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Development of MOX Fuel Database

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We developed MOX Fuel Database, which included valuable data from several irradiation tests in FUGEN and Halden reactor, for help of LWR MOX use.

This database includes the data of fabrication and irradiation, and the results of post-irradiation examinations for seven fuel assemblies, i.e. P06, P2R, E03, E06, E07, E08 and E09, irradiated in FUGEN. The highest pellet peak burn-up reached ~48 GWd/t in MOX fuels, of which the maximum plutonium content was ~6 wt%, irradiated in E09 fuel assembly without any failure.

Also the data from the instrumented MOX fuels irradiated in HBWR to study the irradiation behavior of BWR MOX fuels under the steady state condition (IFA-514/565 and IFA-529), under the load-follow operation condition (IFA-554/555) and under the transit condition (IFA-591) are included in this database. The highest assembly burn-up reached ~56 GWd/t in IFA-565 steady state irradiation test, and the maximum linear power of MOX fuel rods was 58.3-68.4 kW/m without any failure in IFA-591 ramp test. In addition, valuable instrument data, i.e. cladding elongation, fuel stack elongation, fuel center temperature and rod inner pressure were obtained from IFA-554/555 load-follow test.

Keywords: LWR MOX Fuel, Irradiation Test, PIE, FUGEN, HALDEN

MOX 燃料データベースの開発

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新型転換炉原型炉ふげん及びハルデン炉(HBWR)で実施された様々な MOX 照射試験のデータベースを開発した。

データベースには、ふげんで照射された燃料集合体(P06、P2R、E03、E06、E07、E08、及び E09)の製造データ、照射データ及び照射後試験データが含まれている。このうち E09 燃料集合体は Pu 富化度約 6wt%で、ふげんで照射された MOX 燃料集合体で最も燃焼の進んだものでありペレットピーク燃焼度 48GWd/t まで健全に照射された。

一方、HBWR では BWR-MOX 燃料の定常運転時の挙動評価(IFA-514/565、IFA-529)、ATR-MOX 燃料の日負荷追従時の挙動評価(IFA-554/555)及び過出力時の挙動評価(IFA-591)の試験が行われた。IFA-565 は定常状態で照射され、最高燃焼度約 56GWd/t に達している。また、IFA-591 は最高線出力 58.3–68.4kW/m まで破損することなく照射され、IFA-554/555 では出力変動に伴う被覆管・スタック伸び、燃料中心温度、要素内圧などのデータが取得された。データベースには、これら HBWR で照射された燃料の製造データ、照射データ及び照射後試験データ及び炉内計装データも格納している。

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Contents

1. Introduction	1
2. Outline of MOX Fuel Data	2
3. FUGEN MOX Fuel Irradiation	3
3.1 FUGEN Driver Fuel Assembly (P06, P2R)	3
3.2 36-Rod Fuel Assembly (E03,E06,E07) and Gadolinia Fuel Assembly (E08,E09)	3
4. HBWR Instrument MOX Fuel Irradiation	5
4.1 BWR MOX Fuel Irradiation Test (IFA-514/565,IFA-529)	5
4.2 Daily Load-Follow Test (IFA-554/555)	5
4.3 Ramp Test (IFA-591)	6
5. Conclusions	7
Acknowledgement	8
References	8
Appendix1: Image of Uranium-Plutonium Mixed Oxide Fuel Database	43

目次

1. 緒言	1
2. MOX 燃料データの概要	2
3. ふげん MOX 燃料照射	3
3.1 ふげん炉心燃料集合体(P06, P2R)	3
3.2 36 本型 MOX 燃料集合体(E03, E06, E07)、ガドリニア燃料集合体(E08, E09) ..	3
4. ハルデン計装線付 MOX 燃料照射	5
4.1 BWR MOX 燃料照射試験(IFA-514/565, IFA-529)	5
4.2 日負荷追従試験(IFA-554/555)	5
4.3 出力急昇試験(IFA-591)	6
5. 結言	7
謝辞	8
参考文献	8
付録 MOX 燃料データベースの画面	43

List of Tables

Table 2-1	Irradiation Condition and Major Specification of FUGEN MOX Fuel Assemblies and HBWR MOX Fuel Assemblies	9
Table 2-2	Irradiation Data	10
Table 2-3	Fabrication Data	11
Table 2-4	PIE Data	12
Table 3-1	Major Specifications of FUGEN Assemblies.....	13
Table 4-1	Major Specifications of IFA-514/565	14
Table 4-2	Major Specifications of IFA-529.....	15
Table 4-3	Major Specifications of IFA-554/555	16
Table 4-4	Major Specifications of IFA-591.....	17

List of Figures

Figure 2-1	The Rod Average Burn-up and The Peak Linear Power	18
Figure 3-1	Structures of FUGEN Fuel Assemblies	19
Figure 3-2	History of Rod Average Linear Power (P06)	20
Figure 3-3	History of Rod Average Linear Power (P2R)	20
Figure 3-4	History of Rod Average Linear Power (E03)	21
Figure 3-5	Structure of E06 and E07 Fuel Assembly	22
Figure 3-6	History of Rod Average Linear Power (E06)	23
Figure 3-7	History of Rod Average Linear Power (E07)	23
Figure 3-8	History of Rod Average Linear Heat Rate (E08)	24
Figure 3-9	History of Rod Average Linear Power (E09)	24
Figure 4-1	Structure of IFA-514/565	25
Figure 4-2	Structure of IFA-529	26
Figure 4-3 (1)	History of Rod Average Linear Power of IFA-514 Rod-1	27
Figure 4-3 (2)	History of Rod Average Linear Power of IFA-514 Rod-2	27
Figure 4-3 (3)	History of Rod Average Linear Power of IFA-514/565 Rod-3	27
Figure 4-3 (4)	History of Rod Average Linear Power of IFA-514/565 Rod-4	28
Figure 4-3 (5)	History of Rod Average Linear Power of IFA-514 Rod-5	28
Figure 4-3 (6)	History of Rod Average Linear Power of IFA-514/565 Rod-6	28
Figure 4-4 (1)	History of Rod Average Linear Heat Rate of IFA-529 Rod-1	29
Figure 4-4 (2)	History of Rod Average Linear Heat Rate of IFA-529 Rod-2	29
Figure 4-4 (3)	History of Rod Average Linear Heat Rate of IFA-529 Rod-3	29
Figure 4-4 (4)	History of Rod Average Linear Heat Rate of IFA-529 Rod-4	30
Figure 4-4 (5)	History of Rod Average Linear Heat Rate of IFA-529 Rod-5	30
Figure 4-4 (6)	History of Rod Average Linear Heat Rate of IFA-529 Rod-6	30
Figure 4-4 (7)	History of Rod Average Linear Heat Rate of IFA-529 Rod-7	31
Figure 4-4 (8)	History of Rod Average Linear Heat Rate of IFA-529 Rod-8	31
Figure 4-4 (9)	History of Rod Average Linear Heat Rate of IFA-529 Rod-9	31
Figure 4-4 (10)	History of Rod Average Linear Heat Rate of IFA-529 Rod-10	32
Figure 4-4 (11)	History of Rod Average Linear Heat Rate of IFA-529 Rod-11	32
Figure 4-4 (12)	History of Rod Average Linear Heat Rate of IFA-529 Rod-12	32
Figure 4-5	Structure of IFA-554/555	33
Figure 4-6	Typical Power Pattern during Load-Follow Test	34
Figure 4-7 (1)	History of Rod Average Linear Power of IFA-554 Rod-A1	35
Figure 4-7 (2)	History of Rod Average Linear Power of IFA-554 Rod-A2	35
Figure 4-7 (3)	History of Rod Average Linear Power of IFA-554 Rod-A3	35
Figure 4-7 (4)	History of Rod Average Linear Power of IFA-554/555 Rod-B1	36
Figure 4-7 (5)	History of Rod Average Linear Power of IFA-554/555 Rod-B2	36
Figure 4-7 (6)	History of Rod Average Linear Power of IFA-554/555 Rod-B3	36
Figure 4-7 (7)	History of Rod Average Linear Power of IFA-554/555 Rod-B4	37

