,32E+5
2-3/5	4,68E+7		7,08E+6	4,20E+6	1,79E+5	1,85E+7	1,92E+5
2-7/1	5,06E+7		7,35E+6	4,37E+6	1,83E+5	1,91E+7	2,09E+5
2-7/2	4,76E+7		7,38E+6	4,39E+6	1,68E+5	1,94E+7	2,11E+5
2-7/3				Kernbruch			
2-7/4	4,54E+7		5,97E+6	3,53E+6	1,33E+5	1,77E+7	1,88E+5
2-7/5	4,11E+7		5,85E+6	3,48E+6	1,41E+5	1,59E+7	1,55E+5

Table 4.41 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-4/1	1,83E+7		1,21E+6	1,22E+6	2,77E+4	9,01E+5	1,91E+5
2-4/2	1,79E+7		1,20E+6	1,21E+6	2,22E+4	9,01E+5	1,90E+5
2-4/3	1,83E+7		1,28E+6	1,28E+6	2,92E+4	8,76E+5	2,02E+5
2-4/4	1,76E+7		1,19E+6	1,19E+6	1,87E+4	9,28E+5	1,82E+5
2-4/5	1,98E+7		1,31E+6	1,33E+6	2,62E+4	1,03E+6	2,09E+5
2-8/1	1,82E+7		1,29E+6	1,29E+6	2,27E+4	9,96E+5	1,99E+5
2-8/2				Kernbruch			
2-8/3	1,62E+7		1,19E+6	1,21E+6	2,84E+4	8,81E+5	1,88E+5
2-8/4	1,71E+7		1,27E+6	1,28E+6	2,92E+4	9,63E+5	2,04E+5
2-8/5	1,74E+7		1,20E+6	1,22E+6	2,32E+4	8,45E+5	1,87E+5

Table 4.42 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-3/1	4,29E+7		5,91E+6	4,18E+6	1,61E+5	1,50E+7	1,96E+5
3-3/2	4,65E+7		5,79E+6	4,05E+6	1,51E+5	1,50E+7	1,98E+5
3-3/3	4,37E+7		5,83E+6	4,11E+6	1,63E+5	1,49E+7	1,87E+5
3-3/4	4,78E+7		5,99E+6	4,21E+6	1,60E+5	1,58E+7	2,01E+5
3-3/5	4,40E+7		5,65E+6	3,97E+6	1,40E+5	1,47E+7	1,80E+5
3-7/1	3,34E+7		3,95E+6	3,00E+6	9,90E+4	1,06E+7	1,48E+5
3-7/2	4,21E+7		5,04E+6	3,85E+6	1,38E+5	1,34E+7	1,80E+5
3-7/3	3,63E+7		4,08E+6	3,09E+6	1,07E+5	1,11E+7	1,47E+5
3-7/4	4,06E+7		5,09E+6	3,88E+6	1,49E+5	1,37E+7	1,84E+5
3-7/5	4,59E+7		5,01E+6	3,81E+6	1,53E+5	1,34E+7	1,66E+5

Table 4.43 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-4/1	1,25E+7		7,62E+5	9,54E+5		7,76E+5	1,50E+5
3-4/2	1,35E+7		8,16E+5	1,01E+6	1,96E+4	6,39E+5	1,59E+5
3-4/3	1,45E+7		7,86E+5	9,74E+5	1,67E+4	6,66E+5	1,61E+5
3-4/4	1,37E+7		7,75E+5	9,59E+5		7,12E+5	1,53E+5
3-4/5	1,27E+7		7,49E+5	9,17E+5	1,79E+4	6,26E+5	1,48E+5
3-8/1	1,22E+7		6,16E+5	8,28E+5		6,16E+5	1,26E+5
3-8/2	1,14E+7		5,71E+5	7,71E+5		5,90E+5	1,27E+5
3-8/3	1,20E+7		6,20E+5	8,40E+5		5,78E+5	1,43E+5
3-8/4	1,27E+7		6,29E+5	8,54E+5		6,31E+5	1,43E+5
3-8/5	1,23E+7		6,41E+5	8,59E+5		6,40E+5	1,36E+5

Fig. 4.105 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, German

Fig. 4.106 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Aktivität
[Bq]

Fig. 4.107 Inventory (Bq) of individual kernels from fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, German

Fig. 4.108 Inventory (Bq) of individual kernels from fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.44 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-3/1			1,46E+5	7,89E+4	5,55E+3		
2-3/2			1,75E+5	9,83E+4	8,07E+3		
2-3/3			1,18E+5	6,23E+4	5,48E+3		
2-3/4		4,93E+2	1,13E+5	5,98E+4	5,98E+3		
2-3/5			1,18E+5	6,30E+4	5,45E+3		
2-7/1			8,78E+4	4,97E+4	8,67E+3		
2-7/2			1,06E+5	5,91E+4	8,75E+3		
2-7/3				Kernbruch			
2-7/4			7,48E+5	4,33E+5	3,37E+4		
2-7/5		7,48E+3	1,54E+5	8,69E+4	1,23E+4		

Table 4.45 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-4/1		3,50E+2	2,46E+4	2,32E+4	3,32E+2		1,56E+3
2-4/2		4,31E+2	1,52E+4	1,42E+4			1,31E+3
2-4/3		5,47E+2	2,16E+4	2,05E+4			1,60E+3
2-4/4	2,88E+5		2,71E+4	2,63E+4		2,41E+4	4,14E+3
2-4/5		3,55E+2	1,80E+4	1,68E+4			6,87E+2
2-8/1		6,37E+2	1,03E+4	1,04E+4			
2-8/2				Kernbruch			
2-8/3	1,99E+5		2,94E+4	2,83E+4		1,33E+4	3,16E+3
2-8/4			4,04E+3	3,79E+3			
2-8/5		5,30E+2	1,31E+4	1,26E+4			

Table 4.46 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-3/1			1,13E+3	1,04E+3			
3-3/2			2,31E+4	1,50E+4			
3-3/3			2,49E+4	1,67E+4	1,27E+3		
3-3/4		1,21E+3	2,15E+4	1,40E+4			
3-3/5		2,46E+3	2,18E+4	1,39E+4	1,88E+3		
3-7/1			2,45E+4	1,69E+4			
3-7/2			2,24E+4	1,64E+4			
3-7/3			3,02E+4	2,04E+4			
3-7/4			1,50E+4	1,12E+4			
3-7/5			1,64E+4	1,16E+4			

Table 4.47 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-4/1			6,63E+3	7,27E+3			
3-4/2			1,03E+4	8,54E+3			
3-4/3			1,66E+3	5,63E+3			
3-4/4			1,12E+4	1,24E+4			
3-4/5		3,13E+2	5,30E+3	5,26E+3			
3-8/1			2,18E+4	2,23E+4			
3-8/2			1,77E+4	2,34E+4			
3-8/3			7,03E+3	6,34E+3			
3-8/4	2,65E+5		1,01E+4	1,26E+4			1,94E+3
3-8/5			8,66E+3	1,08E+4

Fig. 4.109 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.110 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.111 Inventory (Bq) of the coatings from fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.112 Inventory (Bq) of the coatings from fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.48 Inventory (Bq) of bare kernels plus the associated coatings from fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-3/1	4,45E+7	4,93E+2	6,89E+6	4,06E+6	1,93E+5	1,78E+7	2,02E+5
2-3/2	2,60E+7		4,02E+6	2,37E+6	1,13E+5	1,00E+7	1,06E+5
2-3/3	4,91E+7		7,59E+6	4,45E+6	1,82E+5	1,91E+7	1,99E+5
2-3/4	4,94E+7		7,77E+6	4,59E+6	2,03E+5	1,97E+7	2,32E+5
2-3/5	4,68E+7		7,20E+6	4,26E+6	1,84E+5	1,85E+7	1,92E+5
2-7/1	5,06E+7	7,48E+3	7,44E+6	4,42E+6	1,92E+5	1,91E+7	2,09E+5
2-7/2	4,76E+7		7,49E+6	4,45E+6	1,77E+5	1,94E+7	2,11E+5
2-7/3				Kernbruch			
2-7/4	4,54E+7		6,72E+6	3,96E+6	1,67E+5	1,77E+7	1,88E+5
2-7/5	4,11E+7		6,00E+6	3,57E+6	1,53E+5	1,59E+7	1,55E+5

