11A

NUREG/CR-0560

PNL-2673

R-3

Data Report for the NRC/PNL Halden Assembly IFA-432

C. R. Hann	D. D. Lanning
E. R. Bradley	R. K. Marshall
M. E. Cunningham	R. E. Williford

August 1978

**Prepared for
Fuel Behavior Research Branch
Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission
under a Related Services Agreement
with the U.S. Department of Energy
Contract EY-76-C-06-1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

PNL-2673

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Nuclear Regulatory Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes 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.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ ____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

3 3679 00049 3108

DATA REPORT FOR THE NRC/PNL
HALDEN ASSEMBLY IFA-432

C. R. Hann	D. D. Lanning
E. R. Bradley	R. K. Marshall
M. E. Cunningham	R. E. Williford

August 1978

Prepared for
Fuel Behavior Research Branch
Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission
under a Related Services Agreement
with the U.S. Department of Energy
Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Richland, Washington 99352

"The NRC will make available data tapes and operational computer codes on research programs dealing with postulated accidents in light water reactors. Persons requesting this information must reimburse the NRC contractors for their expenses in preparing copies of the data tapes and the operational computer codes. Requests should be submitted to the Research Support Branch, Office of Nuclear Regulatory Research, Nuclear Regulatory Commission, Washington, DC 20555."

ACKNOWLEDGEMENTS

The support of Dr. W. V. Johnston and H. H. Scott of the Fuel Behavior Research Branch is appreciated. J. A. Christensen contributed to the design and was instrumental in coordinating the final assembly and reactor loading, and, with the Halden Project staff, guiding the assembly through a successful irradiation. N. J. Wildung and W. D. Bennett produced the many data plots for this report.

CONTENTS

SUMMARY	iv
LIST OF FIGURES	v
LIST OF TABLES	xix
1.0 INTRODUCTION	1-1
2.0 TEST RATIONALE	2-1
2.1 Cross-Correlation Efforts	2-1
2.2 Test Facility	2-6
2.3 Fuel Rod Thermal Design Parameters.	2-6
2.4 Fuel and Cladding Precharacterization	2-11
3.0 DATA PRESENTATION	3-1
3.1 Power Histories	3-1
3.2 Fuel Temperature Histories.	3-1
3.3 Cladding Elongation Histories	3-2
3.4 Rod Internal Pressure Histories	3-2
REFERENCES	Ref-1
APPENDIX A - FUEL ROD AND FUEL COLUMN SCHEMATICS FOR IFA-432	A-1
APPENDIX B - INSTRUMENT DESCRIPTIONS AND CALIBRATION	B-1
APPENDIX C - ASSEMBLY POWER CALIBRATION	C-1
APPENDIX D - DATA PROCESSING	D-1

SUMMARY

This report presents the in-reactor data collected from the NRC/PNL Halden Assembly IFA-432 as a part of the program entitled "Experimental Verification of Steady State Fuel Codes," sponsored by the Fuel Behavior Research Branch of the USNRC. The purpose of this program is to reduce the uncertainties of calculating the thermal stored energy in an operating nuclear fuel rod.

This report presents fuel centerline thermocouple readings, cladding elongation monitor readings, rod internal pressure readings, and neutron detector readings. The neutron detector readings were corrected to represent rod local powers at the thermocouple locations. These data are presented in the form of plots of the variables versus time during the portion of the irradiation period from December 1975 to January 1978. Also included are descriptions of the test rationale, assembly and rod designs, test facility, instrument array and calibration, and data processing methods. Topical reports discussing specific aspects and results of the data analysis are referenced.

As of May 1978, the assembly burnup had reached its design goal of 20,000 MWd/MTM. However, it has been decided to leave the assembly in core to collect high burnup fission gas release data. The xenon-filled Rod 4 was replaced with the non-instrumented Rod 8 (Rod 1 design) after the first cycle. Six of the twelve original thermocouples, four of the six cladding elongation monitors, all SPND'S and all pressure transducers remain operable at this writing.

FIGURES

2.1	Arrangement of Temperature Sensors, Neutron Detectors, and Fuel Relative to Reference Axial Thermal Flux Profile, IFA-431 and 432	2-3
2.2	Schematic of Instrumented Fuel Assembly--IFA-432	2-5
2.3	IFA-431 and IFA-432 Arrangements in the Flow Channel	2-7
2.4	Schematic of Rod 4 Fuel Column	2-10
2.5	IFA-432 Fuel Thermal Conductivity 95% TD Stable, Rods 1, 2, 3, 4	2-12
3.2	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - December 1975	3-3
3.3	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1975	3-3
3.3	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - December 1975	3-4
3.4	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - December 1975	3-4
3.5	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1975	3-5
3.6	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1975	3-5
3.7	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1975	3-6
3.8	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - January 1975	3-6
3.9	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - January 1975	3-7
3.10	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - January 1975	3-7
3.11	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1975	3-8
3.12	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1975	3-8

3.13	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - February 1976	3-9
3.14	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - February 1976	3-9
3.15	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - February 1976	3-10
3.16	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - February 1976	3-10
3.17	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - February 1976	3-11
3.18	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - February 1976	3-11
3.19	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - June 1976	3-12
3.20	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - June 1976	3-12
3.21	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - June 1976	3-13
3.22	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - June 1976	3-13
3.23	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - June 1976	3-14
3.24	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - June 1976	3-14
3.25	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - July 1976	3-15
3.26	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - July 1976	3-15
3.27	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - July 1976	3-16
3.28	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - July 1976	3-16

3.29	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - July 1976	3-17
3.30	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - July 1976	3-17
3.31	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - August 1976	3-18
3.32	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - August 1976	3-18
3.33	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - August 1976	3-19
3.34	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - August 1976	3-19
3.35	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - August 1976	3-20
3.36	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - August 1976	3-20
3.37	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - September 1976	3-21
3.38	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - September 1976	3-21
3.39	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - September 1976	3-22
3.40	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - September 1976	3-22
3.41	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - September 1976	3-23
3.42	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - September 1976	3-24
3.43	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - October 1976	3-24
3.44	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - October 1976	3-24
3.45	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - October 1976	3-25

3.46	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - October 1976	3-25
3.47	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - October 1976	3-26
3.48	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - October 1976	3-26
3.49	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1976	3-27
3.50	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1976	3-27
3.51	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - December 1976	3-28
3.52	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - December 1976	3-28
3.53	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1976	3-29
3.54	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1976	3-29
3.55	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1977	3-30
3.56	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1977	3-30
3.57	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - January 1977	3-31
3.58	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - January 1977	3-31
3.59	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1977	3-32
3.60	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1977	3-32
3.61	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - February 1977	3-33
3.62	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - February 1977	3-33

3.63	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - February 1977	3-34
3.64	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - February 1977	3-34
3.65	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - February 1977	3-35
3.66	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - February 1977	3-35
3.67	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - March 1977	3-36
3.68	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - March 1977	3-36
3.69	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - March 1977	3-37
3.70	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - March 1977	3-37
3.71	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - March 1977	3-38
3.72	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - March 1977	3-38
3.73	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - April 1977	3-39
3.74	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - April 1977	3-39
3.75	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - April 1977	3-40
3.76	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - April 1977	3-40
3.77	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - April 1977	3-41
3.78	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - April 1977	3-41
3.79	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - May 1977	3-42

3.80	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - May 1977	3-42
3.81	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - May 1977	3-43
3.82	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - May 1977	3-43
3.83	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - May 1977	3-44
3.84	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - May 1977	3-44
3.85	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - June 1977	3-45
3.86	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - June 1977	3-45
3.87	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - June 1977	3-46
3.88	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - June 1977	3-46
3.89	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - June 1977	3-47
3.90	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - June 1977	3-47
3.91	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - July 1977	3-48
3.92	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - July 1977	3-48
3.93	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - July 1977	3-49
3.94	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - July 1977	3-49
3.95	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - July 1977	3-50
3.96	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - July 1977	3-50

3.97	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - August 1977	3-51
3.98	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - August 1977	3-51
3.99	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - August 1977	3-52
3.100	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - August 1977	3-52
3.101	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - August 1977	3-53
3.102	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - August 1977	3-53
3.103	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - October 1977	3-54
3.104	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - October 1977	3-54
3.105	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - October 1977	3-55
3.106	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - October 1977	3-55
3.107	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - October 1977	3-56
3.108	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - October 1977	3-56
3.109	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - December 1977	3-57
3.110	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1977	3-57
3.111	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - December 1977	3-58
3.112	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - December 1977	3-58
3.113	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1977	3-59

3.114	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1977	3-59
3.115	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1978	3-60
3.116	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - January 1978	3-60
3.117	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - January 1978	3-61
3.118	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - January 1978	3-61
3.119	Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1978	3-62
3.120	Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1978	3-62
3.121	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - December 1975	3-63
3.122	Lower Thermocouple Readings for Rods 1,3 of IFA 432 - December 1975	3-63
3.123	Upper Thermocouple Readings for Rod 4 of IFA 432 - December 1975	3-64
3.124	Lower Thermocouple Readings for Rods 2,4 of IFA 432 - December 1975	3-64
3.125	Upper Thermocouple Readings for Rods 5,6 of IFA 432 - December 1975	3-65
3.126	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - December 1975	3-65
3.127	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - January 1976	3-66
3.128	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - January 1976	3-66
3.129	Upper Thermocouple Readings for Rods 5,6 of IFA 432 - January 1976	3-67
2.130	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - January 1976	3-67

3.131	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - February 1976	3-68
3.132	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - February 1976	3-68
3.133	Upper Thermocouple Readings for Rods 5,6 of IFA 432 - February 1976	3-69
3.134	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - February 1976	3-69
3.135	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - June 1976	3-70
3.136	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - June 1976	3-70
3.137	Upper Thermocouple Readings for Rods 5,6 of IFA 432 - June 1976	3-71
3.138	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - June 1976	3-71
3.139	Upper Thermocouple Readings for Rods 1,3,6 of IFA 432 - July 1976	3-72
3.140	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - July 1976	3-72
3.141	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - July 1976	3-73
3.142	Upper Thermocouple Readings for Rods 1,3,6 of IFA 432 - August 1976	3-73
3.143	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - August 1976	3-74
3.144	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - August 1976	3-74
3.145	Upper Thermocouple Readings for Rods 1,3,6 of IFA 432 - September 1976	3-75
3.146	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - September 1976	3-75
3.147	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - September 1976	3-76