Figure 4-8	Structure of IFA-591	38
Figure 4-9 (1)	History of Rod Average Linear Heat Rate of IFA-591 Rod-1	39
Figure 4-9 (2)	History of Rod Average Linear Heat Rate of IFA-591 Rod-2	39
Figure 4-9 (3)	History of Rod Average Linear Heat Rate of IFA-591 Rod-3	39
Figure 4-9 (4)	History of Rod Average Linear Heat Rate of IFA-591 Rod-4	40
Figure 4-9 (5)	History of Rod Average Linear Heat Rate of IFA-591 Rod-5	40
Figure 4-9 (6)	History of Rod Average Linear Heat Rate of IFA-591 Rod-6	40
Figure 4-9 (7)	History of Rod Average Linear Heat Rate of IFA-591 Rod-7	41
Figure 4-9 (8)	History of Rod Average Linear Heat Rate of IFA-591 Rod-8	41
Figure 4-9 (9)	History of Rod Average Linear Heat Rate of IFA-591 Rod-9	41
Figure 4-9 (10)	History of Rod Average Linear Heat Rate of IFA-591 Rod-10	42
Figure 4-9 (11)	History of Rod Average Linear Heat Rate of IFA-591 Rod-11	42
Figure A-1	Typical Image of Uranium-Plutonium Mixed Oxide Fuel Database (1).....	43
Figure A-1	Typical Image of Uranium-Plutonium Mixed Oxide Fuel Database (2).....	44

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1. Introduction

Japan Atomic Energy Agency developed the advanced thermal reactor (ATR), which was heavy-water-moderated, boiling-light-water-cooled and pressure tube reactor and MOX fuels for this reactor^{1,2)}. The prototype ATR “FUGEN” had been operated safely and reliably for 25 years before it was permanently shut down in March 2003. Over its 25 year lifetime, 772 MOX fuel assemblies were irradiated without failure³⁾. The maximum pellet peak burn-up was reached ~48 GWd/t. Some MOX fuel assemblies in FUGEN were examined to study irradiation behavior and integrity of ATR MOX fuel assembly⁴⁾ after irradiation.

In addition, some irradiation tests with instruments, i.e. LWR MOX fuel test, daily load follow test and ramp test, were performed in Halden reactor (HBWR) in Norway to study the irradiation performance of MOX fuel rod under irradiation⁵⁾.

We developed the database, Uranium-Plutonium Mixed Oxide Fuel Database, including the various kinds of useful data from these irradiation tests mentioned above. In this report, the detailed contents of this database are summarized.

2. Outline of MOX Fuel Data

Table 2-1 shows the irradiation conditions and the major specifications of FUGEN MOX fuel assemblies and HBWR irradiation rigs in the database. The FUGEN MOX data of standard type A and B, i.e. P06 and P2R, 36-rods cluster type, E03, 36-rods segmented type, i.e. E06 and E07, and 36-rods Gadolinia type, E08 and E09, are included in this database. In addition, the HALDEN data of MOX used in BWR irradiation test, IFA-514/565 and IFA-529, load-follow test, IFA-554/555, ramp test, IFA-591, are included. Figure 2-1 shows the rod average burn-up and the pellet peak linear power of fuel rods irradiated in each fuel assembly. As shown in this figure, E09 MOX fuel assembly, which was $\text{UO}_2\text{-Gd}_2\text{O}_3$ fuel assembly fuel assembly, reached the highest fuel average burn-up $\sim 40 \text{ GWd/t}$ in FUGEN, and IFA-565 was irradiated up to the highest burn-up of $\sim 57 \text{ GWd/t}$ in HBWR to study irradiation behavior of LWR MOX fuel rod.

Table 2-2 shows irradiation data items included in the database. The items filled with solid circle have been already included in the database and with annular are under development. As shown in this table, the histories of reactor power, assembly power and flux, rod power and flux for FUGEN MOX fuel assemblies have been already included in the database. Moreover, the data of coolant water quality are also included. On the other hand, for HBWR irradiation, the histories of reactor power, assembly power and burn-up, and rod power and burn-up are included with the instrument data which were in-pile data of fuel center temperature, rod inner pressure, fuel stack elongation and cladding elongation.

Table 2-3 and Table 2-4 show fabrication data and post-irradiation examination data of MOX fuel assembly respectively. Various fabrication data are included, but ceramographs and a-autoradiographs of as-fabricated MOX fuel pellets for E03 and E07 are still under development, as shown in Table 2-3. In addition, the results of visual examination of assembly and fuel rods, bundle diameter measurement, ceramography and a-autoradiography of post-irradiated fuel for P06, P2R, E06 and E07, are still under development. There are some items under development as shown in Table 2-4.

Figure A-1 shows typical image of Uranium-Plutonium Mixed Oxide Fuel Database. This database is available under "Microsoft Office Access" software.

3. FUGEN MOX Fuel Irradiation

MOX Fuel Database includes the fabrication and irradiation data, and the results of post-irradiation examination (PIE) for FUGEN MOX fuel assembly, i.e. P06, P2R, E03, E06, E07, E08 and E09, as mentioned above. In this section, the outline of FUGEN MOX fuel assembly is introduced.

Figure 3-1 shows the structure of FUGEN MOX fuel assembly. There are two types of driver fuel assemblies, i.e. type A and type B, which includes 28 fuel rods. In addition, 36-rod fuel assemblies, i.e. 36-rod cluster type, 36-rod segmented type and 36-rod Gadolinia fuel assembly, were also irradiated to develop the DATR (demonstration advanced thermal reactor) fuels. FUGEN MOX fuel assembly has a cylindrical cluster type structure. The driver fuel assembly consists of fuel rods, a spacer tie rod, the upper and lower tie-plates, and spacers. DATR fuel assembly and Gadolinia type fuel assembly have a spacer support tube instead of a spacer tie rod in the driver fuel assembly. The upper and lower tie plats and spacers are used to hold fuel rods at the designated positions. Table 3-1 shows major specifications of FUGEN MOX fuel assembly.

3.1 FUGEN Driver Fuel Assembly (P06, P2R)^{4),5)}

FUGEN driver fuel assembly had 28 fuel rods divided into three rings as shown in Figure 3-1. The major specifications of FUEGN driver (standard type A and B) are shown in Table 3-1. Cladding outer diameter and pellet outer diameter were 16.46 mm and 14.4 mm, respectively. The cladding material was made of Zyr-2. The maximum plutonium content of P06 was 1 wt%, on the other hand, that of P2R was 2 wt% to aim at the higher burn-up than P06.

P06 fuel assembly was irradiated from 1979 to 1982 in FUGEN. Figure 3-2 shows the burn-up history of each ring in P06 fuel assembly. As shown in this figure, the rod average burn-up reached 15 GWd/t.

P2R fuel assembly was irradiated from 1981 to 1985 and the rod average burn-up reached 20 GWd/t. Figure 3-3 shows the burn-up history of P2R fuel assembly.

Post irradiation examinations of P06 fuel assembly and P2R fuel assembly were carried out to study the irradiation performance and to confirm the integrity of FUGEN diver fuel assembly.

3.2 36-Rod Fuel Assembly (E03, E06, E07) and Gadolinia Fuel Assembly (E08, E09)^{3),6),7),8),9)}

36-rod fuel assembly and Gadolinia fuel assembly were developed for demonstration advanced thermal reactor. The 36-rod fuel assembly was designed to aim at the maximum assembly burn-up of 35 GWd/t. The structure of Gadolinia fuel assembly, which was designed to aim at the maximum assembly burn-up of 40 GWd/t, was basically similar to that of 36-rod fuel assembly. As shown in Table 3-1, the cladding outer diameter and pellet outer diameter of their fuel rods were 14.5 mm and 12.7 mm, respectively. The cladding material was made of Zry-2.

Figure 3-4 shows burn-up history of E03 fuel assembly, which was 36-rod fuel assembly, was irradiated up to the assembly burn-up of 33 GWd/t. Since this assembly was not

examined after irradiation, MOX Fuel Database includes the only fabrication and irradiation data for E03.