Table 4.49 Inventory (Bq) of bare kernels plus the associated coatings from fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
2-4/1	1,83E+7	3,50E+2	1,23E+6	1,24E+6	2,80E+4	9,01E+5	1,93E+5
2-4/2	1,79E+7	4,31E+2	1,22E+6	1,22E+6	2,22E+4	9,01E+5	1,91E+5
2-4/3	1,83E+7	5,47E+2	1,30E+6	1,30E+6	2,92E+4	8,76E+5	2,04E+5
2-4/4	1,79E+7		1,22E+6	1,22E+6	1,87E+4	9,52E+5	1,86E+5
2-4/5	1,98E+7	3,55E+2	1,33E+6	1,35E+6	2,62E+4	1,03E+6	2,10E+5
2-8/1	1,82E+7	6,37E+2	1,30E+6	1,30E+6	2,27E+4	9,96E+5	1,99E+5
2-8/2				Kernbruch			
2-8/3	1,64E+7		1,22E+6	1,24E+6	2,84E+4	8,94E+5	1,91E+5
2-8/4	1,71E+7		1,27E+6	1,28E+6	2,92E+4	9,63E+5	2,04E+5
2-8/5	1,74E+7	5,30E+2	1,21E+6	1,23E+6	2,32E+4	8,45E+5	1,87E+5

Table 4.50 Inventory (Bq) of bare kernels plus the associated coatings from fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-3/1	4,29E+7		5,91E+6	4,18E+6	1,61E+5	1,50E+7	1,96E+5
3-3/2	4,65E+7		5,79E+6	4,05E+6	1,51E+5	1,50E+7	1,98E+5
3-3/3	4,37E+7		5,83E+6	4,11E+6	1,63E+5	1,49E+7	1,87E+5
3-3/4	4,78E+7		5,99E+6	4,21E+6	1,60E+5	1,58E+7	2,01E+5
3-3/5	4,40E+7		5,65E+6	3,97E+6	1,40E+5	1,47E+7	1,80E+5
3-7/1	3,34E+7		3,97E+6	3,02E+6	9,90E+4	1,06E+7	1,48E+5
3-7/2	4,21E+7		5,06E+6	3,87E+6	1,38E+5	1,34E+7	1,80E+5
3-7/3	3,63E+7		4,11E+6	3,11E+6	1,07E+5	1,11E+7	1,47E+5
3-7/4	4,06E+7		5,11E+6	3,89E+6	1,49E+5	1,37E+7	1,84E+5
3-7/5	4,59E+7		5,03E+6	3,82E+6	1,53E+5	1,34E+7	1,66E+5

Table 4.51 Inventory (Bq) of bare kernels plus the associated coatings from fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Aktivität zum Abschaltzeitpunkt [Bq]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-4/1	1,25E+7		7,69E+5	9,61E+5		7,76E+5	1,50E+5
3-4/2	1,35E+7		8,26E+5	1,02E+6	1,96E+4	6,39E+5	1,59E+5
3-4/3	1,45E+7		7,88E+5	9,80E+5	1,67E+4	6,66E+5	1,61E+5
3-4/4	1,37E+7		7,86E+5	9,71E+5		7,12E+5	1,53E+5
3-4/5	1,27E+7	3,13E+2	7,54E+5	9,22E+5	1,79E+4	6,26E+5	1,48E+5
3-8/1	1,22E+7		6,38E+5	8,50E+5		6,16E+5	1,26E+5
3-8/2	1,14E+7		5,89E+5	7,94E+5		5,90E+5	1,27E+5
3-8/3	1,20E+7		6,27E+5	8,46E+5		5,78E+5	1,43E+5
3-8/4	1,27E+7		6,39E+5	8,67E+5		6,31E+5	1,45E+5
3-8/5	1,23E+7		6,50E+5	8,70E+5		6,40E+5	1,36E+5

Table 4.52 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Spaltproduktanteil pro Kern [%]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	
2-3/1	100,0		97,9	98,1	97,1	100,0	100,0
2-3/2	100,0		95,6	95,8	92,9	100,0	100,0
2-3/3	100,0		98,4	98,6	97,0	100,0	100,0
2-3/4	100,0		98,5	98,7	97,1	100,0	100,0
2-3/5	100,0		98,4	98,5	97,0	100,0	100,0
2-7/1	100,0		98,8	98,9	95,5	100,0	100,0
2-7/2	100,0		98,6	98,7	95,0	100,0	100,0
2-7/3				Kernbruch			
2-7/4	100,0		88,9	89,1	79,8	100,0	100,0
2-7/5	100,0		97,4	97,6	92,0	100,0	100,0

Table 4.53 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Spaltproduktanteil pro Kern [%]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	
2-4/1	100,0		98,0	98,1	98,8	100,0	99,2
2-4/2	100,0		98,7	98,8	100,0	100,0	99,3
2-4/3	100,0		98,3	98,4	100,0	100,0	99,2
2-4/4	98,4		97,8	97,8	100,0	97,5	97,8
2-4/5	100,0		98,6	98,8	100,0	100,0	99,7
2-8/1	100,0		99,2	99,2	100,0	100,0	100,0
2-8/2				Kernbruch			
2-8/3	98,8		97,6	97,7	100,0	98,5	98,3
2-8/4	100,0		99,7	99,7	100,0	100,0	100,0
2-8/5	100,0		98,9	99,0	100,0	100,0	100,0

Table 4.54 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Spaltproduktanteil pro Kern [%]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-3/1	100,0		100,0	100,0	100,0	100,0	100,0
3-3/2	100,0		99,6	99,6	100,0	100,0	100,0
3-3/3	100,0		99,6	99,6	99,2	100,0	100,0
3-3/4	100,0		99,6	99,7	100,0	100,0	100,0
3-3/5	100,0		99,6	99,7	98,7	100,0	100,0
3-7/1	100,0		99,4	99,4	100,0	100,0	100,0
3-7/2	100,0		99,6	99,6	100,0	100,0	100,0
3-7/3	100,0		99,3	99,3	100,0	100,0	100,0
3-7/4	100,0		99,7	99,7	100,0	100,0	100,0
3-7/5	100,0		99,7	99,7	100,0	100,0	100,0

Table 4.55 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Partik.Nr.	Spaltproduktanteil pro Kern [%]						
	Ce 144	Co 60	Cs 134	Cs 137	Eu 154	Ru 106	Sb 124
3-4/1	100,0		99,1	99,2		100,0	100,0
3-4/2	100,0		98,8	99,2	100,0	100,0	100,0
3-4/3	100,0		99,8	99,4	100,0	100,0	100,0
3-4/4	100,0		98,6	98,7		100,0	100,0
3-4/5	100,0		99,3	99,4	100,0	100,0	100,0
3-8/1	100,0		96,6	97,4		100,0	100,0
3-8/2	100,0		97,0	97,1		100,0	100,0
3-8/3	100,0		98,9	99,3		100,0	100,0
3-8/4	97,9		98,4	98,5		100,0	98,7
3-8/5	100,0		98,7	98,8		100,0	100,0

Fig. 4.113 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule
2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.114 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 2 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.115 The percent retention of fission products in the kernels of intact fissile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.116 The percent retention of fission products in the kernels of intact fertile particles for selected nuclides from particle trays in capsule 3 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

4.6.3 Kernel Retention of Fission Products

The retention of the fission products ^{154}Eu , ^{144}Ce , ^{106}Ru , ^{125}Sb and ^{124}Sb (an activation product) was essentially complete. For ^{137}Cs and ^{134}Cs , the release from the kernel was between 1.5 and 3%. The releases for cesium seem to be quite small for an irradiation lasting 446 effective full power days.