3.148	Upper Thermocouple Readings for Rods 1,3,6 of IFA 432 - October 1976	3-76
3.149	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - October 1976	3-77
3.150	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - October 1976	3-77
3.151	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - December 1976	3-78
3.152	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - December 1976	3-78
3.153	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - December 1976	3-79
3.154	Upper Thermocouple Readings for Rods 1,3 of IFA 432 - January 1977	3-79
3.155	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - January 1977	3-80
3.156	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - January 1977	3-80
3.157	Upper Thermocouple Readings for Rod 3 of IFA 432 - February 1977	3-81
3.158	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - February 1977	3-81
3.159	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - February 1977	3-82
3.160	Upper Thermocouple Readings for Rod 3 of IFA 432 - March 1977	3-82
3.161	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - March 1977	3-83
3.162	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - March 1977	3-83
3.163	Upper Thermocouple Readings for Rod 3 of IFA 432 - April 1977	3-84
3.164	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - April 1977	3-84

3.165	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - April 1977	3-85
3.166	Upper Thermocouple Readings for Rod 3 of IFA 432 - May 1977	3-85
3.167	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - May 1977	3-86
3.168	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - May 1977	3-86
3.169	Upper Thermocouple Readings for Rod 3 of IFA 432 - June 1977	3-87
3.170	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - June 1977	3-87
3.171	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - June 1977	3-88
3.172	Upper Thermocouple Readings for Rod 3 of IFA 432 - July 1977	3-88
3.173	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - July 1977	3-89
3.174	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - July 1977	3-89
3.175	Upper Thermocouple Readings for Rod 3 of IFA 432 - August 1977	3-90
3.176	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - August 1977	3-90
3.177	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - August 1977	3-91
3.178	Upper Thermocouple Readings for Rod 3 of IFA 432 - October 1977	3-91
3.179	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - October 1977	3-92
3.180	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - October 1977	3-92
3.181	Upper Thermocouple Readings for Rod 3 Of IFA 432 - December 1977	3-93

3.182	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - December 1977	3-93
3.183	Lower Thermocouple Readings for Rods 5,6, of IFA 432 - December 1977	3-94
3.184	Upper Thermocouple Readings for Rod 3 or IFA 432 - January 1978	3-94
3.185	Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - January 1978	3-95
3.186	Lower Thermocouple Readings for Rods 5,6 of IFA 432 - January 1978	3-95
3.187	Cladding Elongation Sensor Readings for Rods 1,2,5,6 of IFA 432 - December 1975	3-96
3.188	Cladding Elongation Sensor Readings for Rods 3,4 of IFA 432 - December 1975	3-96
3.189	Cladding Elongation Sensor Readings for Rods 1,2,5,6 of IFA 432 - January 1976	3-97
3.190	Cladding Elongation Sensor Readings for Rods 3,4 of IFA 432 - January 1976	3-97
3.191	Cladding Elongation Sensor Readings for Rods 1,2,5,6 of IFA 432 - February 1976	3-98
3.192	Cladding Elongation Sensor Readings for Rods 3,4 of IFA 432 - February 1976	3-98
3.193	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - June 1976	3-99
3.194	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - July 1976	3-99
3.195	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - August 1976	3-100
3.196	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - September 1976	3-100
3.197	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - October 1976	3-101
3.198	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - December 1976	3-101

3.199	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - January 1977	3-102
3.200	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - February 1977	3-102
3.201	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - March 1977	3-103
3.202	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - April 1977	3-103
3.203	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - May 1977	3-104
3.204	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - June 1977	3-104
3.205	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - July 1977	3-105
3.206	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - August 1977	3-105
3.207	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - October 1977	3-106
3.208	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - December 1977	3-106
3.209	Cladding Elongation Sensor Readings for Rods 2,3,6,8 of IFA 432 - January 1978	3-107
3.210	Internal Pressures for Rods 1,5,6 of IFA 432 - December 1975 . . .	3-107
3.211	Internal Pressures for Rods 1,5,6 of IFA 432 - January 1976 . . .	3-108
3.212	Internal Pressures for Rods 1,5,6 of IFA 432 - February 1976 . . .	3-108
3.213	Internal Pressures for Rods 1,5,6 of IFA 432 - June 1976	3-109
3.214	Internal Pressures for Rods 1,5,6 of IFA 432 - August 1976 . . .	3-109
3.215	Internal Pressures for Rods 1,5,6 of IFA 432 - September 1976 . . .	3-110
3.216	Internal Pressures for Rods 1,5,6 of IFA 432 - October 1976 . . .	3-110
3.217	Internal Pressures for Rods 1,5,6 of IFA 432 - December 1976 . . .	3-111
3.218	Internal Pressures for Rods 1,5,6 of IFA 432 - January 1977 . . .	3-111

3.219	Internal Pressures for Rods 1,5,6 of IFA 432 - February 1977 . .	3-112
3.220	Internal Pressures for Rods 1,5,6 of IFA 432 - March 1977 . . .	3-112
3.221	Internal Pressures for Rods 1,5,6 of IFA 432 - April 1977 . . .	3-113
3.222	Internal Pressures for Rods 1,5,6 of IFA 432 - May 1977	3-113
3.223	Internal Pressures for Rods 1,5,6 of IFA 432 - June 1977	3-114
3.224	Internal Pressures for Rods 1,5,6 of IFA 432 - July 1977	3-114
3.225	Internal Pressures for Rods 1,5,6 of IFA 432 - August 1977 . . .	3-115
3.226	Internal Pressures for Rods 1,5,6 of IFA 432 - October 1977 . .	3-115
A-1	Schematic Arrangement of Fuel Rods for IFA 432	A-1
A-2	Stack Arrangement for Rods 1 and 6	A-2
A-3	Stack Arrangement for Rods 2, 3, and 5	A-3
A-4	Stack Arrangement for Rod 2 - IFA 432	A-4
A-5	Stack Arrangement for Rod 4	A-5
A-6	Stack Arrangement for Non-Instrumented Rods 7, 8, 9 - IFA 432 .	A-6
B-1	Schematic of Self-Powered, Beta Current Neutron Detector	B-2
B-2	Schematic of W 5% Re/W 26% Re Thermocouples with Grounded Junction	B-4
B-3	Calibration Curve for W 5% Re/W 26% Re Thermocouples	B-4
B-4	Cladding Elongation Monitor	B-6
B-5	Fission Gas Pressure Transducer	B-8
D-1	Flow Diagram for Processing Halden Data	D-2
D-2	Flow Diagram for Correction of Halden Rod Local Powers	D-3
D-3	Typical Axial Power Profile for IFA 432	D-5
D-4	Flow Diagram for Gap Conductance and Uncertainty Calculations .	D-6

TABLES

2.1	Design Parameters and Instrumentation for IFA-431 and IFA-432 . . .	2-2
2.2	Cross-Correlation Matrix	2-6
2.3	Operating Data for the HBWR	2-6
3.1	IFA-432 Burnup	3-116
B.1	IFA-432 Coolant Temperatures	B-9
B.2	Instrument Failure Dates for IFA-432	B-10
D.1	Typical Power Correction Factors for IFA-432	D-2

1.0 INTRODUCTION

The thermal stored energy in a fuel rod is the driving function for the severest postulated nuclear energy-related accident, the loss-of-coolant-accident (LOCA). Because of this, the final acceptance criteria for emergency core cooling systems requires calculation of the stored energy and gap conductance of a fuel rod, both for normal operation and for the duration of the LOCA. Although these calculations are used in the regulation of commercial nuclear power plants, uncertainties in them have caused temporary derating of many power plants and delays in the startup of additional plants. Many of these uncertainties can be attributed to the lack of well-characterized data for fuel irradiated throughout the normal operating power range of commercial nuclear power plants.

Due to this lack of well-characterized data, some computer-coded mathematical models that have been developed to simulate fuel rod behavior over a wide range of postulated conditions are inadequate. These factors together contribute substantially to the stored energy uncertainty. Specifically, the effects of fuel densification and fission gas on the fuel-cladding gap conductance are difficult to quantify, primarily because the applicable data are extremely sparse. As a result, although the total conductance of the fuel rod must be considered in stored energy calculations, the largest uncertainties in those calculations are associated with changes in the gap conditions and their concomitant effects on the gap conductance.

To focus on these uncertainties, two instrumented fuel assemblies have been designed and are being irradiated in the Halden Boiling Water Reactor (HBWR). The fuel assemblies have been designated: IFA-431 - this assembly had a design power of 10 kW/ft (328 W/cm) and reached its goal burnup of 4000 MWd/MTM in February 1976; IFA-432 - this assembly has a design power of 15 kW/ft (492 W/cm) and reached its goal burnup of 20,000 MWd/MTM in late-1978. However, since most of the instruments are still functioning properly

(See Appendix B), it was decided to leave IFA-432 in the Halden core to obtain much-needed data at higher burnups.

These instrumented fuel assemblies are providing well-characterized experimental data under conditions that realistically simulate light water reactor (LWR) operations. The data will be used to verify United States Nuclear Regulatory Commission (NRC) fuel codes, and it will provide benchmark data for commercial fuel licensing codes submitted by nuclear fuel vendors.

2.0 TEST RATIONALE

Experimental verification of computer codes provides a means to quantify uncertainties in simulating the conditions for an operating nuclear fuel rod. A collection of mathematical models (i.e., a computer code) is used to simulate the wide range of conditions postulated during an evaluation of reactor fuel safety. Any computer code that is forced to rely on a collection of empirical and semiempirical models for much of the analysis is limited and should be primarily used for interpolation. Some extrapolation can be accomplished with models based on first principles; however, well-characterized data are needed in either case to test code predictions. When these tests were designed (July 1974), very little data were available describing the effects of burnup on LWR fuel and no data were available describing the effects of fuel densification on fuel temperatures. Accordingly, a test matrix was developed (Table 2.1), and two instrumented assemblies were designed to provide the data.

2.1 CROSS-CORRELATION EFFORTS

Much thought went into the design of the tests to ensure a means for cross correlating the data, provide as many independent checks of data validity as possible, ensure against instrument failure, ensure at least internal consistency on a relative basis, and provide some reference points to commercial plant designs as well as other fuel research programs.

One of the test design basic premises was to provide a systematic approach that would allow adequate interpolation and extrapolation with computer codes. The first step in this approach was the decision to design IFA-431 and IFA-432 as identical assemblies. An identical design enhances the ability to interpolate over a range of powers and also replicates initial conditions. For example, all the data from the IFA-431 first power ramp was duplicated with IFA-432. Identical assemblies also reduce the uncertainties associated with assembly and rod power distributions.