The structure of E06 and E07 fuel assembly, which consisted of 36 fuel rods including six segmented rods to be used for the ramp tests in HBWR, is shown in Figure 3-5. Figure 3-6 and Figure 3-7 shows the burn-up history of E06 fuel assembly and that of E07 fuel assembly, respectively. E06 was irradiated up to assembly burn-up of 26 GWd/t in FUGEN, and the post-irradiation examinations for E06 were carried out. Also E07 was irradiated up to assembly burn-up of 18 GWd/t in FUGEN, and subsequently, the non-destructive examinations were performed. Eleven segmented rods base-irradiated in E07 were used for the ramp tests (IFA-591) in HBWR. The details of IFA-591 ramp tests are described in chapter 4.

The Gadolinia fuel assembly was designed to aim at the higher burn-up, and the fissile content of fuel pellets for this type was enhanced. Therefore, as shown in Figure 3-1, the axially heterogeneous fissile content had to be adopted in order to reduce the axial difference in linear power. Moreover, in order to reduce the power peaking at the beginning of irradiation, four $\text{UO}_2\text{-Gd}_2\text{O}_3$ fuel rods had to be located in the intermediate ring in this assembly. The Gadolinia fuel assemblies, i.e. E08 and E09, were irradiated in FUGEN from 1991, and the burn-up of E09 fuel assembly reached the highest in others irradiated in FUGEN. The pellet peak burn-up of E09 fuel assembly was about 48 GWd/t. The histories of linear power of E08 and E09 fuel assembly are shown in Figure 3-8 and Figure 3-9, respectively. Various post-irradiation examinations for E09 fuel assembly was carried out to confirm the integrity of ATR MOX fuel assembly under the high burn-up from 2001 to 2005. As the result, the integrity of ATR MOX fuel assembly was confirmed up to pellet peak burn-up of 48 GWd/t.

4. HBWR Instrument MOX Fuel Irradiation

MOX fuel irradiation tests in HBWR were carried out to study the irradiation behavior of BWR-MOX fuels under the steady state condition (IFA-514/565 and IFA-529), under the load-follow operation condition (IFA-554/555) and under the transit condition (IFA-591). These irradiation tests are described in this chapter.

4.1 BWR MOX Fuel Irradiation Test (IFA-514/565, IFA-529)^{5),10)}

IFA-514/565 and IFA-529 irradiation tests were performed to study the irradiation behavior of BWR MOX fuels. The fuel specifications for these irradiation tests were decided in accordance with those of BWR 8 x 8 type fuels, and plutonium content of MOX fuels was set to be 5.8 wt% for IFA-514/565 and 8.3 wt% for IFA-529.

Six MOX fuel rods in IFA-514, of which parameters were pellet geometry (solid or annular) and surface roughness (grinded or as sintered), were irradiated to the assembly average burn-up of ~ 45 GWd/t, and the instrument data during irradiation, i.e. cladding elongation, fuel stack elongation, fuel center temperature, and rod inner pressure, were obtained, and various post-irradiation examinations were carried out. After that, the irradiation for three fuel rods (Rod-2,4,6) of six fuel rods irradiated in IFA-514 irradiation test were continued to the assembly burn-up of ~ 56 GWd/t in IFA-565 irradiation tests. The structure and major specifications of IFA-514/565 are shown in Figure 4-1 and Table 4-1, respectively.

In addition, IFA-529, of which parameters were pellet geometry (solid or annular), pellet-cladding gap (140 μ m, 240 μ m and 340 μ m) and plutonium powder fabrication process (50% PuO₂ -50% UO₂ MH powder, 100% PuO₂ powder), was irradiated up to ~ 30GWd/t. IFA-529 had instrumentations for in-pile measurements of cladding elongation and plenum pressure under irradiation. The structure and major specifications of IFA-529 were shown in Figure 4-2 and Table 4-2.

Figure 4-3 shows the burn-up histories of fuel rods irradiated in IFA-514/565, and Figure 4-4 shows those irradiated in IFA-529.

4.2 Daily Load-Follow Test (IFA-554/555)^{5),11)}

IFA-554/555 irradiation tests were performed in HBWR to study the MOX fuel behavior under the load-follow operation condition. The fuel rods irradiated in IFA-554/555 had the instruments of rod inner pressure, fuel center temperature, fuel stack elongation, and cladding elongation. The design for IFA-554/555 was similar to that for the demonstration advanced thermal reactor (DATR). As shown in Table 4-3, the cladding outer diameter and pellet outer diameter of fuel rods for IFA-554/555 load-follow test was 14.5 mm and 12.4 mm, respectively. Figure 4-5 shows the structure of IFA-554/555.

IFA-554/555 was irradiated for eight years, including twenty-three series of power cycling tests. The power change between 50 % and 100 % of nominal power simulating the typical “14-1-8-1” mode of the daily load-follow operation were usually repeated fourteen times at each power cycling test as shown in Figure 4-6. The rod average linear power of IFA-554/555 was in the range from ~ 20 kW/m to ~ 45 kW/m, and the rod average burn-up was 37 GWd/t. Figure 4-7 shows the burn-up history of each fuel rods irradiated in IFA-554/555.

4.3 Ramp Test (IFA-591)^{5),12),13)}

Eleven segmented fuel rods were base-irradiated in E07 fuel assembly in FUGEN up to 18.4 GWd/t, after that, these segmented fuel rods were constructed in IFA-591 and the ramp tests were performed in HBWR. MOX fuel rods of the instrumental rig IFA-591 were ramped to study the ATR MOX fuel behavior during the transient condition and to determine a failure threshold of MOX fuel rods. Moreover, to study PCMI behaviors of different cladding material under the power transient, the claddings for segment fuel rods were made of two types of materials, i.e. Zry-2 and Zry-2 with Zr-liner. Figure 4-8 and Table 4-4 show the structure and major specifications of IFA-591 fuel rods, respectively.

Figure 4-9 shows the linear power histories of each fuel rod during the base-irradiation and the ramp test. All segments to be used for the ramp tests, which consisted of the multi-step ramp tests and the single-step ramp tests, had instrumentations for in-pile measurements of cladding elongation or plenum pressure, and heated up to the maximum linear power of 58.3 to 68.4 kW/m. There is no difference in PCMI behaviors between two type rods of Zry-2 and Zr-liner claddings from the in-pile measurement of cladding elongation and plenum pressure. Moreover, as the result of the post-irradiation examinations after the ramp tests, it was confirmed that no failure had been occurred during the IFA-591 ramp tests with the final power higher than the failure threshold power of UO₂ fuel rods, and this is expected to indicate that MOX fuel would have a better performance for PCMI failure due to their higher creep rate than UO₂ fuels.

5. Conclusions

We developed MOX Fuel Database, which included valuable data from several irradiation tests in FUGEN and Halden reactor, for help of LWR MOX use.

This database includes the data of fabrication and irradiation, and the results of post-irradiation examinations for seven fuel assemblies, i.e. P06, P2R, E03, E06, E07, E08 and E09, irradiated in FUGEN. The highest pellet peak burn-up reached ~48 GWd/t in MOX fuels, of which the maximum plutonium content was ~6 wt%, irradiated in E09 fuel assembly without any failure. Also the data from the instrumented MOX fuels irradiated in HBWR to study the irradiation behavior of BWR MOX fuels under the steady state condition (IFA-514/565 and IFA-529), under the load-follow operation condition (IFA-554/555) and under the transit condition (IFA-591) are included in this database. The highest assembly burn-up reached ~56 GWd/t in IFA-565 steady state irradiation test, and the maximum linear power of MOX fuel rods was 58.3-68.4 kW/m without any failure in IFA-591 ramp test. In addition, valuable instrument data, i.e. cladding elongation, fuel stack elongation, fuel center temperature and rod inner pressure were obtained from IFA-554/555 load-follow test.