The release of fission products from the kernel in an intact particle is known to be small in comparison with the release from an exposed kernel. For example, in the experiment R2-K13¹⁴, the measured kernel release in intact particles was $13 \pm 7\%$ of that for the exposed kernel. However, the averaged absolute release from the kernels in intact particles was about 15% for ^{137}Cs over the temperature range 900 to 1200°C during an irradiation of 517 effective full power days.

A valid assessment of kernel retention of fission products for experiment HFR-B1, in terms of the previously reported results,¹⁴ can be made only after the thermal analysis of HFR-B1 has been completed.

4.6.4 Cracking of Intact Fuel Particles

Five particles each from trays 2-3, 2-7, 2-4 and 2-8 were selected and cracked using a device which measures the applied load and the force at which the particle cracks. Upon cracking, the force decreases rapidly; the record of the force-time curves displays a maximum as a result. Also measured is the distance the arm, which transmits the applied force, has to move before cracking occurs. In the initial position, the arm touches the particle surface; this position is the zero distance.

The force and distance at which each particle cracks is given in Tables 4.56, 4.57, 4.58, and 4.59 for each of the five particles. In the Tables, the fissile and fertile particles are distinguished. Plots of these data are shown in Figs. 4.117, 4.118, 4.119, and 4.120.

At the 67% confidence level, there is no statistical difference in either the force or the distance movement required to crack fissile or fertile particles from either capsule 2 or 3. The overall average force and standard deviation is 12.5 ± 2.7 N and the overall average distance movement and standard deviation is 0.039 ± 0.021 mm. This average distance movement represents about 5% of the particle diameter for either fissile or fertile particles.

4.7 Heating Tests with Intermittent Water-Vapor Injections

Heating tests with intermittent injections of water vapor have been conducted as indicated on Fig. 4.3 for the two tasks involving fuel compacts and unbonded fuel particles. These tests were conducted in the KORA facility¹⁵ at KFA under postirradiation conditions.

The KORA facility consists of a flow apparatus in which the sweep gas, He, can be mixed with water vapor and sent through a furnace containing the fuel specimen (ie., particles, compacts or fuel spheres). The water vapor interacts or reacts with the exposed kernels and the carbonaceous material in the specimen. The former results in an enhanced release of fission products¹⁶. The sweep gas mixture containing the released fission products passes through and is acted upon by ion chambers and the various filters in the gas train. At the end, the activity of the fission gases is measured. In the tested specimens, the activity of the moderate- and short-lived fission gas isotopes is negligible because of the delay between the end of irradiation and the start of the KORA test. In KORA, only the long-lived gaseous isotope ^{85}Kr has been measured. Technical data for the KORA facility is given in Table 4.60.

Table 4.56 Force and movement conditions under which fissile particles from capsule 2 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1	Zerdrück- Parameter	
Tray/ Partikel	Kraft [N]	Weg [mm]
2-3/1	14,31	0,020
2-3/2	14,70	0,028
2-3/3	12,15	0,033
2-3/4	15,23	0,030
2-3/5	12,75	0,024
Mittelwert	13,83	0,027
Standardabweichung	8,5%	16,9%
2-7/1	20,19	0,038
2-7/2	14,31	0,021
2-7/3	15,09	0,029
2-7/4	12,94	0,018
2-7/5	6,66	0,030
Mittelwert	13,84	0,027
Standardabweichung	31,4%	26,0%

Table 4.57 Force and movement conditions under which fertile particles from capsule 2 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1	Zerdrück- Parameter	
Tray/ Partikel	Kraft [N]	Weg [mm]
2-4/1	11,76	0,029
2-4/2	16,46	0,024
2-4/3	15,48	0,019
2-4/4	17,05	0,023
2-4/5	9,60	0,036
Mittelwert	14,07	0,026
Standardabweichung	20,6%	22,3%
2-8/1	13,13	0,038
2-8/2	12,35	0,083
2-8/3	18,23	0,082
2-8/4	11,76	0,022
2-8/5	17,05	0,039
Mittelwert	14,50	0,053
Standardabweichung	18,1%	47,3%

Zerdrück Parameter = Cracking Parameter

Tray/Partikel = Tray/Particle

Kraft [N] = Force [N]

Weg [mm] = Distance Movement [mm]

Mittelwert = Average Value

Standardabweichung = Standard Deviation

Table 4.58 Force and movement conditions under which fissile particles from capsule 3 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1	Zerdrück- Parameter	
Tray/ Partikel	Kraft [N]	Weg [mm]
3-3/1	12,94	0,037
3-3/2	10,58	0,026
3-3/3	9,60	0,026
3-3/4	12,35	0,026
3-3/5	12,15	0,035
Mittelwert	11,52	0,030
Standardabweichung	10,7%	16,5%
3-7/1	12,74	0,030
3-7/2	6,47	0,070
3-7/3	13,52	0,037
3-7/4	13,92	0,093
3-7/5	11,37	0,024
Mittelwert	11,60	0,051
Standardabweichung	23,4%	52,0%

Table 4.59 Force and movement conditions under which fertile particles from capsule 3 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1	Zerdrück- Parameter	
Tray/ Partikel	Kraft [N]	Weg [mm]
3-4/1	16,86	0,033
3-4/2	12,35	0,026
3-4/3	10,39	0,037
3-4/4	9,80	0,031
3-4/5	12,54	0,025
Mittelwert	12,39	0,030
Standardabweichung	20,0%	14,7%
3-8/1	12,94	0,022
3-8/2	16,66	0,051
3-8/3	10,19	0,087
3-8/4	14,11	0,031
3-8/5	18,03	0,031
Mittelwert	14,39	0,044
Standardabweichung	19,2%	52,5%

Zerdrück Parameter = Cracking Parameter

Tray/Partikel = Tray/Particle

Kraft [N] = Force [N]

Weg [mm] = Distance Movement [mm]

Mittelwert = Average Value

Standardabweichung = Standard Deviation

Kraft [N] = Force [N]; Weg [mm] = Distance Movement [mm]

Fig. 4.117 Force and movement conditions under which fissile particles from capsule 2 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Kraft [N] = Force [N]; Weg [mm] = Distance Movement [mm]

Fig. 4.118 Force and movement conditions under which fertile particles from capsule 2 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Kraft [N] = Force [N]; Weg [mm] = Distance Movement [mm]

Fig. 4.119 Force and movement conditions under which fissile particles from capsule 3 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Kraft [N] = Force [N]; Weg [mm] = Distance Movement [mm]

Fig. 4.120 Force and movement conditions under which fertile particles from capsule 3 crack
Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.60 Technical data for the KORA facility
 Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Resistance furnace with temperature control	
Heating elements	Kantal (MoSi ₂)
Tube inset	Quartz glass up to 1000 °C Alsint / SiC up to 1600 °C
Inner diameter for samples	70 mm
Max. temperature	1600 °C
Gas pressure	~ 1300 mbar
Temperature measurement	Pt/Rh thermocouples
Open gas loop with throughput control	
Throughput	30 ltr/h (max. 100 ltr/h)
Medium	Helium, H ₂ O, Air, CO, CO ₂
Measurements	Throughput, pressure, humidity
Water vapor levels	1-80 kPa
Fission product measurements	
Fission gases	Continuous (ionization chamber, NaI detector)
Solid fission products	Difference of sample inventory before and after test (Cs-137)

The specimens used in the four heating tests conducted with intermittent injections of water vapor were the fuel compacts 2.2.1 plus 2.2.2; 3.2.1 plus 3.2.2; and two sets of 5 kernels taken from 10 particles which had been irradiated in tray 3-7; tray 3-7 contained normally configured fissile UCO TRISO particles. Property data for the specimens are presented in Table 4.61; irradiation and test conditions are presented in Table 4.62.