TABLE 2.1. Design Parameters and Instrumentation for IFA-431 and IFA-432

IFA-431 [Peak Power - 10 kW/ft (328 W/cm)]

Rod No.	Diameter Pellet		Cold Diametral Gap ^(a)		Fill Gas	Fuel Density % TD	Fuel Type ^(b)	Burnup MWd/MTM	Instrumentation			
	in.	mm	in.	mm					Temperature Upper	Temperature Lower	Pressure	Cladding Length
1	0.4205	10.681	0.009	0.229	He	95	Stable	4,000	TC ^(c)	TC	PT ^(d)	ES ^(e)
2	0.4145	10.528	0.015	0.381	He	95	Stable	4,000	TC	TC	--	ES
3	0.4275	10.858	0.002	0.051	He	95	Stable	4,000	TC	TC	--	ES
4	0.4205	10.681	0.009	0.229	Xe	95	Stable	4,000	TC	TC	--	ES
5	0.4205	10.681	0.009	0.229	He	92	Stable	4,000	TC	TC	PT	ES
6	0.4205	10.681	0.009	0.229	He	92	Unstable	4,000	TC	TC	PT	ES

IFA-432 [Peak Power - 15 kW/ft (492 W/cm)]

1	0.4205	10.681	0.009	0.229	He	95	Stable	20,000	TC	TC	PT	ES
2	0.4145	10.528	0.015	0.381	He	95	Stable	4,000 ^(f)	UT ^(g)	TC	--	ES
3	0.4265	10.833	0.003	0.076	He	95	Stable	4,000 ^(f)	TC	TC	--	ES
4	0.4205	10.681	0.009	0.229	Xe	95	Stable	4,000 ^(f)	TC	TC	--	ES
5	0.4205	10.681	0.009	0.229	He	92	Stable	20,000	TC	TC	PT	ES
6	0.4205	10.681	0.009	0.229	He	92	Unstable	20,000	TC	TC	PT	ES
7	0.4145	10.528	0.015	0.381	He	95	Stable	16,000	--	--	--	--
8	0.4205	10.681	0.009	0.229	He	95	Stable	16,000	--	--	--	--
9	0.4225	10.732	0.007	0.179	He	95	Stable	16,000	--	--	--	--

(a) Cladding for all rods has an OD of 0.5035 in. (12.789 mm) and an ID of 0.4295 in. (10.909 mm). Diametral gap is cladding ID minus pellet diameter.

(b) With respect to in-reactor densification.

(c) TC = Thermocouple

(d) PT = Pressure Transducer

(e) ES = Elongation Sensor

(f) Removable rods replaced by Rods 7, 8, and 9.

(g) UT = Ultrasonic Thermometer

The power profile in the Halden BWR (Figure 2.1) was also considered during the design. The top of the rod was placed at the peak, which forced the bottom of the rod to operate at 70 to 80% of the peak rod power. To take advantage of the power distribution, thermocouples were placed in the top and bottom of each rod. Previously, no tests had been run in Halden with thermocouples penetrating both endcaps; however, Halden staff were able to develop a workable design. Thermocouples in both ends allow modelers to check the ability of various codes to extrapolate over a short power range within the same rod. If a code cannot perform these calculations adequately, calculations of the temperature distribution over an ~4 m fuel length are also suspect.

FIGURE 2.1. Arrangement of Temperature Sensors, Neutron Detectors, and Fuel Relative to Reference Axial Thermal Flux Profile, IFA-431 and 432

Using two thermocouples per rod allows modelers to interpolate between ~ 7 kW/ft (230 W/cm) and 15 kW/ft (492 W/cm) with tie points at ~ 10 kW/ft (328 W/cm) and ~ 12 kW/ft (394 W/cm). Single thermocouples would have provided data at only 10 kW/ft (328 W/cm) and 15 kW/ft (492 W/cm). Data is obtained, as a result of reactor cycling, over the entire range of 0 to 15 kW/ft (492 W/cm). This should span most of the anticipated normal operating powers in commercial plants.

Reference points with commercial plants and other fuel research programs were also developed. Selection of the BWR-6 fuel geometry, procurement of commercial quality tubing, and selection of assembly powers connects the data to commercial plants. Some of the cladding procured for this program was shipped to EG&G (INEL) for use in their Halden tests. Both programs also used the

same starting powder for fuel manufacture. The length of the rods in both IFA-431 and 432 were designed to be compatible with the Power Burst Facility (PBF) test trains; well-characterized irradiated fuel is needed for a number of tests in the PBF program. Some of the fuel structures were similar to those investigated in the EEI/EPRI UO_2 fuel densification study,⁽¹⁾ to provide a reference point to a much larger structural characterization program.

The correct assessment of rod powers and the distribution of power within the rods is of utmost importance to assure the best possible thermal data. To attain this, seven neutron sensors were placed in each assembly (Figure 2.2); one in the center of the assembly, three at the top plane of thermocouples, and three at the bottom plane of thermocouples. An extensive calibration of the Vanadium sensors is conducted during the initial startup of any assembly. In addition, Rod 3 (0.051 and 0.076 mm gap for IFA-431 and 432, respectively) was included as an internal standard. The small gap was closed at power; thus, the temperature gradient across the gap was minimized. Since the coolant temperature and fuel centerline temperatures were known, an independent check of rod power at both the top and bottom planes in the assembly was obtained. Rod powers and fuel temperatures in both assemblies were compared to assure consistent data. Each rod had a cladding elongation sensor; Rods 1, 5, and 6 had fission gas pressure transducers.

Design assembly burnups for IFA-431 were set at 4000 MWd/MTM to ensure complete densification, minimize fuel volume changes induced by fission product swelling, and to retain the option of PIE confirmation of gap closure data obtained from low burnup rods. The second assembly, IFA-432, is a sibling to IFA-431. Three major differences exist in the design parameters; the design power is 15 kW/ft (492 W/cm), the goal burnup is 20,000 MWd/MTM, and the assembly contains an option to replace three rods at 4000 MWd/MTM, allowing cross correlation with three identical rods in IFA-431.

Table 2.2 illustrates the amount of cross correlation that is possible. In addition to the rod-to-rod comparisons, top-to-bottom comparisons can be made in each rod, and separate effects as a function of burnup and power can also be evaluated.

FIGURE 2.2. Schematic of Instrumented Fuel Assembly IFA-432

TABLE 2.2. Cross-Correlation Matrix

Rod Number	Gap Size	Fuel Relocation	Fuel Eccentricity	Fuel Stability	Gas Composition	Fuel Density	Rod Powers	Rod Pressures	Dynamic Temperature
1 (9-He-95-S) ^(a)	X	X			X	X		X	X
2 (15-He-95-S)	X	X							X
3 (2-He-95-S)	X	X					X		X
4 (9-Xe-95-S)		X	X		X				X
5 (9-He-92-S)		X		X		X		X	X
6 (9-He-92-U)		X		X				X	X

(a) 1 (9-He-95-S) - the first character identifies the rod, the second the nominal diametral gap in mils, the third the fill gas, the fourth the fuel density, and the fifth stable (S) or unstable (U) fuel.

2.2 TEST FACILITY

The Halden Boiling Water Reactor (HBWR) uses natural circulation of heavy water for cooling. Reactor operating data are shown in Table 2.3.

TABLE 2.3. Operating Data for the HBWR

Power Level	12 MW
Reactor Pressure	500 psi (34 atm)
Heavy Water Saturation Temp.	464°F (240°C)
Plenum Inlet Temp.	459°F (237°C)
Thermal Flux	$\sim 3 \times 10^{13}$ n/cm ² -sec
Fast Flux (>1 MeV)	$\sim 5 \times 10^{11}$ n/cm ² -sec
Average Fuel Power Density	14.8 W/g

A schematic of the plan view of the HBWR core loading in November 1975 is shown in Figure 2.3. The locations of IFA-431 and IFA-432 are also indicated. Both half-length assemblies were charged into the bottom half of the core (Figure 2.1).

2.3 FUEL ROD THERMAL DESIGN PARAMETERS

2.3.1 Contemporary Rod (Rod 1)

It was important to obtain as many reference points as possible to cross correlate the data and provide avenues to extrapolate these test results to U.S. commercial nuclear fuel. Accordingly, the primary reference selected con-

HBWR IV CORE LOADING NO. 19 DATE: NOV - 75

- CONTROL ROD (CS 19)
- INSTRUMENTED FUEL ASSEMBLY (IFA-431)
- STANDARD THIRD CHARGE ASSEMBLY

FIGURE 2.3. IFA-431 and IFA-432 Arrangements in the Flow Channel

sists of a BWR-6 geometry, a 95% TD pellet, a 0.009 in. (0.229 mm) diametral gap, and helium fill gas. In addition to minimizing the difficulty of extrapolating the data from the Halden tests to commercial plants, the larger BWR pellets tend to reduce perturbations induced by thermocouples. Cladding procurement problems were also minimized since atypical cladding dimensions are difficult to obtain from commercial sources. The 95% TD fuel density was selected to assure a densification-resistant fuel, provide a density typical of 1974 vintage fuel designs, and provide a reference point to previous thermal conductivity measurements on unirradiated fuel. Rod 1 in each assembly fulfills the above objectives set for the experiment reference.

2.3.2 Simulated Instantaneous Densification (Rod 2)

The major impact of fuel densification⁽²⁾ was the assumption that the fuel underwent isotropic shrinkage directly proportional to the difference between the fabricated density and the terminal density. For example, a 93.5% TD BWR fuel pellet (0.488-in. [12.395 mm] diameter) would shrink 0.00488 in. (0.124 mm) if the NRC criteria of a 96.5% TD terminal density were applied. Most BWR fuel rods of the above pellet size would contain an initial diametral gap of 0.011 to 0.012 in. (0.279-0.305 mm). Consequently, the shrinkage induced by densification would create a diametral gap of about 0.015 to 0.017 in. (0.381-0.432 mm). Consideration of tolerances (i.e., ± 0.0015 in.) on the initial gap resulted in even larger gaps. Until data became available from the EEI/EPRI UO₂ densification program,^(1,3) the Halden program,⁽⁴⁾ and individual fuel vendor programs, instantaneous densification was assumed.⁽²⁾ That is, a gap of 0.016 in. (0.406 mm), for the example above, was assumed to exist as soon as the plant reached full power.