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Table 2-1 Irradiation condition and major specification of FUGEN MOX fuel assemblies and HBWR MOX fuel assemblies

Reactor	Irradiation Item	Rig No.	Irradiation Conditions					Major Specifications					
			Coolant Press. (MPa)	Coolant Temperature (°C)	Burn-up (GWd/t)	Rod Ave.	Peak linear power (kW/m)	Pu Cont. (wt. %)	Cladding OD (mm)	ID (mm)	Pellet ¹	Stack length (mm)	Rod length (mm)
FUGEN	Standard (A)	P06			14	15	42	1	16.4	14.7	14.4	3700	4045
	Standard (B)	P2R			18	20	40	2					
	36-rod cluster	E03	7.1	260	33	44	44	1.3				3647	4070
	36-rod segmented	E06			26	28	30	2.4				95	0.3
	36-rod segmented	E07			18	20	30	14.5				3647	4070
	36-rod Gadolinia (1)	E08			30	32	46	4.6					
	36-rod Gadolinia (1)	E09			38	42	43					3640	4061
	IF-A-514				45	46	56	6					
	IF-A-565	3.4	240		56	57	51	6				1400	1505 ²
HALDEN	IF-A-529				27	31	50	8					
	IF-A-555	7.2	288		33	37	56	5				10.66~10.46	95
	Ramp test	IF-A-591			18	20	76	4				490	580 ²

¹;() mean the inner diameter (mm). ²: length between v-grooves.

Table 2-2 Irradiation Data

ITEMS	FUGEN						HBWR					
	Standard		36-rod		Segmented		Gadolinia		MOX use in BWR		Load-follow test	
	A	B	Cluster		E06	E07	E08	E09	IFA-514	IFA-565	IFA-529	IFA-554/555
P06	●	●	●	●	●	●	●	●	●	●	●	●
P2R	●	●	●	●	●	●	●	●	-	-	-	-
Reactor	●	●	●	●	●	●	●	●	●	●	●	●
Coolant water quality	-	-	-	-	-	-	-	-	-	-	-	-
Power history	-	-	-	-	-	-	-	-	-	-	-	-
Burn-up history	-	-	-	-	-	-	-	-	-	-	-	-
Flux history	-	-	-	-	-	-	-	-	-	-	-	-
Power history	●	●	●	●	●	●	●	●	-	-	-	-
Burn-up history	●	●	●	●	●	●	●	●	●	●	●	●
Flux history	●	●	●	●	●	●	●	●	●	●	●	●
Axial power profile	●	●	●	●	●	●	●	●	-	-	-	-
Axial burn-up profile	●	●	●	●	●	●	●	●	-	-	-	-
Axial flux profile	●	●	●	●	●	●	●	●	-	-	-	-
Fuel center temperature	-	-	-	-	-	-	-	-	●	●	●	●
Rod inner pressure	-	-	-	-	-	-	-	-	●	●	●	●
Fuel stack elongation	-	-	-	-	-	-	-	-	●	●	●	●
Cladding elongation	-	-	-	-	-	-	-	-	●	●	●	●

●:Completed, ○:under development, -:no data

Table 2-3 Fabrication Data

ITEMS	FUGEN										HBWR					
	Standard		36-rod		Segmented		Gadolinia		MOX use in BWR			Load-follow test			Ramp test	
	P06	P2R	E03	E06	E07	E08	E09	IFA-514	IFA-565	IFA-529	IFA-554/555	IFA-591				
Total length	●	●	●	●	●	●	●	-	-	-	-	-	-	-	-	
Height of tie-plate	●	●	●	●	●	●	●	-	-	-	-	-	-	-	-	
Bundle diameter	-	-	●	●	●	-	-	-	-	-	-	-	-	-	-	
Rod-rod clearance	●	●	●	●	●	●	●	-	-	-	-	-	-	-	-	
Insertion force	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Diameter	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Total length	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Fuel stick length	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Fuel rod	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Plenum length	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Free volume	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Inner pressure	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Diameter	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Density	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Porosity	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Densification	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Pu vector	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Pu spot diameter	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Pellet	-	-	-	-	-	-	-	○	○	○	○	-	-	-	-	
Grain size	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Impurities	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Ceramography	-	-	-	-	-	-	-	○	○	○	○	-	-	-	-	
a-autoradiography	-	-	-	-	-	-	-	○	○	○	○	-	-	-	-	
Diameter	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Composition	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Axial tensile strength	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Ring tensile strength	-	-	-	-	-	-	-	●	●	●	●	-	-	-	-	
Burst strength	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Hardness	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Hydrides	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Corrosion thickness	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	
Grain size	-	-	●	●	●	●	●	-	-	-	-	-	-	-	-	

●:Completed, ○:under development, -:no data

Table 2-4 PIE Data

ITEMS	FUGEN										HBWR					
	Standard		36-rod		Gadolinia		MOX use in BWR		Load-follow test		Ramp test					
	A	B	Cluster	Segmented			E06	E07	E08	E09	IFA-514	IFA-565	IFA-529	IFA-554/555	IFA-591	
P06	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
P2R	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
E03	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
E06	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
E07	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
E08	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
E09	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Visual aspects (photos)	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
Total length	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Height of tie-plate	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Bundle diameter	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
Rod-rod clearance	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Drawing-out force	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Visual aspects (photos)	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
Total length	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Fuel stack length	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Plenum length	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Profilmometry	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Rods	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Oxide thickness	-	-	-	○	○	-	-	-	-	-	-	-	-	-	-	-
Eddy current	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
γ -intensity	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
FP gas release rate	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Release gas analysis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rod inner pressure	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Micro γ -scanning	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Burn-up	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Density	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Grain size	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O/M rate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thermal conductivity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Melting temperature	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ceramography	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
a-autoradiography	○	○	-	○	○	-	-	-	-	-	-	-	-	-	-	-
Axial tensile strength	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Ring tensile strength	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Burst strength	●	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
Hardness	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hydrides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Metallography	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