4.71 Water Vapor Injection Tests with Compacts 2.2.1 and 2.2.2

The fuel compacts 2.2.1 and 2.2.2 were irradiated in capsule 2 and were not exposed to water vapor during irradiation. The release of ^{85}Kr during the heating test and water vapor injections at 800°C with the set of fuel compacts 2.2.1 and 2.2.2 is shown in Fig. 4.121 as a function of time in terms of the fractional release and the release rate; the latter is calculated according to the relation:

$$R/N = \{f(t_i) - f(t_{i-1})\}/(t_i - t_{i-1})$$

where

$$\begin{aligned} R/N &= \text{release rate (1/s)} \\ f(t_i) &= \text{fractional release at time } t_i \end{aligned}$$

The data plotted in Fig. 4.121 are presented in Table 4.63.

The data in Fig. 4.121 show a general decline in the release rate of ^{85}Kr , a trend consistent with a decline in the inventory of this isotope. At the beginning of the two water vapor injections, at a partial pressure of 1 kPa, there is a detectable rapid increase in the release rate. Thus, the ^{85}Kr release is enhanced and therefore the release is a function of the water vapor pressure. The increases are, however, small in accord with a small inventory of ^{85}Kr . The small inventory may be a consequence of the higher temperatures and frequent changes in temperature experienced during the irradiation undergone by the compacts in capsule 2.

It appears, during the first water vapor injection shown in Fig. 4.121, that the release of ^{85}Kr following the initial rapid increase is higher than in the absence of the water vapor as indicated by the noticeable decline in release rate upon termination of the injection. However this persistent, enhanced release is not evident during the second water vapor injection and is somewhat obscured generally by the steady decline in release rate.

4.72 Water Vapor Injection Tests with Compacts 3.2.1 and 3.2.2

The fuel compacts 3.2.1 and 3.2.2 were irradiated in capsule 3 and were exposed to water vapor during irradiation. Unfortunately, after the water-vapor injections, but with one exception, insufficient time was allowed for sintering and annealing; the same can be said of the tests under discussion. These relatively high frequencies of injection complicate the analysis.

The release of ^{85}Kr during the second heating test and associated water vapor injections at 800°C with the set of fuel compacts, 3.2.1 and 3.2.2, is shown in Fig. 4.122 as a function of time in terms of the fractional release and the release rate. The data are presented in Table 4.64. The partial pressure of water vapor ranged from 1 to 50 kPa and altogether there were nine injections. In seven of the injections there were distinct and rapid initial releases of ^{85}Kr in qualitative agreement with previous experiments¹⁶. Of the first three water vapor injections, all at 1 kPa of water vapor, the response of the fuel compacts to the second and third resulted in a distinct decrease to a steady value of the release rate, which at the termination of water vapor injection, returned to the pre-injection level. This is shown clearly in Fig. 4.123. The suggestion was made¹⁵ that the release of ^{85}Kr atoms was

Table 4.61 Property data on the fuel compacts and fuel kernels used in the heating tests with intermittent injections of water vapor

Item	Driver Fissile	Designed-to-Fail Fissile	Fertile
Particles			
Sample number	26157-11-0100	6450-00-0100	6252-12-COMP
Coating type	TRISO	Seal ^a	TRISO
Total part. diam.	824 μm	389 μm	786 μm
Kernel composition	$\text{UC}_{0.5}\text{O}_{1.5}$	$\text{UC}_{0.4}\text{O}_{1.6}$	ThO_2
Kernel diameter	353 μm	347 μm	452 μm
Compacts			
Number of particles	896	87	500
Uranium (g)	0.1715	0.0185	--
U-235 (g)	0.0336	0.0032	--
Thorium (g)	--	--	0.2168

^(a) a 23 μm thick pyrocarbon layer

Table 4.62 Irradiation conditions, ^{85}Kr inventory at beginning of test and test conditions for the fuel compacts and fuel kernels used in the heating tests with intermittent injections of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fuel sample	Sample type	Kernel	Defective particles	Irradiation conditions		
				Burnup (% FIMA) (a)	Fast fluence $1\text{E}25\text{ (1/m}^2\text{)}$ $E>0,1\text{MeV}$ (b)	Irradiation temperature (°C)
HFR-B1, 2.2.1+2	Compacts	UCO	174	21.7	6,6	880-1230
HFR-B1, 3.2.1+2	Compacts	UCO	174	19.7	5,1	820-1050
HFR-B1, tr. 3-7a	Kernels	UCO	5	19.7	5,1	820-1050
HFR-B1, tr. 3-7a	Kernels	UCO	5	19.7	5,1	820-1050

Fuel sample	Kr-85-Inventory at test		
	Sample resp. des.-to-fail part. (Bq) (c)	1 particle (Bq) (c)	1 particle total release from test (Bq)
HFR-B1, 2.2.1+2	6,99E+07	4,02E+05	
HFR-B1, 3.2.1+2	6,56E+07	3,77E+05	
HFR-B1, tr. 3-7a	1,56E+08	3,12E+05	3,20E+05
HFR-B1, tr. 3-7a	1,56E+08	3,12E+05	3,60E+05

Fuel sample	Test conditions		
	Temperature (°C)	Water vapor (kPa)	Number of injections
HFR-B1, 2.2.1+2	800	1	2
HFR-B1, 3.2.1+2	800	1; 14; 50	9
HFR-B1, tr. 3-7a	800	1; 50	4
HFR-B1, tr. 3-7a	800	1; 2	1

(a) Ref. 6

(b) Uncorrected for final gamma scan; values are for the HFR Petten; HGTR values would be smaller by the factor 0.803¹⁷

(c) Calculated from the ^{137}Cs measurements

Fig. 4.121 The fractional release and release rate of ^{85}Kr at 800°C from fuel compacts 2.2.1 and 2.2.2 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.63 The fractional release and release rate of ^{85}Kr at 800°C from fuel compacts 2.2.1 and 2.2.2 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1/2.2.1 u. 2						
Temperature <i>T</i> (°C)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate <i>R/N</i> (1/s)
20	20			-23,5		
100	-			-22,5	4,98E-05	
130	-			-21,5	1,49E-03	
170	-			-19,5	6,28E-03	
180	-			-17	7,27E-03	
270	-			-8	9,26E-03	
410	-			-6	9,92E-03	
570	-			-4	1,05E-02	
705	-			-1,5	1,07E-02	
800	-			0	1,08E-02	1,70E-08
800	5			5	1,10E-02	1,06E-08
800	10			10	1,12E-02	1,06E-08
800	20	0		20	1,16E-02	1,06E-08
800		0,5	1	20,5	1,16E-02	1,88E-08
800		1,5	1	21,5	1,17E-02	1,25E-08
800	1. Water- injection	2,5	1	22,5	1,17E-02	9,65E-09
800		4	1	24	1,18E-02	8,27E-09
800		6	1	26	1,18E-02	8,04E-09
800		10	1	30	1,19E-02	7,90E-09
800		15	1	35	1,21E-02	7,49E-09
800		20	1	40	1,22E-02	6,89E-09
800		30	1	50	1,24E-02	4,60E-09
800		40	1	60	1,26E-02	4,14E-09
800		50	1	70	1,27E-02	3,68E-09
800		70	1	90	1,30E-02	3,68E-09
800		90	1	110	1,31E-02	3,68E-09
800		110	1	130	1,33E-02	3,22E-09
800		130	1	150	1,36E-02	2,99E-09
800		150	1	170	1,38E-02	2,30E-09
800	0	188	1	188	1,40E-02	2,07E-09
800	20			208	1,40E-02	9,19E-10
800	40			228	1,41E-02	4,60E-10
800	60			248	1,41E-02	3,22E-10
800	80			268	1,41E-02	2,30E-10
800	100			288	1,42E-02	2,07E-10
800	120			308	1,42E-02	2,07E-10
800	160			248	1,42E-02	1,38E-10
800	200			388	1,42E-02	1,15E-10
800	240			428	1,42E-02	6,89E-11
800	281	0		449	1,42E-02	4,60E-11