Accordingly, Rod 2 was designed with a 0.015-in. (0.381 mm) diametral gap to simulate instantaneous densification. The 0.015-in. gap in the BWR-6 geometry (0.4205-in. [10.681 mm] reference pellet diameter) yields a gap/diameter (G/D) ratio of 0.036 which approximates the G/D ratios typically postulated for densified fuel in either the older BWR or PWR fuel designs.

2.3.3 Internal Reference (Rod 3)

Rod 3 was designed primarily for an independent check of rod powers. This rod contained 95% TD fuel with an initial diametral gap of 0.002 in. (0.051 mm) (0.003 in. in IFA-432). These gaps were chosen to provide good contact at power

and yet minimize the potential for cladding failure induced by mechanical interaction. The small gap was closed at power, which produced very high gap conductances and thus minimized the temperature gradient across the fuel-cladding interface. Minimizing the temperature gradients across the gap is a good check of the effective thermal conductivity of the fuel in-reactor. Since cladding temperatures are calculable, and thermocouples indicated the fuel centerline temperatures, rod powers in the assembly could be checked. The technique that was used was based on the conductivity integral.⁽⁵⁾

A series of controlled power drops were requested for each assembly. Three cycles in each series consisted of a 20% linear drop in power over a 60-sec time interval. These tests yielded transient gap conductance data for comparison with the steady-state measurements.⁽⁶⁾ Steady-state values were available for powers at the beginning and end of a ramp for boundary conditions. Data from the transient provided a cross-check on the steady-state data, as well as a data base for developing or verifying portions of the transient gap conductance models needed to satisfy the final acceptance criteria for emergency core cooling system.

Rod 3 also provided an upper bound for gap conductance.

2.3.4 Effects of Xenon and Eccentricity (Rod 4)

Previous experiments have indicated that gap conductances are not as sensitive to different fill gas compositions as some models would predict. In particular, Cohen et al.,⁽⁷⁾ Horn⁽⁸⁾ and Lawrence et al.,⁽⁹⁾ have reported that large portions of Xenon must be mixed with helium before significant changes in gap conductance can be detected. In addition, analytical work had indicated that asymmetric pellet cladding gap geometries could have a significant effect on fuel temperatures and gap conductances.⁽¹⁰⁾ The experimental resolution of the above was considered in the design of the NRC-RSR/PNL Halden assemblies IFA-431 and IFA-432.

To understand the anomalous thermal behavior of Xenon-filled rods, we designed a rod (Number 4) that contained 95% TD stable fuel, a 0.009-in. (0.229 mm) diametral gap, and Xenon fill gas. Instrumented portions of the fuel column were mechanically constrained to be held concentric (near the top)

and eccentric (near the bottom) of the rod (Figure 2.4). This was accomplished using the fuel centerline thermocouples, molybdenum rods, and oversized pellets. These oversized pellets were of the same design as Rod 3 of each respective assembly. They had flats ground on the periphery to allow axial fill gas communication.

Results of the analysis of the data from this rod may be seen in Reference 11.

FIGURE 2.4. Schematic of Rod 4 Fuel Column

2.3.5 Verification of Fuel Stability (Rod 5)

Results of recent experimental work^(1,12) provide the technology required to fabricate low density (e.g., 92% TD) fuel with various degrees of stability or resistance to irradiation-induced densification. New commercial designs under consideration will use low density, stable fuel. Rod 5 contained 92% TD stable fuel and provided one means of verifying recent fuel fabrication technology with regard to the effects of fuel structures on irradiation temperatures. This rod will also be a cross-correlation with Rod 6.

2.3.6 Densification Kinetics (Rod 6)

Rod 6 contains 92% TD unstable fuel and a 0.009 in. (0.229 mm) gap. Unstable fuel with similar structure^(1,12) underwent significant densification.

Densification models utilizing kinetic information obtained from Halden⁽⁴⁾, terminal densities derived from the EEI/EPRI studies,⁽¹⁾ and resintering tests were developed to simulate time-dependent densification. Data from Rod 6 will be used to verify NRC densification models^(13,14) and provide a check of applicant-supplied models.

2.4 FUEL AND CLADDING PRECHARACTERIZATION

Extensive precharacterization of the fuel and cladding was essential to assure quality data and to reduce calculational uncertainties. Since this is presented elsewhere,⁽¹⁵⁾ only the main objectives will be discussed here.

The previous discussion describes the importance of knowing the correct power distribution. Thermal diffusivity measurements were made on each fuel type up to 1600°C. This spans most of the fuel volume in either test. From previous experimental work, the heat capacity and density were obtained to calculate the thermal conductivity of the fuel as a function of temperature. Substitution of these data for the Lyons⁽¹⁶⁾ thermal conductance equation used in the GAPCON-THERMAL-2⁽¹⁷⁾ pretest predictions improved the power calibration calculation using Rod 3. In addition, the thermal diffusivity data reduced the uncertainty associated with calculating gap conductances from the experimental data. Figure 2.5 shows the differences between the Lyons and IFA-432 precharacterization fuel thermal conductivities.

Establishing the initial dimensions and void volumes within the pins was also an essential part of assessing all thermal calculations. Consequently, the lengths and diameters of each pellet and the cladding for each rod were measured. Each pellet was identified with a unique number to trace pellet types and position within the rod (see Appendix A). With this information the axial distribution of gap volume and the plenum volume were obtained with considerable accuracy. Pellet and cladding roundness profiles were also obtained to illustrate the departure from ideal coaxial cylinders used in most computer code models.

Geometric densities were determined for all pellets and immersion densities for a significant fraction of the pellets. A correlation was developed

FIGURE 2.5. IFA-432 Fuel Thermal Conductivity, 95% TD Stable, Rods 1, 2, 3, 4

relating immersion density to geometric densities. These data were used in two ways, 1) in a correction to rod powers caused by differences in mass distribution and 2) in the verification of NRC resintering models used to characterize fuel's propensity to densify. Resintering tests conducted on each fuel type are discussed in Reference 15.

The EEI/EPRI UO₂ densification program⁽¹⁾ demonstrated the importance of pore-size distribution measurements in characterizing the stability of various fuel types. We wanted to assure that the 95% TD stable fuel types were indeed stable. On the other hand, we wanted the 92% TD unstable fuel to undergo large

amounts of densification in-reactor to determine the effects on fuel temperatures. Both fuel densities and pore-size distribution will be measured in a post-irradiation examination (PIE) for Rods 1, 5 and 6 at Harwell, UK. Archive pellets from each fuel type were retained to provide a means of reducing variances associated with potential differences in examination techniques used in the pre-and post-test measurements.

3.0 DATA PRESENTATION

Figures 3.1 through 3.226 show the in-reactor data collected from IFA-432 during its irradiation period from December 1975 to January 1978 plotted versus time by months. All data except the rod internal pressures were obtained by the Halden IBM/1800 on-line computer data acquisition system. Data densities (versus time) vary from 15 minutes to 12 hours, depending on whether the reactor was experiencing transient (startup, power cycling) or steady state conditions.

In each figure, the rod number for each curve appears in the upper left hand corner. The relative position of the rod number corresponds to the relative position of the curve in each figure.

3.1 POWER HISTORIES

Figures 3.1 through 3.120 show the power histories of the upper and lower thermocouple locations for all six rods. These values were deduced from the vanadium self-powered neutron detector readings after applying correction factors to account for local mass distribution, radial flux tilt, and axial flux shape. This is described in Appendix D.

Corrections were also made for the burnup dependent depletion of ^{235}U , but no plutonium buildup was considered. Halden recommended the depletion correction that was used (-.66% per 1000 MWd/MTM).

The neutron detector readings during transient periods have not been corrected for the response lag of the detector caused by incomplete saturation of the vanadium emitter. This lag amounts to about 5 minutes during a power ramp, or one-third of the normal data collection frequency.

3.2 FUEL TEMPERATURE HISTORIES

Figures 3.121 through 3.186 show the fuel centerline temperature histories for the upper and lower thermocouple locations for all six rods. These data were collected from the W 5% Re/W 26% Re sheathed, grounded thermocouples inserted in each end of each rod (see Appendix B). The ultrasonic thermometer at the top of Rod 2 failed, and there is no data for this position.

In using these data, the reader should be aware that some anomalies have been seen between upper and lower thermocouples in the same rod, suggesting that the fuel at one end of the rod may be relatively decoupled from that at the other end. Future PNL reports will discuss these data.

3.3 CLADDING ELONGATION HISTORIES

Figures 3.187 through 3.209 show the cladding elongation histories for all six rods. Each rod was equipped with an LVDT-type elongation sensor of Halden design to monitor length changes throughout life. The results of the analysis of these data are discussed in Reference 18.

3.4 ROD INTERNAL PRESSURE HISTORIES

Figures 3.210 through 3.226 show the internal gas pressure histories for Rods 1, 5 and 6 throughout their irradiation history. These measurements were taken manually at various assembly powers using a null balance technique to complete an electrical connection in the diaphragm-type pressure transducers. The pressure readings were taken from the gas feed line that supplied the pressure to balance the transducer, and indicate gauge pressure. The data points connected by straight lines in Figures 3.210 through 3.226 indicate the number of times that the pressure data was manually collected throughout the life of the assembly. Results of the analysis of these data will be discussed in future PNL reports.

3.5 BURNUP

Table 3.1 shows the calculated burnups at each thermocouple location for each rod. These are the local burnups at the end of each month of operation. They were calculated by numerically integrating the power history over time and then correcting for the depletion of ^{235}U . Comparisons of this method and PIE data for Rod 6 of IFA-431 showed good agreement.