●:Completed, ○:under development, -:no data

Table 3-1 Major Specifications of FUGEN Assemblies

ITEMS	Standard	36-rod		
	A and B (P06(A), P2R(B))	Cluster (E03)	Segmented (E06, E07)	Gadolinia (1) (E08, E09)
1.Fuel Pellet				
(1)MOX Fuel Rod				
Fissile Content ^{*1}				
Inner and				
Intermediate Rod	2.27 wt% (P2R) (Axial Uniform Content)	3.21 wt% (Axial Uniform Content)	3.71 wt% (Axial Uniform Content)	5.0 wt% 4.3 wt%
Upper and Lower				
Middle				
Outer Rod	1.84 wt% (P2R) (Axial Uniform Content)	1.71 wt% (Axial Uniform Content)	2.21 wt% (Axial Uniform Content)	3.0 wt% 2.6 wt%
Upper and Lower				
Middle				
Pu Content ^{*2}				
Inner and				
Intermediate Rod	1.0 wt% (P06) (Axial Uniform Content)	-	-	-
Upper and Lower				
Middle				
Outer Rod	0.7 wt% (P06) (Axial Uniform Content)	-	-	-
Upper and Lower				
Middle				
²³⁵ U Enrichment	0.65 ~ 1.44 wt%	0.71 wt%	0.71 wt%	0.7 ~ 1.4 wt%
(2)UO ₂ -Gd ₂ O ₃ Fuel Rod				
²³⁵ U Enrichment				
Upper and Lower	-	-	-	3.8 wt%
Middle	-	-	-	3.4 wt%
Gadolinium Content				
Upper and Lower	-	-	-	0.8 wt%
Middle	-	-	-	1.4 wt%
Diameter	14.4 mm	12.4 mm	12.4 mm	12.4 mm
Inner Diameter	-	-	3.5 mm	-
Height	18 mm	13 mm	13 mm	13 mm
Density	95 %T.D.	95 %T.D.	95 %T.D.	95 %T.D.
Type	Chamfered and Dish	Chamfered and Dish	Chamfered and Dish (Annular Pellet : Chamfered)	Chamfered and Dish
2.Fuel Rod				
Cladding Material	Zry-2	Zry-2	Zry-2 (standard), Zr Liner Zry-2	Zry-2 (standard), Zr Liner Zry-2 Corrosion Resist Type-A and Corrosion Resist Type-B
Cladding Outer Diameter	16.46 mm	14.5 mm	14.5 mm	14.5 mm
Cladding Inner Diameter	14.7 mm	12.7 mm	12.7 mm	12.7 mm
Cladding Thickness	0.88 mm	0.9 mm	0.9 mm	0.9 mm
Zr Liner Thickness	-	-	0.075 mm	0.07 mm
Overall Length	4045 mm	4070 mm	4070 mm	4061 mm
Fuel Active length	3700 mm	3647 mm	3647 mm	3640 mm
Plenum Length				
Upper / Lower	251 mm / 24 mm	355 mm / 30 mm	355 mm / 30 mm	357 mm / 30 mm
Filling Gas and Filling Pressure	He, 0.1 MPa * a	He, 0.3 MPa * a	He, 0.3 MPa * a	He, 0.3 MPa * a
3.Spacer				
Material	Inconel-718	Inconel-718	Inconel-718	Inconel-718
Arrangement	28 Rods, 3 Rings cluster	36 Rods, 3 Rings cluster	36 Rods, 3 Rings cluster	36 Rods, 3 Rings cluster
4.Spacer support tube				
Material	Zry-2	Zry-2	Zry-2	Zry-2
Overall Length	4132 mm	4070 mm	4070 mm	4061 mm
Diameter	9 mm	14.5 mm	14.5 mm	14.5 mm
5.Assembly				
Overall Length	4388 mm	4388 mm	4398 mm	4393 mm
Outer Diameter	111.6 mm	111.6 mm	111.6 mm	111.6 mm
Number of Spacer	12	12	12	12
Number of Spacer Support Tube	4 (Spacer tie rod)	1	1	1
Number of Rod				
Inner (Free Rod)	4	6	6	6
Intermediate (Free Rod)	-	6	6	-
Intermediate (Free Rod) (UO ₂ -Gd ₂ O ₃ Rod)	-	-	-	4
Intermediate (Tied Rod)	8	6	6	8
Outer (Free Rod)	16	18	18	18
Rod-Rod Clearance	2.1 mm (Minimum)	2.04 mm (Minimum)	2.04 mm (Minimum)	2.04 mm (Minimum)
6.Designed Burn-up and Linear Power				
Maximum of Assembly Average	20 GWd/t	35 GWd/t	30 GWd/t	40 GWd/t
Maximum Linear Power	57.4 kW/m	49.2 kW/m	39.4 kW/m	49.2 kW/m

*1) Fissile Content means (²³⁹Pu+²⁴¹Pu+²³⁵U)/(Pu+U)

*2) Pu Content means (Pu)/(Pu+U)

Table 4-1 Major Specifications of IFA-514/565

ITEMS	IFA-514		IFA-514 / IFA-565		IFA-514	IFA-514 / IFA-565
	Rod-1	Rod-2	Rod-3	Rod-4	Rod-5	Rod-6
1.Fuel Pellet						
Pu Fissile Content*1	4.64 wt%	4.64 wt%	4.64 wt%	4.64 wt%	4.64 wt%	4.64 wt%
U Enrich	0.71 wt%	0.71 wt%	0.71 wt%	0.71 wt%	0.71 wt%	0.71 wt%
Diameter	10.55 mm	10.55 mm	10.55 mm	10.55 mm	10.55 mm	10.55 mm
Inner Diameter				3.5 mm		3.5 mm
Height	10 mm	10 mm	10 mm	10 mm	10 mm	10 mm
Density	94 %T.D.	94 %T.D.	94 %T.D.	94 %T.D.	94 %T.D.	94 %T.D.
Fabrication Method	MB*2	MB*2	MB*2	MB*2	MB*2	MB*2
Type	Chamfered and Dish , Ground	Chamfered and Dish , Ground	Chamfered and Dish , As*3	Hollow and Chamfered , As*3	Chamfered and Dish , As*3	Hollow and Chamfered , As*3
2.Fuel Rod						
Cladding Material	Zry-2	Zry-2	Zry-2	Zry-2	Zry-2	Zry-2
Cladding Outer Diameter	12.52 mm	12.52 mm	12.52 mm	12.52 mm	12.52 mm	12.52 mm
Cladding Inner Diameter	10.8 mm	10.8 mm	10.8 mm	10.8 mm	10.8 mm	10.8 mm
Rod Length*4	1505 mm	1505 mm	1505 mm	1505 mm	1505 mm	1505 mm
Fuel Active length	1380 mm	1380 mm	1380 mm	1380 mm	1380 mm	1380 mm
Plenum Volume	7.6 cc	5.6 cc	5.7 cc	7.7 cc	6.3 cc	5.7 cc
Filling Gas and Filling Pressure	He , 0.1 MPa * a	He , 0.1 MPa * a	He , 0.1 MPa * a 1.05 MPa (at 121 °C)*5	He , 0.1 MPa * a 1.05 MPa (at 121 °C)*5	He , 0.1 MPa * a	He , 0.1 MPa * a 1.05 MPa (at 121 °C)*5
3.Instruments						
Upper / Lower*6	PF / TF	EF / EC	EF / EC (IFA-514) EF / EC (IFA-565)	PF / - (IFA-514) PF / EC (IFA-565)	- / TF	EF / EC (IFA-514) EF / EC (IFA-565)

*1) Pu Fissile Content means (²³⁹Pu+²⁴¹Pu)/(Pu+U)

*2) Mechanical Blending

*3) As-Sintered Pellet

*4) Length between v-grooves

*5) at start of irradiation in IFA-565

*6) EC : Cladding elongation, TF : Fuel center temperature, EF : Fuel stack elongation, PF : Rod inner pressure

Table 4-2 Major Specifications of IFA-529

ITEMS	Low Cluster						Upper Cluster					
	Rod-1	Rod-2	Rod-3	Rod-4	Rod-5	Rod-6	Rod-7	Rod-8	Rod-9	Rod-10	Rod-11	Rod-12
1.Fuel Pellet												
Pu Fissile Content*1	6.0 wt%											
U Enrich	0.71 wt%											
Diameter	10.66 mm	10.56 mm	10.46 mm	10.36 mm	10.26 mm	10.16 mm	10.06 mm	9.96 mm	9.86 mm	9.76 mm	9.66 mm	9.56 mm
Inner Diameter	-	-	-	-	-	-	-	-	-	-	-	-
Height	10 mm											
Fabrication Method*2	94 %T.D. CP	94 %T.D. CP	94 %T.D. CP	94 %T.D. MB								
Type	Chamfered and Dish, As ^{*3}											
2.Fuel Rod												
Cladding Material	Zry-2											
Cladding Outer Diameter	12.52 mm											
Cladding Inner Diameter	10.8 mm											
Rod Length ^{*4}	635 mm											
Fuel Active length	550 mm											
Plenum Volume	4.1 cc	3.8 cc	4.2 cc	4.2 cc	3.8 cc	4.2 cc						
Filling Gas and Filling Pressure	He, 0.1 MPa · a											
3.Instruments												
Upper / Lower ^{*5}	- / PF											

*1) Pu Fissile Content means (²³⁹Pu+²⁴¹Pu)/(Pu+U)

*2) CP : Co-Processing , MB : Mechanical Blending

*3) As-Sintered Pellet

*4) Length between v-grooves

*5) EC : Cladding elongation, TF : Fuel center temperature, EF : Fuel stack elongation, FF : Rod inner pressure