Table 4.63 (continued)

HFR-B1/2.2.1 u. 2						
Temperature T (°C)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate R/N (1/s)
800	2. Water- injection	5	1	454	1,42E-02	1,84E-10
800		10	1	449	1,42E-02	1,61E-10
800		20	1	469	1,42E-02	1,61E-10
800		40	1	489	1,43E-02	1,38E-10
800		60	1	509	1,43E-02	1,15E-10
800		80	1	529	1,43E-02	9,19E-11
800	0	96	1	545	1,43E-02	9,19E-11
800	10			555	1,43E-02	9,19E-11
800	20			565	1,43E-02	9,19E-11
800	40			585	1,43E-02	6,89E-11
800	60			605	1,43E-02	6,89E-11
800	80			625	1,43E-02	6,89E-11
800	120			665	1,43E-02	5,51E-11
800	160			705	1,43E-02	3,45E-11
800	191			736	1,43E-02	2,30E-11

Fig. 4.122 The fractional release and release rate of ^{85}Kr at 800°C from fuel compacts 3.2.1 and 3.2.2 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.123 The fractional release and release rate of ^{85}Kr at 800°C from fuel compacts 3.2.1 and 3.2.2 during the second 1 kPa water vapor injection Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.64 The fractional release and release rate of ^{85}Kr at 800°C from fuel compacts 3.2.1 and 3.2.2 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1/3.2.1 u. 2						
Temperature T ($^{\circ}\text{C}$)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate R/N (1/s)
500	-			-1,5	7,32E-05	
800	0			0	1,32E-04	1,15E-08
800	1			1	1,32E-04	1,17E-08
800	2			2	1,71E-04	1,17E-08
800	2,5			2,5	2,44E-04	2,92E-08
800	3,5			3,5	2,93E-04	7,55E-08
800	4,5			4,5	5,61E-04	7,55E-08
800	6			6	6,95E-04	2,40E-08
800	8			8	8,05E-04	1,89E-08
800	10			10	9,51E-04	1,58E-08
800	15			15	1,07E-03	1,58E-08
800	17			17	1,34E-03	1,58E-08
800			1	17,5	1,43E-03	1,27E-08
800			1	18	1,48E-03	4,94E-07
800			1	18,5	2,20E-03	3,02E-07
800			1	19	2,48E-03	1,51E-07
800			1	19,5	2,68E-03	6,86E-08
800			1	20,5	2,80E-03	3,09E-08
800			1	22,5	2,85E-03	8,24E-09
800			1	28	2,90E-03	6,18E-08
800			1	32	2,98E-03	5,49E-09
800			1	37	3,07E-03	5,49E-09
800			1	41	3,17E-03	5,49E-09
800	0			43	3,24E-03	5,49E-09
800	2			45	3,28E-03	9,61E-09
800	4			50	3,35E-03	9,61E-09
800	9			53	3,52E-03	8,24E-09
800	12			60	3,59E-03	6,32E-09
800	19			70	3,76E-03	6,32E-09
800	29			80	3,95E-03	6,04E-09
800	39					
800	48			89	4,17E-03	5,49E-09
800			1	91	4,34E-03	4,80E-09
800			1	94	4,37E-03	2,54E-09
800			1	99	4,39E-03	2,54E-09
800			1	104	4,44E-03	2,54E-09
800			1	109	4,49E-03	2,54E-09
800			1	113	4,53E-03	2,54E-09
800	0			115	4,57E-03	2,54E-09
800	2			118	4,59E-03	2,88E-09
800	5			123	4,62E-03	5,15E-09
800	10			133	4,72E-03	5,15E-09
800	20			138	4,80E-03	5,15E-09
800	25			143	5,00E-03	4,80E-09
800	30			148	5,08E-03	4,80E-09
800	35			153	5,15E-03	4,12E-09
800	40			158	5,22E-03	4,12E-09
800	45					

Table 4.64 (continued)

HFR-B1/3.2.1 u. 2						
Temperature <i>T</i> (°C)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate <i>R/N</i> (1/s)
800	48	0	1	161	5,32E-03	2,40E-09
800		2	1	163	5,34E-03	2,40E-09
800		5	1	166	5,37E-03	2,08E-09
800	3. Water- injection	10	1	171	5,40E-03	1,78E-09
800		15	1	176	5,43E-03	1,65E-09
800		20	1	181	5,46E-03	1,65E-09
800	0	24	1	185	5,48E-03	1,65E-09
800	2			187	5,49E-03	1,65E-09
800	5			190	5,52E-03	2,95E-09
800	10			195	5,57E-03	2,95E-09
800	20			205	5,67E-03	2,88E-09
800	30			215	5,77E-03	2,75E-09
800	40			225	5,88E-03	2,61E-09
800	48	0	14	233	5,92E-03	2,20E-09
800		2	14	235	5,94E-03	2,20E-09
800		5	14	238	5,96E-03	2,81E-09
800		7,5	14	240,5	6,01E-03	1,24E-08
800		9	14	242	6,10E-03	2,20E-08
800	4. Water- injection	10	14	243	6,59E-03	3,43E-07
800		10,5	14	243,5	8,29E-03	1,17E-06
800		11	14	244	9,76E-03	3,43E-07
800		12	14	245	1,00E-02	1,17E-08
800		14	14	247	1,00E-02	6,86E-09
800		18	14	251	1,01E-02	6,18E-09
800	0	24	14	257	1,01E-02	5,49E-09
800	5			262	1,02E-02	2,08E-09
800	10			267	1,02E-02	1,37E-09
800	20			277	1,03E-02	1,17E-09
800	30			287	1,03E-02	1,17E-09
800	40			297	1,04E-02	1,17E-09
800	50			307	1,04E-02	1,10E-09
800	60			317	1,04E-02	9,61E-10
800	72	0	14	329	1,05E-02	8,24E-10
800		2	14	331	1,05E-02	8,24E-10
800		4	14	333	1,05E-02	4,80E-09
800		6	14	335	1,05E-02	4,80E-09
800		8	14	337	1,06E-02	1,37E-09
800	5. Water- injection	10	14	339	1,06E-02	1,37E-09
800		12	14	341	1,06E-02	1,37E-09
800		13	14	342	1,06E-02	1,37E-08
800		14	14	343	1,07E-02	2,40E-08
800		15	14	344	1,07E-02	3,84E-09
800		17	14	346	1,07E-02	3,84E-09
800		19	14	348	1,08E-02	3,84E-09
800		20	14	349	1,08E-02	1,51E-09
800		20,5	14	349,5	1,09E-02	2,27E-07

Table 4.64 (continued)