FIGURE 3.1. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - December 1975

FIGURE 3.2. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1975

FIGURE 3.3. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - December 1975

FIGURE 3.4. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - December 1975

FIGURE 3.5. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1975

FIGURE 3.6. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1975

FIGURE 3.7. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1976

FIGURE 3.8. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - January 1976

FIGURE 3.9. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - January 1976

FIGURE 3.10. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - January 1976

FIGURE 3.11. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1976

FIGURE 3.12. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1976

FIGURE 3.13. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - February 1976

FIGURE 3.14. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - February 1976

FIGURE 3.15. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,4 of IFA 432 - February 1976

FIGURE 3.16. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,4 of IFA 432 - February 1976

FIGURE 3.17. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - February 1976

FIGURE 3.18. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - February 1976

FIGURE 3.21. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - June 1976

FIGURE 3.22. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - June 1976

FIGURE 3.19. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - June 1976

FIGURE 3.20. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - June 1976

FIGURE 3.23. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - June 1976

FIGURE 3.24. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - June 1976

FIGURE 3.25. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - July 1976

FIGURE 3.26. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - July 1976

FIGURE 3.27. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - July 1976

FIGURE 3.28. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - July 1976

FIGURE 3.29. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - July 1976

FIGURE 3.30. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - July 1976

FIGURE 3.31. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - August 1976

FIGURE 3.32. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - August 1976

FIGURE 3.33. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - August 1976

FIGURE 3.34. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - August 1976

FIGURE 3.35. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - August 1976

FIGURE 3.36. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - August 1976

FIGURE 3.37. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - September 1976

FIGURE 3.38. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - September 1976

FIGURE 3.39. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - September 1976

FIGURE 3.40. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - September 1976

FIGURE 3.41. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - September 1976

FIGURE 3.42. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - September 1976

FIGURE 3.43. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - October 1976

FIGURE 3.44. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - October 1976

FIGURE 3.45. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - October 1976

FIGURE 3.46. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - October 1976

FIGURE 3.47. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - October 1976

FIGURE 3.48. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - October 1976

FIGURE 3.49. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - December 1976

FIGURE 3.50. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1976

FIGURE 3.51. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - December 1976

FIGURE 3.52. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - December 1976

FIGURE 3.53. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1976

FIGURE 3.54. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1976

FIGURE 3.55. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1977

FIGURE 3.56. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - January 1977

FIGURE 3.57. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - January 1977

FIGURE 3.58. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - January 1977

FIGURE 3.59. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1977

FIGURE 3.60. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1977

FIGURE 3.61. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - February 1977

FIGURE 3.62. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - February 1977

FIGURE 3.63. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - February 1977

FIGURE 3.64. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - February 1977

FIGURE 3.65. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - February 1977

FIGURE 3.66. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - February 1977

FIGURE 3.67. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - March 1977

FIGURE 3.68. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - March 1977

FIGURE 3.69. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - March 1977

FIGURE 3.70. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - March 1977

FIGURE 3.71. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - March 1977

FIGURE 3.72. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - March 1977

FIGURE 3.73. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - April 1977

FIGURE 3.74. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - April 1977

FIGURE 3.75. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - April 1977

FIGURE 3.76. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - April 1977

FIGURE 3.77. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - April 1977

FIGURE 3.78. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - April 1977

FIGURE 3.79. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - May 1977

FIGURE 3.80. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - May 1977

FIGURE 3.81. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - May 1977

FIGURE 3.82. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - May 1977

FIGURE 3.83. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - May 1977

FIGURE 3.84. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - May 1977

FIGURE 3.85. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - June 1977

FIGURE 3.86. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - June 1977

FIGURE 3.87. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - June 1977

FIGURE 3.88. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - June 1977

FIGURE 3.89. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - June 1977

FIGURE 3.90. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - June 1977

FIGURE 3.91. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - July 1977

FIGURE 3.92. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - July 1977

FIGURE 3.93. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - July 1977

FIGURE 3.94. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - July 1977

FIGURE 3.95. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - July 1977

FIGURE 3.96. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - July 1977

FIGURE 3.97. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - August 1977

FIGURE 3.98. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - August 1977

FIGURE 3.99. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - August 1977

FIGURE 3.100. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - August 1977

FIGURE 3.101. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - August 1977

FIGURE 3.102. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - August 1977

FIGURE 3.103. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - October 1977

FIGURE 3.104. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - October 1977

FIGURE 3.105. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - October 1977

FIGURE 3.106. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - October 1977

FIGURE 3.107. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - October 1977

FIGURE 3.108. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - October 1977

FIGURE 3.109. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - December 1977

FIGURE 3.110. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - December 1977

FIGURE 3.111. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - December 1977

FIGURE 3.112. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - December 1977

FIGURE 3.113. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - December 1977

FIGURE 3.114. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - December 1977

FIGURE 3.115. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 1,3 of IFA 432 - January 1978

FIGURE 3.116. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 1,3 of IFA 432 - January 1978

FIGURE 3.117. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 2,8 of IFA 432 - January 1978

FIGURE 3.118. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 2,8 of IFA 432 - January 1978

FIGURE 3.119. Local Linear Heat Ratings at Upper Thermocouple Locations for Rods 5,6 of IFA 432 - January 1978

FIGURE 3.120. Local Linear Heat Ratings at Lower Thermocouple Locations for Rods 5,6 of IFA 432 - January 1978

FIGURE 3.121. Upper Thermocouple Readings for Rods 1,3
of IFA 432 - December 1975

FIGURE 3.122. Lower Thermocouple Readings for Rods 1,3
of IFA 432 - December 1975

FIGURE 3.123. Upper Thermocouple Readings for Rod 4
of IFA 432 - December 1975

FIGURE 3.124. Lower Thermocouple Readings for Rods 2,4
of IFA 432 - December 1975

FIGURE 3.125. Upper Thermocouple Readings for Rods 5,6
of IFA 432 - December 1975

FIGURE 3.126. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - December 1975

FIGURE 3.127. Upper Thermocouple Readings for Rods 1,3 of IFA 432 - January 1976

FIGURE 3.128. Lower Thermocouple Readings for Rods 1,2,3 of IFA 432 - January 1976

FIGURE 3.129. Upper Thermocouple Readings for Rods 5,6 of IFA 432 - January 1976

FIGURE 3.130. Lower Thermocouple Readings for Rods 5,6 of IFA 432 - January 1976

FIGURE 3.131. Upper Thermocouple Readings for Rods 1,3
of IFA 432 - February 1976

FIGURE 3.132. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - February 1976

FIGURE 3.133. Upper Thermocouple Readings for Rods 5,6
of IFA 432 - February 1976

FIGURE 3.134. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - February 1976

FIGURE 3.135. Upper Thermocouple Readings for Rods 1,3
of IFA 432 - June 1976

FIGURE 3.136. Lower Thermocouple Readings for Rods 1, 2,3
of IFA 432 - June 1976

FIGURE 3.137. Upper Thermocouple Readings for Rods 5,6
of IFA 432 - June 1976

FIGURE 3.138. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - June 1976

FIGURE 3.139. Upper Thermocouple Readings for Rods 1, 3, 6 of IFA 432 - July 1976

FIGURE 3.140. Lower Thermocouple Readings for Rods 1, 2, 3 of IFA 432 - July 1976

FIGURE 3.141. Lower Thermocouple Readings for Rods 5, 6 of IFA 432 - July 1976

FIGURE 3.142. Upper Thermocouple Readings for Rods 1, 3, 6 of IFA 432 - August 1976

FIGURE 3.143. Lower Thermocouple Readings for Rods 1, 2, 3 of IFA 432 - August 1976

FIGURE 3.144. Lower Thermocouple Readings for Rods 5, 6 of IFA 432 - August 1976

FIGURE 3.145. Upper Thermocouple Readings for Rods 1, 3, 6
of IFA 432 - September 1976

FIGURE 3.146. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - September 1976

FIGURE 3.147. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - September 1976

FIGURE 3.148. Upper Thermocouple Readings for Rods 1, 3, 6
of IFA 432 - October 1976

FIGURE 3.149. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - October 1976

FIGURE 3.150. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - October 1976

FIGURE 3.151. Upper Thermocouple Readings for Rods 1,3 of IFA 432 - December 1976

FIGURE 3.152. Lower Thermocouple Readings for Rods 1, 2, 3 of IFA 432 - December 1976

FIGURE 3.153. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - December 1976

FIGURE 3.154. Upper Thermocouple Readings for Rods 1,3
of IFA 432 - January 1977

FIGURE 3.155. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - January 1977

FIGURE 3.156. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - January 1977

FIGURE 3.157. Upper Thermocouple Readings for Rod 3
of IFA 432 - February 1977

FIGURE 3.158. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - February 1977

FIGURE 3.159. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - February 1977

FIGURE 3.160. Upper Thermocouple Readings for Rod 3
of IFA 432 - March 1977

FIGURE 3.161. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - March 1977

FIGURE 3.162. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - March 1977

FIGURE 3.163. Upper Thermocouple Readings for Rod 3
of IFA 432 - April 1977

FIGURE 3.164. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - April 1977

FIGURE 3.165. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - April 1977

FIGURE 3.166. Upper Thermocouple Readings for Rod 3
of IFA 432 - May 1977

FIGURE 3.167. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - May 1977

FIGURE 3.168. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - May 1977

FIGURE 3.169. Upper Thermocouple Readings for Rod 3 of IFA 432 - June 1977

FIGURE 3.170. Lower Thermocouple Readings for Rods 1, 2, 3 of IFA 432 - June 1977

FIGURE 3.171. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - June 1977

FIGURE 3.172. Upper Thermocouple Readings for Rod 3
of IFA 432 - July 1977

FIGURE 3.173. Lower Thermocouple Readings for Rods 1,2,3
of IFA 432 - July 1977

FIGURE 3.174. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - July 1977

FIGURE 3.175. Upper Thermocouple Readings for Rod 3
of IFA 432 - August 1977

FIGURE 3.176. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - August 1977

FIGURE 3.177. Lower Thermocouple Readings for Rods 5,6
of IFA 432 - August 1977

FIGURE 3.178. Upper Thermocouple Readings for Rod 3
of IFA 432 - October 1977

FIGURE 3.179. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - October 1977

FIGURE 3.180. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - October 1977

FIGURE 3.181. Upper Thermocouple Readings for Rod 3
of IFA 432 - December 1977

FIGURE 3.182. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - December 1977

FIGURE 3.183. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - December 1977

FIGURE 3.184. Upper Thermocouple Readings for Rod 3
of IFA 432 - January 1978

FIGURE 3.185. Lower Thermocouple Readings for Rods 1, 2, 3
of IFA 432 - January 1978

FIGURE 3.186. Lower Thermocouple Readings for Rods 5, 6
of IFA 432 - January 1978

FIGURE 3.187. Cladding Elongation Sensor Readings for Rods 1, 2, 5, 6 of IFA 432 - December 1975

FIGURE 3.188. Cladding Elongation Sensor Readings for Rods 3, 4 of IFA 432 - December 1975

FIGURE 3.189. Cladding Elongation Sensor Readings for Rods 1, 2, 5, 6 of IFA 432 - January 1976

FIGURE 3.190. Cladding Elongation Sensor Readings for Rods 3, 4 of IFA 432 - January 1976

FIGURE 3.191. Cladding Elongation Sensor Readings for Rods 1, 2, 5, 6 of IFA 432 - February 1976