Table 4-3 Major Specifications of IFA-554/555

ITEMS	IFA554 Upper cluster			IFA554 Lower cluster / IFA-555 Rig			
	Rod-A1	Rod-A2	Rod-A3	Rod-B1	Rod-B2	Rod-B3	Rod-B4
1.Fuel Pellet							
Pu Fissile Content*1	3.4 wt%	3.4 wt%	3.4 wt%	3.4 wt%	3.4 wt%	3.4 wt%	3.4 wt%
Diameter	12.4 mm	12.4 mm	12.4 mm	12.4 mm	12.4 mm	12.4 mm	12.4 mm
Inner Diameter			3.5 mm			3.5 mm	
Height	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm
Density	95 %T.D.	95 %T.D.	95 %T.D.	95 %T.D.	95 %T.D.	95 %T.D.	95 %T.D.
Type	Chamfered and Dish	Chamfered and Dish	Hollow and Chamfered	Chamfered and Dish	Chamfered and Dish	Hollow and Chamfered	Chamfered and Dish
2.Fuel Rod							
Cladding Material	Zry-2	Zry-2	Zr Liner Zry-2	Zry-2	Zry-2	Zr Liner Zry-2	Zry-2
Cladding Outer Diameter	14.5 mm	14.5 mm	14.5 mm	14.5 mm	14.5 mm	14.5 mm	14.5 mm
Cladding Inner Diameter	12.7 mm	12.7 mm	12.7 mm	12.7 mm	12.7 mm	12.7 mm	12.7 mm
Zr Liner Thickness	-	-	0.075 mm	-	-	0.075 mm	-
Rod Length*2	581 mm	581 mm	581 mm	581 mm	581 mm	581 mm	581 mm
Fuel Active length	500 mm	500 mm	500 mm	500 mm	500 mm	500 mm	500 mm
Plenum Volume	6.0 cc	5.7 cc	6.3 cc	5.7 cc	5.7 cc	6.1 cc	5.8 cc
Filling Gas and Filling Pressure	He, 0.3 MPa · a	He, 0.3 MPa · a	He, 0.3 MPa · a	He, 0.3 MPa · a	He, 0.3 MPa · a	He, 0.3 MPa · a	He, 0.3 MPa · a
3.Instruments							
Upper / Lower*3	EC / TF	EC / TF	EC / TF	EF / PF	EF / PF	EF / PF	EC / PF

*1) Pu Fissile Content means ($^{239}\text{Pu} + ^{241}\text{Pu}$)/(Pu+U)

*2) Length between v-grooves

*3) EC : Cladding elongation, TF : Fuel center temperature, EF : Fuel stack elongation, PF : Rod inner pressure

Table 4-4 Major Specifications of IFA-591

ITEMS	IFA-591-1	IFA-591-2	IFA-591-3	IFA-591-4	IFA-591-5	IFA-591-6	IFA-591-7	IFA-591-8	IFA-591-9	IFA-591-10	IFA-591-11
1.Fuel Pellet											
Fissile Content ^{*1}	3.71 wt%										
U Enrich	0.71 wt%										
Diameter	12.4 mm										
Height	13 mm										
Density	95 %T.D.										
Type	Chamfered and Dish										
2.Fuel Rod											
Cladding Material	Zry-2	Zr Liner Zry-2	Zr Liner Zry-2	Zr Liner Zry-2	Zr Liner Zry-2						
Cladding Outer Diameter	14.5 mm										
Cladding Inner Diameter	12.7 mm										
Rod Length	520 mm										
Fuel Active length	365 mm										
Plenum Volume	10.3 cc	10.3 cc	10.3 cc	10.4 cc							
Filling Gas and Filling Pressure	He 0.3 MPa · a										
3.Instruments^{*2}	EC	EC	EC	PF	PF	PF	EC	EC	EC	EC	EC

*1) Fissile Content means (^{239}Pu + ^{241}Pu + ^{235}U)/(Pu+U)