HFR-B1/3.2.1 u. 2						
Temperature T (°C)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate R/N (1/s)
800	5. Water- injection	21	14	350	1,12E-02	2,27E-07
800		22	14	351	1,15E-02	2,75E-08
800		23	14	352	1,15E-02	1,17E-08
800		24	14	353	1,16E-02	1,10E-08
800		25	14	354	1,16E-02	1,03E-08
800		27	14	356	1,17E-02	1,03E-08
800		30	14	359	1,18E-02	1,03E-08
800		35	14	364	1,20E-02	1,72E-08
800		37,5	14	366,5	1,21E-02	2,75E-08
800		40	14	369	1,24E-02	5,22E-08
800		42	14	371	1,28E-02	5,22E-08
800		44	14	373	1,31E-02	2,75E-08
800		46	14	375	1,33E-02	1,37E-08
800		48	14	377	1,33E-02	1,30E-08
800	0					
800		4		381	1,34E-02	6,86E-09
800		10		387	1,35E-02	3,43E-09
800		15		392	1,35E-02	2,75E-09
800		20		397	1,36E-02	1,72E-09
800		30		407	1,36E-02	1,37E-09
800		40		417	1,37E-02	1,17E-09
800		50		427	1,37E-02	1,17E-09
800		70		447	1,38E-02	1,10E-09
800		90		467	1,39E-02	1,03E-09
800	6. Water- injection	0	1	489	1,40E-02	8,92E-10
800		0,5	20	489,5	1,40E-02	2,40E-07
800		1	50	490	1,54E-02	3,78E-07
800		1,5	50	490,5	1,57E-02	5,49E-08
800		2,5	50	491,5	1,57E-02	1,24E-08
800		5	50	494	1,58E-02	2,06E-09
800		7,5	50	496,5	1,58E-02	7,55E-09
800		10	50	499	1,59E-02	7,55E-09
800		15	50	504	1,60E-02	5,49E-09
800		20	50	509	1,60E-02	4,12E-09
800		24	50	513	1,61E-02	2,75E-09
800	0					
800						
800	10			523	1,61E-02	4,12E-10
800	30			543	1,61E-02	2,75E-10
800	50	0	1	563	1,61E-02	2,75E-10
800		2,5	50	565,5	1,62E-02	2,40E-09
800		5	50	568	1,62E-02	2,40E-09
800		10	50	573	1,62E-02	2,40E-09
800		11,5	50	574,5	1,63E-02	2,75E-08
800		12	50	575	1,64E-02	1,37E-07
800		12,5	50	575,5	1,65E-02	1,85E-08
800		14	50	577	1,66E-02	4,80E-09
800		20	50	583	1,66E-02	4,12E-09
800		30	50	593	1,68E-02	4,19E-09

Table 4.64 (continued)

HFR-B1/3.2.1 u. 2						
Temperature <i>T</i> (°C)	Time without humidity (h)	Time with humidity (h)	Relative humidity (%)	Heating time (h)	Kr 85	
					Fractional release	Release rate <i>R/N</i> (1/s)
800	7. Water- injection	35	50	598	1,69E-02	4,19E-09
800		40	50	603	1,69E-02	5,83E-09
800		45	50	608	1,70E-02	8,58E-09
800		48	50	611	1,72E-02	1,58E-08
800	0					
800	2			613	1,73E-02	1,03E-08
800	5			616	1,73E-02	2,75E-09
800	10			621	1,74E-02	6,86E-10
800	20			631	1,74E-02	4,12E-10
800	30			641	1,74E-02	4,12E-10
800	49	0		660	1,74E-02	4,12E-10
800	8. Water- injection	0,5		660,5	1,74E-02	4,12E-08
800		1		661	1,83E-02	1,78E-06
800		1,5	50	661,5	1,99E-02	3,09E-07
800		2	50	662	2,01E-02	5,49E-08
800		2,5	50	662,5	2,02E-02	8,24E-09
800		3	50	663	2,02E-02	6,86E-09
800		5	50	665	2,02E-02	6,86E-10
800		10	50	670	2,03E-02	4,12E-10
800		13	50	673	2,03E-02	4,12E-10
800		15	50	675	2,03E-02	1,17E-09
800		17	50	677	2,03E-02	4,12E-09
800		20	50	680	2,03E-02	4,12E-09
800		23	50	683	2,04E-02	4,12E-09
800	0					
800	5			688	2,04E-02	5,49E-10
800	10			693	2,04E-02	5,49E-10
800	15			698	2,04E-02	1,37E-10
800	24	0		707	2,04E-02	1,37E-10
800	9. Water- injection	1	45	708	2,04E-02	4,12E-09
800		2	45	709	2,04E-02	8,24E-09
800		3	45	710	2,05E-02	6,86E-09
800		5	45	712	2,05E-02	4,80E-09
800		7,5	45	714,5	2,05E-02	3,84E-09
800		10	45	717	2,05E-02	2,40E-09
800		15	45	722	2,06E-02	2,06E-09
800		20	45	727	2,06E-02	1,85E-09
800		24	45	731	2,07E-02	1,72E-09
800	0					
800	2			733	2,07E-02	1,72E-09
800	10			741	2,07E-02	6,86E-10
800	24			755	2,07E-02	6,86E-11

retarded by the "moisturizing" of fuel and graphite grain surfaces.

Over the range of water-vapor partial pressures, a more or less typical release rate pattern is observed. There is an initial rapid release which declines to a level showing a much less rapid decline and then again, after the termination of the injection of water vapor, to a level with a still more gentle decline, a decline that over the period of 755 h of the test, apparently represents a roughly steady depletion rate for the inventory of ^{85}Kr .

4.73 Water Vapor Injection Tests with UCO Kernels

The kernels of $\text{UC}_{0.5}\text{O}_{1.5}$ from unbonded particles irradiated in tray 7 in the central hole of capsule 3 were heated at 800°C in the KORA facility with intermittent injections of water vapor. The properties of the kernels and associated coatings are given in Table 4.61, and the irradiation conditions, ^{85}Kr inventory and KORA test conditions are given in Table 4.62. Two KORA experiments were conducted using 5 kernels in each test; the kernels had been removed from the particles after cracking the particles. The release profiles of ^{85}Kr during the heating tests are shown in Figs. 4.124 and 4.125 and the corresponding data are presented in Tables 4.65 and 4.66, for the two separate tests with the assumed identical sets of 5 kernels.

Figs. 4.124 and 4.125 indicate that a strong variation occurs between the two release rate profiles shown. In one case, a large release occurs upon bringing the sample to the test temperature and a smaller release upon injecting water vapor at a partial pressure of 1 kPa. In the other case, the inverse occurs, i.e., the release is smaller upon bringing the kernels to the test temperature and larger upon injecting water vapor at a partial pressure of 1 kPa. Thus a consistent response to the experimental conditions is absent. Such fuel behavior was not observed¹⁶ with essentially bare kernels embedded in fuel compacts heated under irradiation conditions with intermittent water vapor injections. Furthermore, the lack of a strong response to the injection of water vapor at a partial pressure of 50 kPa as in Fig. 4.124, indicated that the ^{85}Kr inventory in gas bubbles is depleted.

4.8 STATUS OF THE PIE OF CAPSULES 2 AND 3

An overview of the status of the PIE of capsules 2 and 3 is given in Fig. 4.126 by using the modified PIE flow chart (Fig. 4.3) and indicating the remaining tasks.