FIGURE 3.192. Cladding Elongation Sensor Readings for Rods 3, 4 of IFA 432 - February 1976

FIGURE 3.193. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - June 1976

FIGURE 3.194. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - July 1976

FIGURE 3.195. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - August 1976

FIGURE 3.196. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - September 1976

FIGURE 3.197. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - October 1976

FIGURE 3.198. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - December 1976

FIGURE 3.199. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - January 1977

FIGURE 3.200. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - February 1977

FIGURE 3.201. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - March 1977

FIGURE 3.202. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - April 1977

FIGURE 3.203. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - May 1977

FIGURE 3.204. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - June 1977

FIGURE 3.205. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - July 1977

FIGURE 3.206. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - August 1977

FIGURE 3.207. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - October 1977

FIGURE 3.208. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - December 1977

FIGURE 3.209. Cladding Elongation Sensor Readings for Rods 2, 3, 6, 8 of IFA 432 - January 1978

FIGURE 3.210. Internal Pressures for Rods 1, 5, 6 of IFA 432 - December 1975

FIGURE 3.211. Internal Pressures for Rods 1, 5, 6
of IFA 432 - January 1976

FIGURE 3.212. Internal Pressures for Rods 1, 5, 6
of IFA 432 - February 1976

FIGURE 3.213. Internal Pressures for Rods 1, 5, 6 of IFA 432 - June 1976

FIGURE 3.214. Internal Pressures for Rods 1, 5, 6 of IFA 432 - August 1976

FIGURE 3.215. Internal Pressures for Rods 1, 5, 6
of IFA 432 - September 1976

FIGURE 3.216. Internal Pressures for Rods 1, 5, 6
of IFA 432 - October 1976

FIGURE 3.217. Internal Pressures for Rods 1, 5, 6 of IFA 432 - December 1976

FIGURE 3.218. Internal Pressures for Rods 1, 5, 6 of IFA 432 - January 1977

FIGURE 3.219. Internal Pressures for Rods 1, 5, 6 of IFA 432 - February 1977

FIGURE 3.220. Internal Pressures for Rods 1, 5, 6 of IFA 432 - March 1977

FIGURE 3.221. Internal Pressures for Rods 1, 5, 6 of IFA 432 - April 1977

FIGURE 3.222. Internal Pressures for Rods 1, 5, 6 of IFA 432 - May 1977

FIGURE 3.223. Internal Pressures for Rods 1, 5, 6 of IFA 432 - June 1977

FIGURE 3.224. Internal Pressures for Rods 1, 5, 6 of IFA 432 - July 1977

FIGURE 3.225. Internal Pressures for Rods 1, 5, 6 of IFA 432 - August 1977

FIGURE 3.226. Internal Pressures for Rods 1, 5, 6 of IFA 432 - October 1977

TABLE 3.1. IFA-432 Burnup (MWD/MTM).

Month	Year	Upper TC						Lower TC					
		Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
12	75	813.2	793.4	837.4	864.5	383.4	846.6	596.0	596.5	623.5	630.9	637.7	616.0
1	76	2210.2	2153.8	2254.4	2312.9	2366.4	2285.2	1609.3	1611.2	1687.7	1710.7	1728.4	1666.4
2	76	2746.7	2675.2	2796.2	2866.8	2934.7	2837.6	1989.4	1991.9	2088.1	2118.3	2140.0	2061.6
6	76	3510.7	3418.6	3564.1	784.1	3733.6	3618.7	2507.3	2512.0	2632.1	549.6	2693.3	2595.6
7	76	4978.1	4843.4	5030.9	2281.2	5261.9	5117.5	3529.8	3536.6	3696.7	1621.1	3773.8	3645.2
8	76	5853.8	5694.6	5907.2	3174.7	6172.9	6011.0	4121.8	4131.1	4317.6	2247.7	4404.3	4254.6
9	76	6627.5	6448.9	6680.8	3959.0	6970.6	6795.9	4656.9	4667.3	4871.9	2803.3	4964.4	4801.2
10	76	7805.2	7597.7	7856.8	5148.8	8179.6	7987.7	5489.9	5500.4	5735.2	3671.9	5841.6	5655.6
12	76	8485.3	8241.1	8502.0	5808.9	8870.7	8682.5	6001.7	5996.1	6234.3	4176.3	6367.1	6181.9
1	77	9757.8	9449.6	9716.1	7048.8	10163.7	9980.2	6958.6	6924.4	7163.9	5109.3	7337.7	7159.2
2	77	10130.6	9801.5	10068.0	7409.2	10541.8	10361.2	7231.5	7189.0	7429.0	5375.7	7614.9	7438.1
3	77	10313.2	9978.5	10249.0	7593.3	10730.0	10546.9	7376.8	7330.3	7574.2	5524.7	7769.4	7589.9
4	77	11528.5	11139.4	11423.8	8795.2	11975.8	11788.6	8305.7	8229.9	8495.7	6471.3	8754.4	8560.8
5	77	12334.2	11908.8	12201.5	9590.5	12800.5	12611.4	8914.5	8819.6	9100.1	7092.6	9400.4	9197.2
6	77	12389.3	11961.7	12254.5	9644.0	12855.6	12666.9	8958.6	8863.4	9144.8	7137.2	9445.9	9242.2
7	77	13560.6	13031.4	13273.2	10676.8	13979.1	13849.9	9760.2	9616.4	9875.1	7873.0	10236.8	10062.2
8	77	14762.8	14134.1	14325.9	11742.0	15132.5	15061.9	10578.8	10387.4	10622.0	8623.1	11041.2	10896.9
10	77	15556.2	14881.8	15056.5	12476.3	15905.3	15857.7	11160.8	10945.0	11185.7	9201.7	11649.4	11503.7
11	77	15677.4	14995.3	15166.0	12585.8	16021.3	15978.5	11246.5	11027.5	11268.8	9286.2	11737.7	11592.2
12	77	16393.6	15693.5	15865.8	13282.4	16729.4	16690.6	11770.4	11542.2	11796.9	9822.8	12288.3	12133.7
1	78	16931.6	16207.4	16373.5	13791.4	17257.6	17228.9	12150.4	11913.0	12175.6	10208.3	12686.3	12527.0

REFERENCES

1. D. W. Brite, J. L. Daniel, N. C. Davis, M. D. Freshley, P. E. Hart, and R. K. Marshall, EEI/EPRI Fuel Densification Project Research Project 131 Final Report prepared for Electric Power Research Institute by Battelle, Pacific Northwest Laboratories, March 1975, Revised June 1975.
2. Regulatory Staff, U.S. Atomic Energy Commission, Technical Report on Densification of Light Water Reactor Fuels, WASH-1236, November 1972.
3. M. D. Freshley, P. E. Hart, J. L. Daniel, D. W. Brite, and T. D. Chikalla, "The Effect of Pellet Characteristics and Irradiation Conditions on UO₂ Fuel Densification." Presented at the ANS/CNA Topical Meeting on "Commercial Nuclear Fuel - Current Technology," Toronto, Canada, April 1975.
4. A. Hanevik, K. D. Knudsen, and P. Arnesen, "In-Reactor Measurements of Fuel Stack Shortening." Proceedings of the British Nuclear Energy Society Conference, London, England, October 1973.
5. J. A. L. Robertson, λ_{KDO} in Fuel Irradiations. CRFD-835, Chalk River, Ontario, Canada, April 1959.
6. D. D. Lanning and C. R. Hann, Verification of Fuel Centerline Thermocouple Readings Through Response to Linear Power Decreases, BNWL-2189, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, April 1977.
7. I. Cohen, B. Lustman and J. D. Eichenberg, Measurement of the Thermal Conductivity of Metal-Clad Uranium Oxide Rods During Irradiation. WAPD-228, Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, Pittsburgh, PA, August 1960.
8. G. R. Horn, "The Effects of Xenon on Fuel-to-Cladding Gap Conductivity." Trans. ANS, Vol. 12, p. 607, 1969.
9. L. A. Lawrence, G. R. Horn and J. A. Christensen, "Fuel-Clad Gap Conductions in Fast Reactor Fuels." Trans. ANS. Vol. 13, p. 572, 1970.
10. D. J. Bradley and C. R. Hann, An Evaluation of the Discrepancies Between Predicted and Experimental Effects of Xenon and Krypton in Nuclear Fuel Rods. BNWL-1955, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, November 1975.
11. R. E. Williford and C. R. Hann, Effects of Fill Gas Composition and Pellet Eccentricity, BNWL-2285, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, July 1977.
12. P. E. Hart and J. L. Daniel, "The Role of Microstructure in Thermal and Irradiation-Induced Densification of UO₂ Fuels." Presented at 77th Annual Meeting of the American Ceramic Society, Washington, D.C., May 3-8, 1975.

13. Core Performance Branch, U.S. Nuclear Regulatory Commission, The Analysis of Fuel Densification, NUREG-0085, July 1976.
14. "An Acceptable Model and Related Statistical Methods for the Analysis of Fuel Densification," Regulatory Guide 1.126, U.S. Nuclear Regulatory Commission, March 1977.
15. C. R. Hann, J. L. Bates, D. W. Brite, J. L. Daniel, N. C. Davis, P. E. Hart, R. K. Marshall, G. Mellinger, and R. E. Williford, Test Design, Pre-Characterization and Fuel Assembly Fabrication for Instrumented Fuel Assemblies IFA-431 and IFA-432. BNWL-1988, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, November 1977.
16. M. F. Lyons, D. H. Coplin, T. J. Pashos, and B. Weidenbaum, UO2 Pellet Thermal Conductivity from Irradiation with Central Melting, GEAP-4624, 1964.
17. C. E. Beyer, C. R. Hann, D. D. Lanning, F. E. Panisko and L. J. Parchen, GAPCON-THERMAL-2: A Computer Program for Calculating the Thermal Behavior of an Oxide Fuel Rod. BNWL-1898, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, November 1975.
18. C. R. Hann and R. K. Marshall, Comparative Analysis of Pellet-Cladding Interaction from IFA-431 and IFA-432 Halden Reactor Tests, BNWL-2240, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, July 1977.
19. C. R. Hann, D. D. Lanning, R. K. Marshall, A. R. Olsen, and R. E. Williford, A Method for Determining the Uncertainty of Gap Conductance Deduced from Measured Fuel Centerline Temperatures, BNWL-2091, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, February 1977.
20. Magnetic Properties; Metallic Materials for Thermostats, Electrical Resistance, Heating, Contacts; Temperature Measurements; Illuminating Standards. 01-044077-40, 1977 Annual Book of ASTM Standards (part 44), Proposed Standard, pg. 867-873.
21. L. C. Lynnworth, et. al., "Ultrasonic Thermometry for Nuclear Reactors", IEEE Trans. Am. Nuc. Soc., NS-16, February 1969, pp. 184-187.
22. C. R. Hann, et. al., Data Report for the NRC/PNL Halden Assembly IFA-431, PNL-2494, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, June 1978.