*2) EC : Cladding elongation, PF : Rod inner pressure

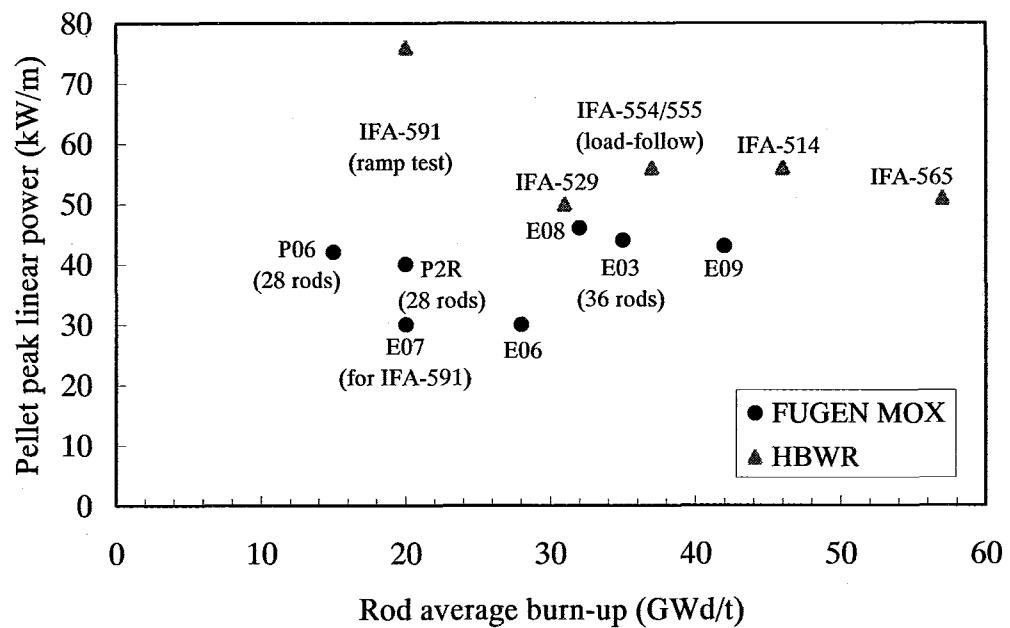


Figure 2-1 The Rod average burn-up and the peak linear power

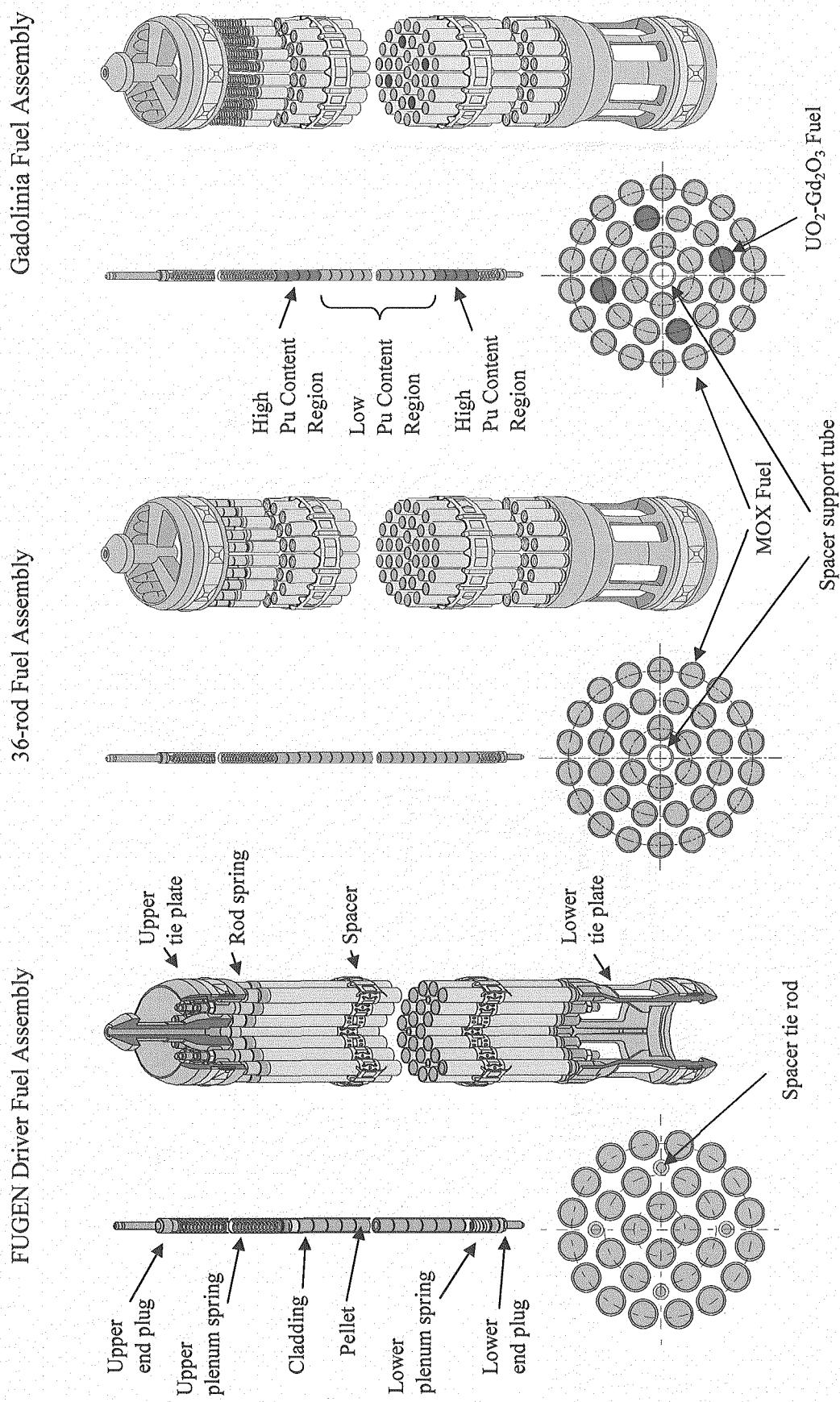


Figure 3-1 Structures of FUGEN Fuel Assemblies

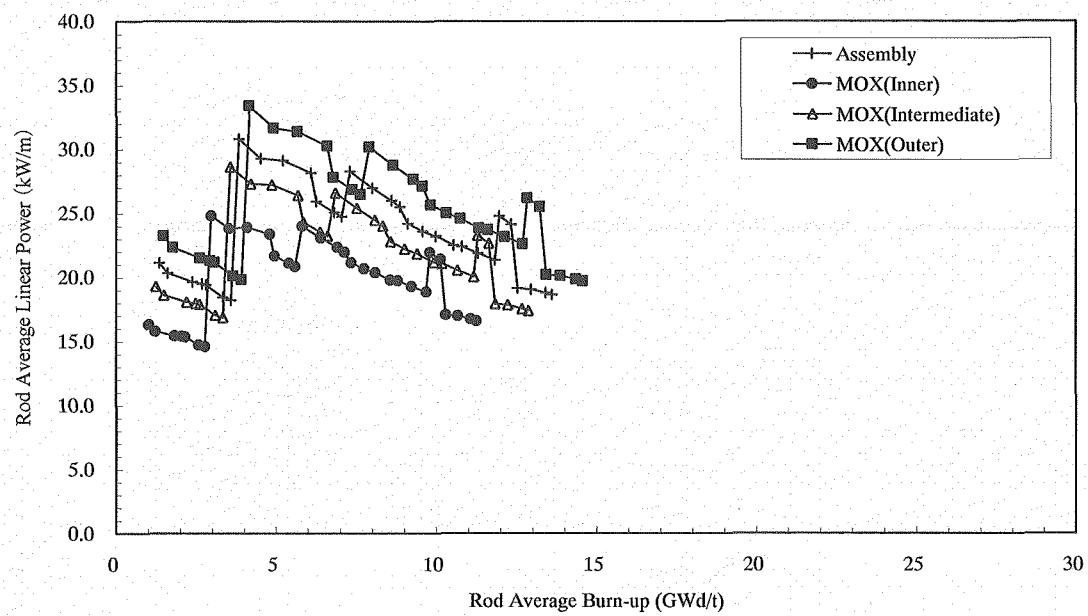


Figure 3-2 History of Rod Average Linear Power (P06)

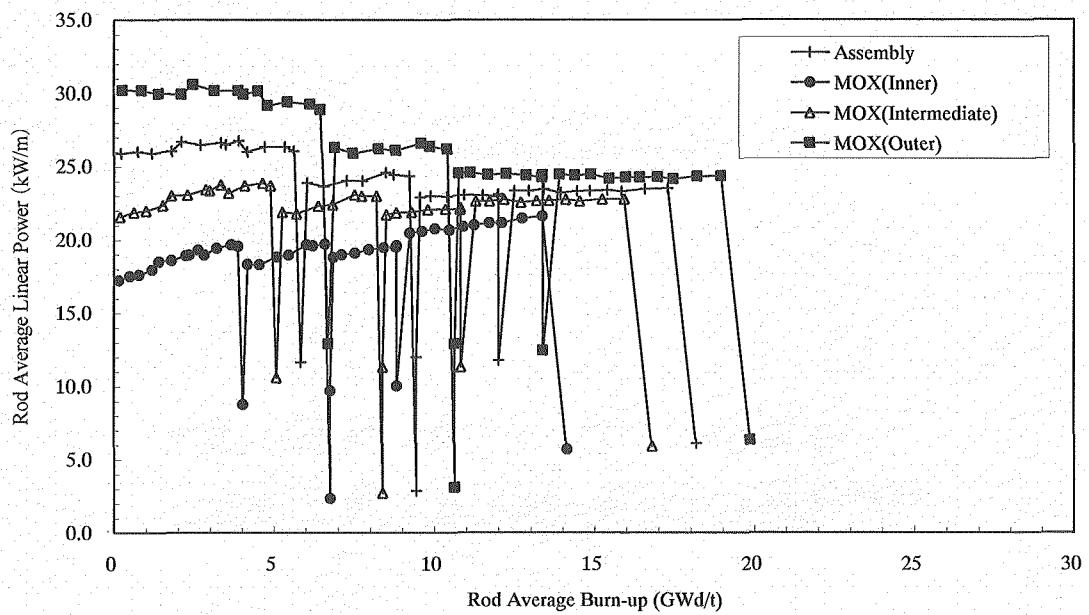


Figure 3-3 History of Rod Average Linear Power (P2R)

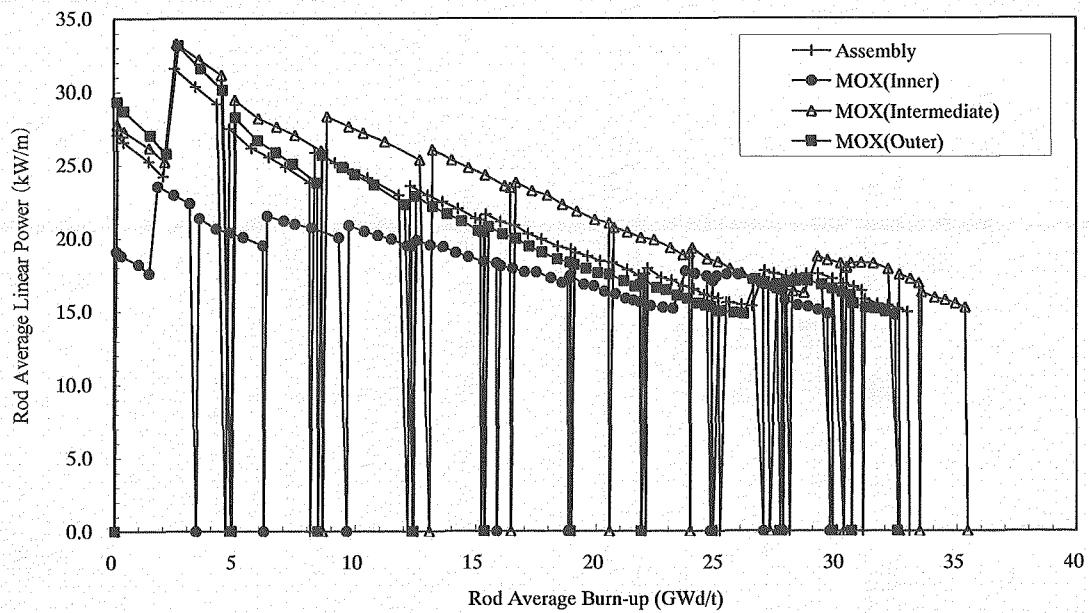


Figure 3-4 History of Rod Average Linear Power (E03)