Fig. 4.124 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Fig. 4.125 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

Table 4.65 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1, 3-7a						
Temperature T ($^\circ\text{C}$)	Time without water vapor (h)	Water vapor		Heating time (h)	Kr 85	
		Time (h)	Partial pressure (kPa)		Fractional release	Release rate R/N (1/s)
800	1			1	4,38E-04	1,06E-07
800	2			2	6,88E-04	7,50E-08
800	3			3	1,00E-03	8,13E-08
800	4			4	1,63E-03	2,00E-07
800	5			5	2,50E-03	2,75E-07
800	6			6	1,66E-01	4,69E-05
800	7			7	2,15E-01	2,04E-06
800	8			8	2,18E-01	3,88E-07
800	9			9	2,19E-01	2,56E-07
800	10			10	2,20E-01	2,31E-07
800	11			11	2,21E-01	2,94E-07
800	12			12	2,22E-01	2,75E-07
800	13			13	2,23E-01	2,75E-07
800	14			14	2,24E-01	3,00E-07
800	15			15	2,26E-01	2,81E-07
800	16			16	2,27E-01	2,94E-07
800	17			17	2,28E-01	3,13E-07
800	18			18	2,29E-01	2,94E-07
800	19			19	2,30E-01	2,75E-07
800	20	0	0	20	2,31E-01	3,00E-07
800		1	1	21	2,32E-01	3,13E-08
800		2	1	22	8,23E-01	4,69E-05
800		3	1	23	8,77E-01	2,31E-08
800		4	1	24	8,82E-01	9,13E-07
800	1. Water- injection	5	1	25	8,85E-01	8,25E-07
800		6	1	26	8,88E-01	1,06E-08
800		7	1	27	8,90E-01	1,06E-08
800		8	1	28	8,93E-01	6,88E-07
800		9	1	29	8,95E-01	5,94E-07
800	0	10	1	30	8,97E-01	5,81E-07
800	1			31	8,99E-01	6,19E-07
800	2			32	9,01E-01	4,81E-07
800	3			33	9,03E-01	5,00E-07
800	4			34	9,05E-01	3,94E-07
800	5			35	9,06E-01	2,56E-07
800	6			36	9,07E-01	2,00E-07
800	7			37	9,08E-01	1,38E-07
800	8			38	9,08E-01	1,25E-07
800	9			39	9,09E-01	9,38E-08
800	10			40	9,09E-01	1,00E-07

Table 4.65 (continued)

HFR-B1, 3-7a						
Temperature T (°C)	Time without water vapor (h)	Water vapor		Heating time (h)	Kr 85	
		Time (h)	Partial pressure (kPa)		Fractional release	Release rate R/N (1/s)
800	11			41	9,10E-01	1,13E-07
800	12			42	9,11E-01	5,63E-08
800	13			43	9,11E-01	1,06E-07
800	14	0	1	44	9,11E-01	1,25E-07
800		1	50	45	9,12E-01	1,25E-07
800		2	50	46	9,13E-01	2,69E-07
800		3	50	47	9,16E-01	8,69E-07
800	2. Water injection	4	50	48	9,19E-01	6,94E-07
800		5	50	49	9,21E-01	6,94E-07
800		6	50	50	9,24E-01	6,69E-07
800		7	50	51	9,26E-01	5,94E-07
800		8	50	52	9,28E-01	5,94E-07
800		9	50	53	9,30E-01	6,06E-07
800	0	10	50	54	9,32E-01	5,06E-07
800	1			55	9,34E-01	4,81E-07
800	2			56	9,36E-01	4,81E-07
800	3			57	9,38E-01	4,00E-07
800	4			58	9,39E-01	3,06E-07
800	5			59	9,40E-01	2,88E-07
800	6			60	9,41E-01	2,31E-07
800	7			61	9,42E-01	2,25E-07
800	8			62	9,43E-01	1,94E-07
800	9			63	9,44E-01	1,38E-07
800	10			64	9,44E-01	1,25E-07
800	11			65	9,45E-01	1,19E-07
800	12			66	9,45E-01	1,06E-07
800	13			67	9,46E-01	8,13E-08
800	14	0	1	68	9,46E-01	9,38E-08
800		1	50	69	9,47E-01	1,06E-07
800		2	50	70	9,47E-01	2,25E-07
800		3	50	71	9,49E-01	3,50E-07
800	3. Water injection	4	50	72	9,50E-01	2,75E-07
800		5	50	73	9,51E-01	2,81E-07
800		6	50	74	9,52E-01	3,19E-07
800		7	50	75	9,53E-01	2,69E-07
800		8	50	76	9,54E-01	2,56E-07
800		9	50	77	9,55E-01	2,69E-07
800	1	10	50	78	9,56E-01	2,44E-07
800	2			79	9,57E-01	2,06E-07
800	3			80	9,58E-01	2,19E-07

Table 4.65 (continued)

HFR-B1, 3-7a						
Temperature T (°C)	Time without water vapor (h)	Water vapor		Heating time (h)	Kr 85	
		Time (h)	Partial pressure (kPa)		Fractional release *	Release rate R/N (1/s)
800	3			81	9,59E-01	1,88E-07
800	4			82	9,60E-01	1,44E-07
800	5			83	9,60E-01	1,06E-07
800	6			84	9,61E-01	1,13E-07
800	7			85	9,61E-01	1,08E-07
800	8			86	9,61E-01	7,50E-08
800	9			87	9,62E-01	8,13E-08
800	10			88	9,62E-01	5,00E-08
800	11			89	9,62E-01	5,63E-08
800	12			90	9,62E-01	3,75E-08
800	13	0	0	91	9,63E-01	5,00E-08
800		1	50	92	9,63E-01	6,25E-08
800		2	50	93	9,63E-01	8,13E-08
800		3	50	94	9,64E-01	1,38E-07
800	4. Water- injection	4	50	95	9,65E-01	3,75E-07
800		5	50	96	9,66E-01	2,13E-07
800		6	50	97	9,67E-01	2,38E-07
800		7	50	98	9,68E-01	2,00E-07
800		8	50	99	9,69E-01	2,44E-07
800		9	50	100	9,70E-01	2,00E-07
800		10	50	101	9,70E-01	2,44E-07
800	0	11	50	102	9,71E-01	1,84E-07
800	1			103	9,72E-01	1,88E-07
800	2			104	9,73E-01	2,56E-07
800	3			105	9,74E-01	2,44E-07
800	4			106	9,75E-01	1,75E-07
800	5			107	9,75E-01	1,00E-07
800	6			108	9,76E-01	1,25E-07
800	7			109	9,76E-01	8,13E-08
800	8			110	9,77E-01	6,25E-08
800	9			111	9,77E-01	6,88E-08
800	10			112	9,77E-01	6,25E-08
800	11			113	9,77E-01	5,63E-08
800	12			114	9,78E-01	5,00E-08
800	12			115	9,78E-01	8,75E-08

* Kr 85 inventory of 5 particles is 1,60E+06 (100% release). The inventory calculated from measured Cs 137 is 1,58E+06

Table 4.66 The fractional release and release rate of ^{85}Kr at 800°C from 5 UCO kernels taken from particles in tray 3-7 as a function of time and the partial pressure of water vapor Source: Forschungszentrum Jülich GmbH, Jülich, Germany