APPENDIX A

FUEL ROD AND FUEL COLUMN
SCHEMATICS FOR IFA-432

FIGURE A-1. Schematic Arrangement of Fuel Rods for IFA-432

TOTAL NUMBER OF PELLETS IN EACH STACK - 49

NUMBER OF FUEL PELLETS - 45 32 SOLID, 13 DRILLED - 0.175 CM $\pm$ 0.005 CM (0.069 $\pm$ 0.002 INCH) FURNISHED BY BNW

NUMBER OF POISON PELLETS - 4 DRILLED - 0.175 CM $\pm$ 0.005 CM (0.069 $\pm$ 0.002 INCH) FURNISHED BY HALDEN

ROD NO.	PELLET DIAMETER		FUEL DENSITY % TD	FUEL TYPE	FILL GAS 1 ATM
	IFA-431 CM (inch)	IFA-432 CM (inch)			
1	1.0681 (0.4205)	1.0681 (0.4205)	95	STABLE	HELIUM
6	1.0681 (0.4205)	1.0681 (0.4205)	92	UNSTABLE	HELIUM

FIGURE A-2. Stack Arrangement for Rods 1 and 6

TOTAL NUMBER OF PELLETS IN EACH STACK - 48

NUMBER OF FUEL PELLETS - 44 32 SOLID, 12 DRILLED - 0.175 ± 0.005 CM (0.069 ± 0.002 INCH) FURNISHED BY BNW

NUMBER OF POISON PELLETS - 4 DRILLED - 0.175 ± 0.005 CM (0.069 ± 0.002 INCH) FURNISHED BY HALDEN

ROD NO.	PELLET DIAMETER		FUEL DENSITY % TD	FUEL TYPE	FILL GAS 1 ATM
	IFA-431 CM (inch)	IFA-432 CM (inch)			
2	1.0528 (0.4145)	--	95	STABLE	HELIUM
3	1.0858 (0.4275)	1.0833 (0.4265)	95	STABLE	HELIUM
5	1.0681 (0.4205)	1.0681 (0.4205)	92	STABLE	HELIUM

FIGURE A-3. Stack Arrangement for Rods 2, 3, and 5

TOTAL NUMBER OF PELLETS IN EACH STACK - 48

NUMBER OF FUEL PELLETS - 44 32 SOLID, 12 DRILLED - 0.175 ± 0.005 CM (0.069 ± 0.002 INCH) FURNISHED BY BNW

NUMBER OF POISON PELLETS - 4 DRILLED - 0.175 ± 0.005 CM (0.069 ± 0.002 INCH) FURNISHED BY HALDEN

ROD NO.	PELLET DIAMETER	FUEL DENSITY % TD	FUEL TYPE	FILL GAS 1 ATM
	IFA-432 CM(INCH)			
2	1.0528 (0.4145)	95	STABLE	HELIUM

FIGURE A-4. Stack Arrangement for Rod 2, IFA-432

TOTAL NUMBER OF PELLETS IN STACK - 48
 NUMBER OF FUEL PELLETS - 44 27 SOLID, 17 DRILLED (FURNISHED BY BNW), 95% TD, STABLE
 NUMBER OF POISON PELLETS - 4 DRILLED - 0.175 ± 0.005 CM (0.069 ± 0.002 INCH) (FURNISHED BY HALDEN)
 FILL GAS - 1 ATM XENON

PELLET POSITION	PELLET DIAMETER		HOLE DIAMETER CM (inch)	ON CENTER	0.0127 CM (0.005 INCH) OFF CENTER
	IFA-431 CM (inch)	IFA-432 CM (inch)			
12-38	1.0681 (0.4205)	1.0681 (0.4205)	--	--	--
3- 5 45-46	1.0681 (0.4205)	1.0681 (0.4205)	0.175 ± 0.005 (0.069 ± 0.002)	YES	--
7-10	1.0681 (0.4205)	1.0687 (0.4205)	0.160 ± 0.005 (0.063 ± 0.002)	YES	--
40-43	1.0681 (0.4205)	1.0681 (0.4205)	0.160 ± 0.005 (0.063 ± 0.002)	--	YES
6, 11, 39, 44	1.0858 (0.4275)	1.0833 (0.4265)	0.160 ± 0.005 (0.063 ± 0.002)	YES	--

FIGURE A-5. Stack Arrangement for Rod 4 - Xenon Fill Gas

TOTAL NUMBER OF PELLETS IN EACH STACK - 49
 NUMBER OF FUEL PELLETS - 45 FURNISHED BY BNW
 NUMBER OF POISON PELLETS - 4 FURNISHED BY HALDEN

ROD NO.	PELLET DIAMETER	FUEL DENSITY % TD	FUEL TYPE	FILL GAS 1 ATM
	IFA-432 CM (INCH)			
7	1.0528 (0.4145)	95	STABLE	HELIUM
8	1.0681 (0.4205)	95	STABLE	HELIUM
9	1.0732 (0.4225)	95	STABLE	HELIUM

FIGURE A-6. Stack Arrangement for Non-Instrumental Replacement Rods 7, 8, and 9 IFA-432

APPENDIX B

INSTRUMENT DESCRIPTIONS AND
CALIBRATION

APPENDIX B

INSTRUMENT DESCRIPTIONS AND CALIBRATION

IFA-432 was equipped with a comprehensive array of in-pile instrumentation to collect the data. The placement of these instruments was shown in Figures 2.1 and 2.2. The most important of these instruments were:

- Six vanadium beta emitter self-powered neutron detectors
- One cobalt fast response self-powered neutron detector
- Eleven W5%Re/W26%Re sheathed fuel centerline thermocouples
- One Ultrasonic thermometer
- Six LVDT cladding elongation monitors
- Three diaphragm-type rod internal pressure transducers.

Each of these is briefly discussed below. The accuracy and uncertainty of their respective outputs is discussed more completely in Reference 19.

NEUTRON DETECTORS

IFA-432 was equipped with six vanadium, self-powered, beta current neutron detectors (Figure B-1) to monitor the power in the fuel assembly after the initial thermal-hydraulic calibration.

Each vanadium neutron detector was 3.93 in. (100 mm) long and was positioned so that the center of the detector and the thermocouple junction were located on essentially the same plane.

The neutron detectors used in IFA-432 were not calibrated. Their precisions were based on the results of the irradiation of 30 similar type vanadium neutron detectors in the Studsvik R2-0 Reactor in Sweden. The 30 detectors were irradiated in a thermal neutron flux of 1.1×10^{10} n/cm²-sec. The error limits for the outputs of the detectors were estimated to be $\pm 2.5\%$ at a neutron flux of 1.1×10^{10} n/cm²-sec.

FIGURE B-1. Schematic of Self-Powered,
Beta Current Neutron Detector

In addition to correlating the detector outputs to the neutron flux in the Studsvik reactor, Halden has conducted long-term tests of similar neutron detectors in the HBWR. These long-term tests have established the detectors as reliable and accurate instruments without a measurable change in sensitivity at the higher flux levels in the HBWR.

The sensitivities of the test assembly neutron detectors were calculated from the sensitivities of the calibrated detectors and the physical characteristics of the test assembly detectors supplied by the manufacturer. The gamma sensitivity is not measured and is considered by Halden to be negligible.

The vanadium detectors have a calculated burnup rate of 0.013%/month at a neutron flux of 1×10^{13} n/cm²-sec. Based on this rate, the neutron detector end-of-life (EOL) burnup for IFA-432 is 0.3%. Because of this low value, the neutron detector outputs were not corrected for burnup.

A disadvantage of the vanadium detectors is their slow response time (5.5 min, 0 to 63%) to power changes. Consequently, during up and down power ramps, a correction factor should be considered for the output values.

The cobalt detector, similar in appearance but 20 cm long, was placed in the center of the assembly to monitor average assembly power during transient tests.⁽⁶⁾

FUEL THERMOCOUPLES

Eleven thermocouples were used in IFA-432 for measuring the central fuel temperatures. The thermocouples had grounded junctions with 0.062 in. (1.575 mm) OD tungsten/22% rhenium sheaths and W 5% Re/W 26% Re seven-stranded thermocouple wires with thorium oxide insulators (Figure B-2). The sensor in the top of Rod 2 was an ultrasonic thermometer (Reference 21). It failed early in life.

The thermocouples were fabricated and calibrated by the Idaho National Engineering Laboratory (INEL). The calibration curve for the tungsten-rhenium thermocouples is shown in Figure B-3. Calibration of the thermocouples over the range of use produces a brittle assembly which is fragile and subject

FIGURE B-2. Schematic of W 5% Re/W 26% Re Thermocouples with Grounded Junction

FIGURE B-3. Calibration Curve for W 5% Re/W 26% Re Thermocouples

to breakage. Consequently, only one thermocouple, which was not used in the in-reactor test, was calibrated.

The tungsten rhenium thermocouple was calibrated against a reference thermocouple of bare W 5% Re/W 26% Re and an optical pyrometer as a second reference. The reference thermocouple and the optical pyrometer agreed within 40°F (22°C) up to 4000°F (2204°C), but as the temperature approached 4500°F (2482°C), the two differed more widely. The optical pyrometer was thought to be closer since the 4500°F temperature is above that given in most calibration tables for W/Re thermocouples. The calibrated thermocouple had the following limits of error:

Ambient to 1000°F (538°C)	= ±10°F (5.5°C)
1000°F (538°C) to 4000°F (2204°C)	= ±1% of reading
4000°F (2204°C) to 4500°F (2482°C)	= ±2% of reading.

Irradiation of the thermocouples will have long term effects caused by the shunting of the EMF's by conduction across the insulators, by transmutations in the thermocouple materials, and by temperature gradients along the thermocouple wires. The insulator shunting effect was reduced to a negligible level by using thorium oxide insulators.

The expected fluence for IFA-432 is about 5×10^{20} nvt. This fluence would indicate a downward EMF drift of 5% for IFA-432 at EOL. No correction factor is applied to the IFA-432 data. However, an error value of ±5% is assumed for the irradiation effects.

CLADDING ELONGATION MONITORS

Figure B-4 is a schematic of the LVDT cladding elongation sensors used in IFA-432. These instruments are mounted upside down at the bottom of the assembly, the core extension contacting the lower end plug of the rod. The ferromagnetic core is attached to the extension and moves inside a coil system with the central primary coil carrying 50 mA 400 Hz excitation. A secondary coil consisting of two balanced halves flanks the primary coil. The output voltage is zero when the core is in its central position, and increases linearly when the cladding elongation moves the core. Sample calibration curves for these instruments may be found in Reference 22.

FIGURE B-4. Cladding Elongation Monitor
(Halden Project Design)

FISSION GAS PRESSURE TRANSDUCERS

Figure B-5 shows a schematic of the diaphragm-type pressure transducer used to measure the internal rod pressures due to fission gas release during irradiation. This is essentially an on-off type measurement. The thin platinum alloy membrane is exposed to the rod internal gases on one side, while the other side is connected to an external pressure manifold. When the external pressure equals the internal pressure, the deflection of the membrane causes it to make an electrical contact. The step increase in voltage signals a null pressure balance. Over a range of 100 Kg/cm^2 , the instrument's sensitivity is 0.1 Kg/cm^2 . The accuracy and repeatability are $\pm 1 \text{ Kg/cm}^2$ and $\pm 0.4 \text{ Kg/cm}^2$, respectively.

Calibration is out-of-reactor and consists of checking the deflection sensitivity of the membrane, which does not change appreciably with pressure level. The effects of irradiation on the membrane are not known, but are assumed by Halden to be minimal. Halden has made no recommendation for temperature compensation for this instrument. Any temperature compensation deemed necessary would be due to differential thermal expansion between the membrane and gage body, and to the temperature level of the membrane itself. Table B-1 is provided for this purpose. It lists coolant temperatures corresponding to the pressure measurements when the coolant temperature was not $235 \pm 10^\circ\text{C}$. Details of the pressure transducer must be obtained from the Halden Project.

FIGURE B-5. Fission Gas Pressure Transducer
(Halden Project Design)

TABLE B-1. IFA-432 Coolant Temperatures Other Than $235 \pm 10^{\circ}\text{C}$

<u>Date</u>	<u>Time</u>	<u>Moderator Temperature ($^{\circ}\text{C}$)</u>
11-30-75	1235	76.0
12-1-75	745	150.0
12-1-75	1930	153.6
12-2-75	845	208.0
12-9-75	215	221.0
12-30-75	1230	222.0
1-7-76	1015	220.0
1-4-77	626	222.7
3-24-77	1247	174.5
3-25-77	1628	203.1
5-21-77	28	199.6
5-21-77	218	198.9
5-21-77	1840	68.8
5-21-77	2056	70.4
5-22-77	1950	70.6
6-16-77	1931	79.0
6-19-77	2250	183.3
6-22-77	1556	73.0
6-23-77	555	153.2
6-24-77	921	215.7
6-24-77	1543	213.5
6-28-77	2234	200.2
7-7-77	1209	145.2
7-15-77	1309	206.5
8-3-77	1420	216.1
8-3-77	1816	211.6
8-5-77	1428	215.1
8-26-77	1607	220.6
8-26-77	1659	220.1
10-1-77	1941	73.0
10-2-77	2307	167.8
10-3-77	1806	197.1
10-7-77	845	186.3
10-7-77	906	189.5

TABLE B.2. Instrument Failure Dates for IFA - 432

<u>Rod</u>	<u>UTC</u>	<u>LTC</u>	<u>EC</u>	<u>PT</u>
1	January 31, 1977		February 14, 1976	
2	STARTUP			NA
3				NA
4	December 31, 1975	December 31, 1975	(a)	NA
5	June 30, 1976		February 14, 1976	
6	November 31, 1976			

(a) Note that Rod 4 was withdrawn on February 20, 1976 and replaced with the non-instrumented Rod 8 (see Table 2.1). Cladding extensometer readings are for Rod 8 after this date.

APPENDIX C

ASSEMBLY POWER CALIBRATION

APPENDIX C

ASSEMBLY POWER CALIBRATION

The data report for the IFA-431 assembly (PNL-2494) explained briefly the usual method for calibrating assemblies in the Halden reactor. This procedure was not used in the case of IFA-432 since the calibration flow valve (Figure 2.2) failed in the normal operating position, allowing only natural circulation. However, both assemblies were in core simultaneously at the time of IFA-432 startup. The second assembly was calibrated by comparisons of total assembly power and Rod 3 (small gap) power. The uncertainty in assembly power for IFA-432 is estimated to be $\pm 6\%$.

APPENDIX D

DATA PROCESSING

APPENDIX D

DATA PROCESSING

Processing of the data received from Halden on magnetic tape proceeds as shown in Figure D-1. After reception of the data tape, it must be translated from the Halden IBM/1800 language (EBCDIC) to the PDP11/45 language (ANSI), and the translated version stored on tape. Then this tape is reformatted so that all the data from a particular time on a particular date is in one block. This is simultaneously stored on a disc file.

Once the raw data is stored on disc, another program (Figure D-2) is applied to each block of data to correct the rod local heat ratings at the thermocouple locations for radial flux tilt across the assembly. This was necessary for IFA-432 since the powers on the original data tape actually represented the powers at the neutron detector locations and not at the thermocouple locations (Figure 2.2). Rod local and assembly powers are also corrected for axial flux shape and heat losses to the moderator. Corrections for local mass distributions of fissile material for each rod are also made. Table D-1 indicates typical values for these correction factors.

While this is being done, other checks are being made on the data. For the assembly and rod average powers, a total heat balance check is made. This is done during application of the axial correction factor to account for the difference between the average and true mean of the axial flux distribution. The first attempt at this uses an axial profile that represents normal operating conditions. If the heat balance for this profile does not check, an error message is printed and a second attempt is made with an axial flux shape that represents a disturbed flux profile. This occurs when a nearby control rod is partially inserted. In nearly all cases, the normal profile produces a heat balance that checks to within less than 1/2%.

When this step is complete, another program corrects the burnups and heat ratings for depletion of ^{235}U . Plutonium buildup is not taken into account.

FIGURE D-1. Flow Diagram for Processing Halden Data

TABLE D-1. Typical Power Correction Factors for IFA-432

Rod	Fuel	Radial Tilt	Axial Shape	Calibration Factor		Total
				Neutron Detector Average	Gamma Heating	
1	1.0190	1.106	0.952	1.038	0.988	1.1003
2	0.9628	0.945	0.952	1.038	0.988	0.8883
3	1.0614	0.926	0.952	1.038	0.988	0.9596
4	1.0044	1.125	0.952	1.038	0.988	1.1032
5	0.9791	0.987	0.952	1.038	0.988	0.9435
6	0.9878	0.957	0.952	1.038	0.988	0.9229

Burnup Correction = -0.66% per 1000 MWD/MTM

FIGURE D-2. Flow Diagram for Correction of Halden Rod Local Powers

After the data are corrected, four paths are possible and usually are executed simultaneously. The data are plotted, relative flux profiles and mean power histories are calculated for input to safety related codes, an error analysis is performed on the corrected data, and the data is analyzed by subsets (i.e., transient, steady state) to separate out the effects of the major variables. A sample of the relative axial power profile seen by the assembly is shown in Figure D-3. Figure D-4 is a flow diagram of the gap conductance and uncertainty calculations performed.⁽¹⁹⁾

FIGURE D-3. Typical Axial Power Profile for IFA-432

FIGURE D-4. Flow Diagram for Gap Conductance and Uncertainty Calculations

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

10	Chief, Fuel Behavior Research Branch Division of Reactor Safety Research U.S. Nuclear Regulatory Commission Washington, D.C 20555 Librarian, Technical Lib. Argonne National Laboratory 9700 South Cass Avenue Argonne, IL 60439 Manager, Product Developmt. Division Babcock & Wilcox Company P.O. Box 1260 Lynchburg, VA 24505 R. Duncan Vice-President - Developmt. Nuclear Power Systems Combustion Engineering, Inc. P.O. Box 500 Windsor, CT 06095 Manager Code Verification & Appl. Br. EG&G Idaho, Inc. P.O. Box 1625 Idaho Falls, ID 83401	J. T. A. Roberts Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94304 Manager Fuel Technology Exxon Nuclear Company, Inc. 2955 George Washington Way Richland, WA 99352 Manager Program Development & Evaluation Thermal Fuel Behavior Div. EG&G Idaho, Inc. P.O. Box 1625 Idaho, Falls ID 83401 Director Nuclear Safety & Anal. Development Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94304 Manager Reactor Systems Safety Development General Electric Company 175 Curtner Avenue San Jose, CA 95125
2	DOE Technical Information Center	

No. of
Copies
OFFSITE

No. of
Copies
ONSITE

	<p>Joel R. Buchanan Assistant Director Nuclear Safety Information Center P.O. Box Y Oak Ridge, TN 37830</p>	<p>48 <u>Pacific Northwest Laboratory</u></p>
40	<p>NRC Safety Research Exchange ORNL Laboratory Records Nuclear Safety Information Ctr. P.O. Box X, Bldg. 4500 Oak Ridge, TN 37830</p> <p>Executive Director ACRS US NRC H1016 Washington, D.C. 20555</p> <p>Robert Ritzmann Science Applications, Inc. 2680 Hanover Street Palo Alto, CA 94303</p>	<p>W. J. Bailey J. L. Bates J. O. Barner E. R. Bradley D. W. Brite E. L. Courtright M. E. Cunningham J. L. Daniel N. C. Davis M. D. Freshley J. F. Garnier R. L. Goodman R. J. Guenther C. R. Hann (10) P. E. Hart P. L. Hendrick K. A. Hsieh F. M. Kustas D. D. Lanning R. K. Marshall R. P. Marshall G. Mellinger C. L. Mohr C. Neally T. G. Odekird F. E. Panisko P. J. Pankaskie R. E. Schreiber S. R. Wagoner G. D. White R. E. Williford C. L. Wilson Tech. Info. Files (5) Publishing Coordination (2)</p>
40	<p>Adm. Dist. Serv. Branch - Shelf US NRC Washington, D.C. 20555</p> <p>Engineering Manager Nuclear Fuel Division Westinghouse Electric Corp. P.O. Box 355 Pittsburgh, PA 15230</p> <p>Branch Chief NRC Core Performance Branch US NRC P-1114 Washington, D.C. 20555</p>	