HFR-B1, 3-7b						
Temperature T ($^\circ\text{C}$)	Time without water vapor (h)	Water vapor		Heating time (h)	Kr 85	
		Time (h)	Partial pressure (kPa)		Fractional release	Release rate R/N (1/s)
300	-2,5			-2,5	4,42E-04	
520	-1,5			-1,5	1,38E-03	1,99E-07
630	-0,5			-0,5	2,38E-03	2,38E-07
770	-0,3			-0,3	2,38E-03	1,66E-06
800	0,0			0,0	2,38E-03	3,78E-05
800	0,2			0,2	9,96E-02	9,56E-05
800	0,5			0,5	9,96E-02	4,81E-05
800	0,8			0,8	9,96E-02	2,07E-05
800	1,1			1,1	9,96E-02	9,23E-05
800	1,3			1,3	2,90E-01	6,46E-05
800	1,4			1,4	2,90E-01	5,32E-05
800	1,6			1,6	2,90E-01	1,23E-04
800	2,4			2,4	5,22E-01	1,38E-05
800	2,7			2,7	5,22E-01	9,83E-05
800	3,3			3,3	7,06E-01	1,68E-05
800	3,8			3,8	7,06E-01	3,70E-06
800	4,3			4,3	7,81E-01	9,94E-07
800	5,3			5,3	7,82E-01	3,81E-07
800	6,3			6,3	7,83E-01	1,93E-07
800	7,3			7,3	7,83E-01	1,60E-07
800	8,3			8,3	7,83E-01	1,22E-07
800	9,3			9,3	7,84E-01	1,10E-07
800	10,3			10,3	7,84E-01	1,60E-07
800	11,3			11,3	7,84E-01	1,49E-07
800	19,3			19,3	7,84E-01	9,94E-08
800	20,3			20,3	7,84E-01	1,44E-07
800	21,3			21,3	7,84E-01	2,32E-07
800	22,3	0,3	1	22,3	7,84E-01	2,38E-07
800	22,7	0,7	1	22,7	7,84E-01	8,54E-05
800	23,3	1,3	1	23,3	9,40E-01	1,74E-05
800	24,3	2,3	1	24,3	9,60E-01	1,38E-06
800	25,3	3,3	1	25,3	9,62E-01	5,52E-07
800	26,3	4,3	1	26,3	9,64E-01	5,25E-07
800	27,3	5,3	1	27,3	9,65E-01	4,59E-07
800	28,3	6,3	1	28,3	9,67E-01	4,42E-07
800	29,3	7,3	1	29,3	9,68E-01	4,42E-07
800	30,3	8,3	1	30,3	9,69E-01	4,03E-07
800	31,3	9,3	1	31,3	9,70E-01	3,87E-07
800	32,3	10,3	1	32,3	9,72E-01	5,25E-07
800	33,3	11,3	2	33,3	9,73E-01	5,14E-07
800	34,3	12,3	2	34,3	9,75E-01	4,53E-07
800	35,3	13,3	2	35,3	9,78E-01	3,76E-07
800	36,3	14,3	2	36,3	9,77E-01	3,59E-07
800	37,3	15,3	2	37,3	9,77E-01	2,71E-07
800	38,3	16,3	2	38,3	9,78E-01	2,43E-07
800	39,3	17,3	2	39,3	9,78E-01	2,49E-07
800	40,3	18,3	2	40,3	9,79E-01	1,88E-07
800	41,3	19,3	2	41,3	9,79E-01	1,55E-07
800	42,3	20,3	2	42,3	9,79E-01	1,55E-07

* Kr 85 inventory of 5 particles is $1,81\text{E}+06$ (100% release). The inventory calculated from measured Cs 137 is $1,56\text{E}+06$

Fig. 4.126 Modified PIE flow chart for capsules 2 and 3 with remaining tasks to be completed or inserted into this report

ORNL-DWG 90-2291R4

5. REFERENCES

1. Myers, B. F., "Plan for the Postirradiation Examination of the HFR-B1 Experiment," ORNL/TM-11498, Oak Ridge National Laboratory, November 1991
2. Bückner, H. J. und F. Nieveler, "Nachuntersuchungsergebnisse des Bestrahlungs-experimentes HFR-B1," Technische Notiz IRW-TN 42/91, Forschungszentrum Jülich GmbH, 03.06.1991
3. Schröder, R. und H. Dahmen, "Gammascan der Stahlkapseln," Technische Notiz IRW-TN-34/91, Forschungszentrum Jülich GmbH, 23.04.1991
4. Schröder, R. und H. Dahmen, "Gammascan der Graphitkörper aus Kapsel 2 und 3 und der Brennstoffrods aus den Kanälen 1.," Technische Notiz IRW-TN 41/91, Forschungszentrum Jülich GmbH, 28.05.1991
5. Schröder, R. and H. Dahmen, "HFR Scan der Gammascandrähte," IRW-TN-29/91, Forschungszentrum Jülich GmbH, 10.04.91.
6. Myers, B. F., "The Burnup and Power Data Reported for Experiment HFR-B1: Circumvention of Discrepancies", to be published as an ORNL/TM report, December 1994
7. Schröder, R., H. Dahmen und F. Nieveler, "Inventar und Abbrand der Brennstoffrods, Dimensionen der Graphitkörper," Technische Notiz IRW-TN 9/92, Forschungszentrum Jülich GmbH, 25.02.1992
8. Conrad, R., "Irradiation of GA Fuel rods HTGR real time simulating operating conditions in The HFR Petten", Project D214.01, "Design and Safety Report", Technical Note P/F1/87/5, Joint Research Centre, Petten Establishment, May 1989.
9. Schröder, R. und H. Dahmen, "Gammascan der leeren Graphitsegmente, Inventar der Graphitproben," Technische Notiz IRW-TN 42/92, Forschungszentrum Jülich GmbH, 10/09/92
10. Hill, D. W. and B. F. Myers, "Temperature, Pressure and Oxidation Effects on Cesium Diffusion in H-451 Graphite," Proceedings of the 16th Biennial Conference on Carbon, Extended Abstracts and Program, University of California at San Diego, 18-22 Jul, 1983, pp 566-577
11. Bückner, H. J., "Dimensionsmessungen und Wägungen, Experiment HFR-B1," Technische Notiz IRW-TN 3/94, Forschungszentrum Jülich GmbH, Januar 1994
12. Bückner, H. J., and F. Nieveler, "Nachuntersuchungsergebnisse des Bestrahlungsexperimentes HFR-B1, Technische Notiz IRW-TN 12/92, Forschungszentrum Jülich GmbH, 12.03.1992
13. Schröder, R., H. Dahmen und K. Landsgeßel, "Kernfreisetzung bei Partikeln aus Probenrägern" Technische Notiz IRW-TN 11/94, Forschungszentrum Jülich GmbH, März, 1994
14. Myers, B. F. et al., "Capsule R2-K13; Final Report on Cells 2 and 3", HTGR-85-068, GA Technologies Inc., September 1985
15. Schenk, W., H. Knauf, und D. Pitzer, "Spaltgasfreisetzung aus Brennstoffproben unter dem Einfluß von Feuchte," IRW-IB-6/93, Forschungszentrum Jülich GmbH (KFA), Heisse Zellen, Juni 1993

16. Myers, B. F., "Effect of Water Vapor on the Release of Fission Gases from Uranium Oxycarbide in High-Temperature, Gas-Cooled Reactor Coated Fuel Particles," J. Am. Ceram. Soc. 75 686-693 1992
17. Myers, B. F., "Dimensional and Thermal Data for Experiment HFR-B1," to be issued

INTERNAL DISTRIBUTION

1-2.	Central Research Library	8-10.	M&C Records Office
3.	Document Reference Section	11.	D. F. Craig
4-5.	Laboratory Records Department	12.	G. E. Michaels
6.	Laboratory Records ORNL-RC	13-17.	B. F. Myers
7.	ORNL Patent Office	18.	P. L. Rittenhouse

EXTERNAL DISTRIBUTION

- 19-20. GENERAL ATOMICS, INC., P.O. Box 85608, San Diego, CA 92186-9784
C. B. Scott
R. F. Turner
- 21-22. FORSCHUNGSZENTRUM JÜLICH, D524225 Jülich, Germany
H. Nabielek, ISR (HTA)
G. Pott, Heisse Zellen
23. MODULAR HTGR PLANT DESIGN CONTROL OFFICE, Merex, Inc.,
3206 Power Oaks Blvd., Suite 300, Rockville, MD 20852
R. R. Mills
- 24-25. MODULAR HTGR PLANT SEDIGN CONTROL OFFICE, P.O. Box 85608,
San Diego, CA 92138-5608
D. Pettycord
J. Kendall
- 26-28. DOE, ACTINIDE RECYCLE DIVISION, Washington, DC 20585
W. P. Chernock, Acting Director
F. J. Goldner
J. W. Herczeg
29. DOE, OAKLAND OPERATIONS OFFICE, 1333 Broadway, Oakland,
CA 94612
S. El-Safwany

30. DOE, OAK RIDGE OPERATIONS OFFICE, P.O. Box 2001, Oak Ridge,
TN 37831-6269

Office of Assistant Manager for Energy Research and Development

- 31-32. DOE, OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION,
P.O. Box 62, Oak Ridge, TN 37831

For distribution by microfiche as shown in DOE/OSTI-4500
Distribution Category UC-522 (Gas-Cooled Reactor Technology)