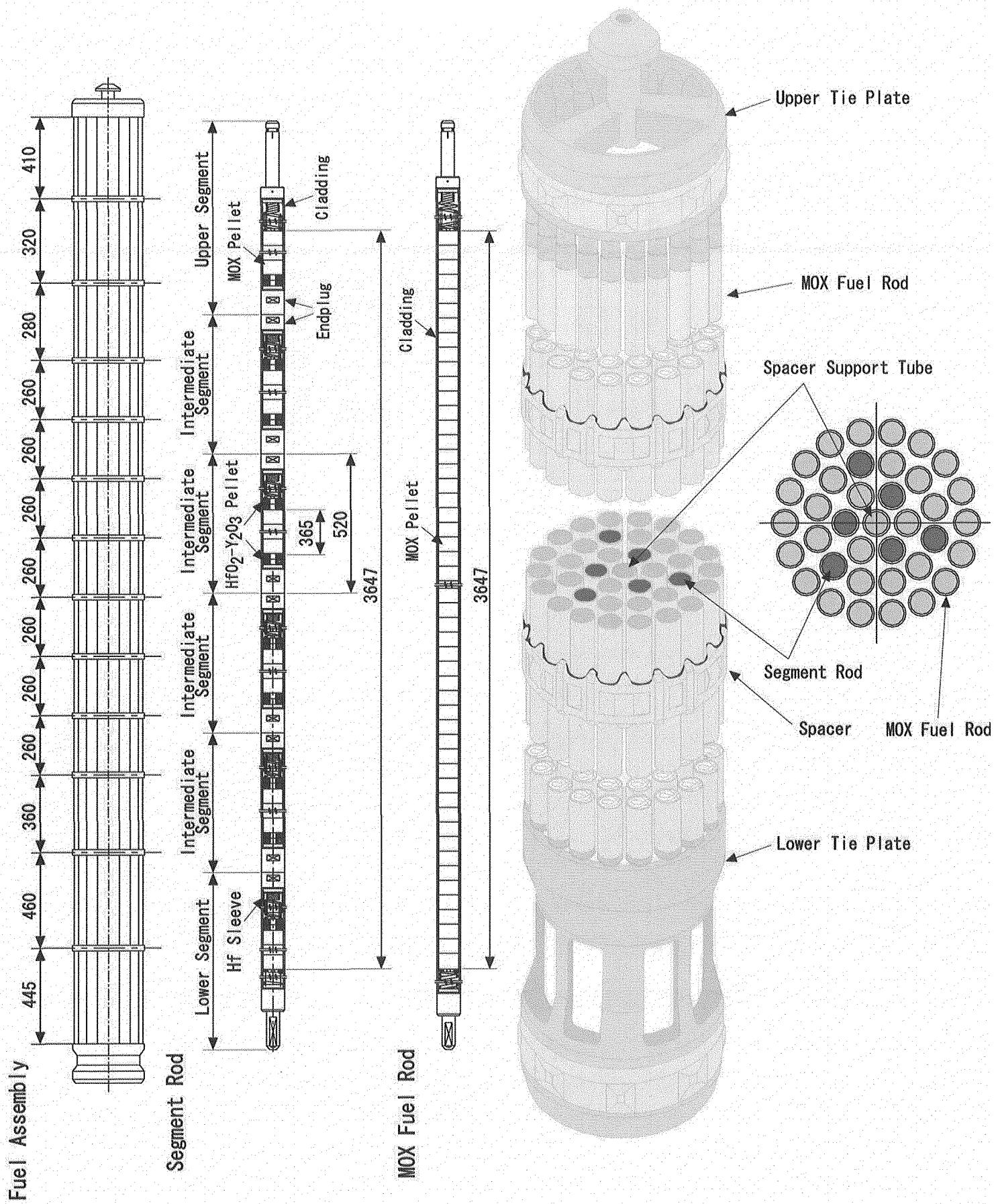


Figure 3-5 Structure of E06 and E07 Fuel Assembly

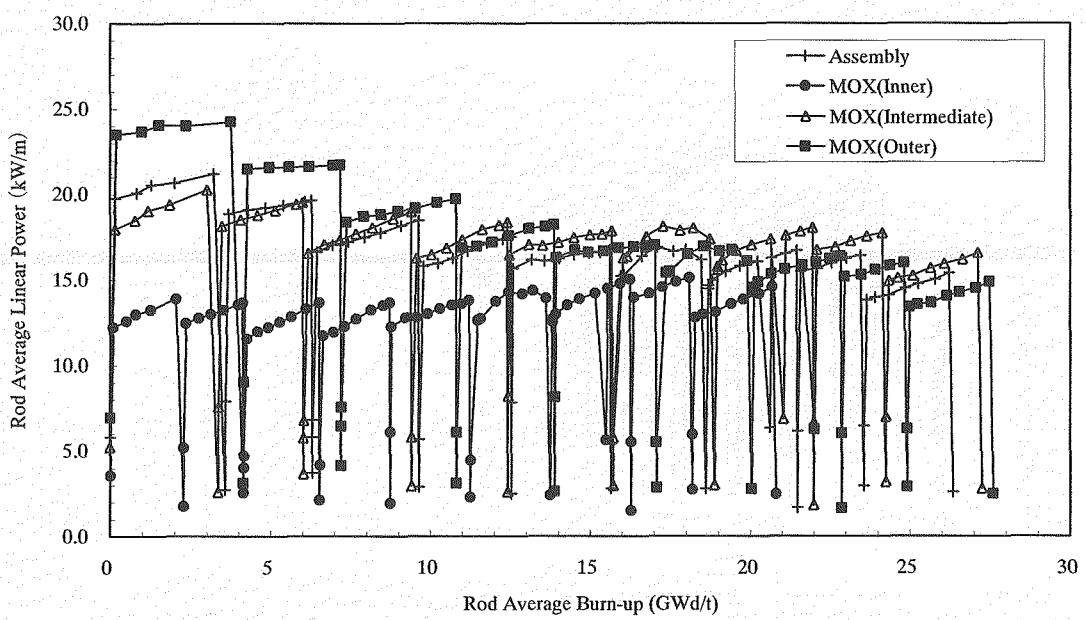


Figure 3-6 History of Rod Average Linear Power (E06)

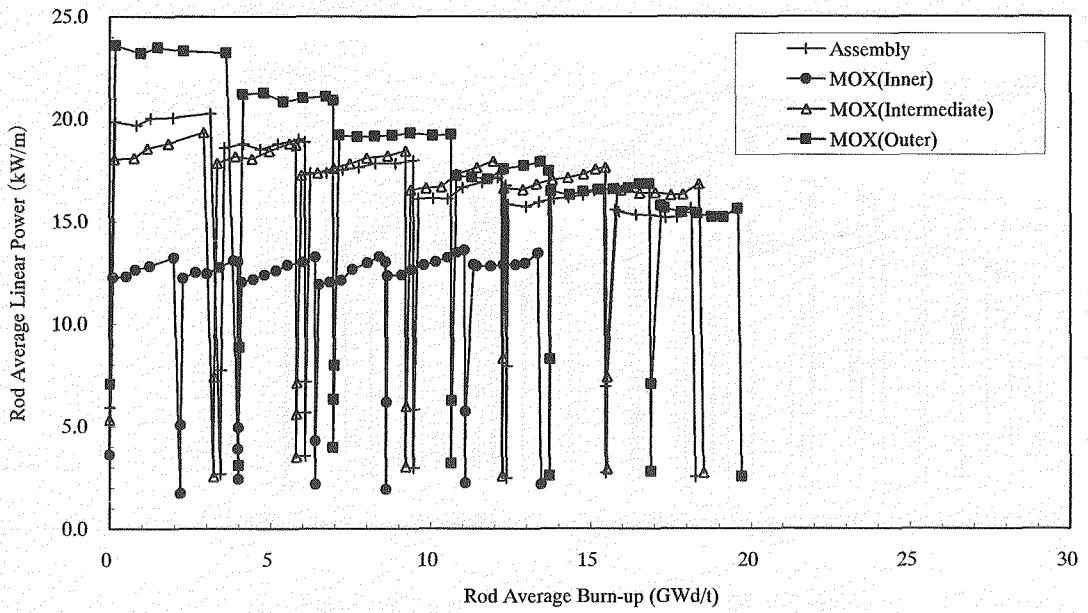


Figure 3-7 History of Rod Average Linear Power (E07)

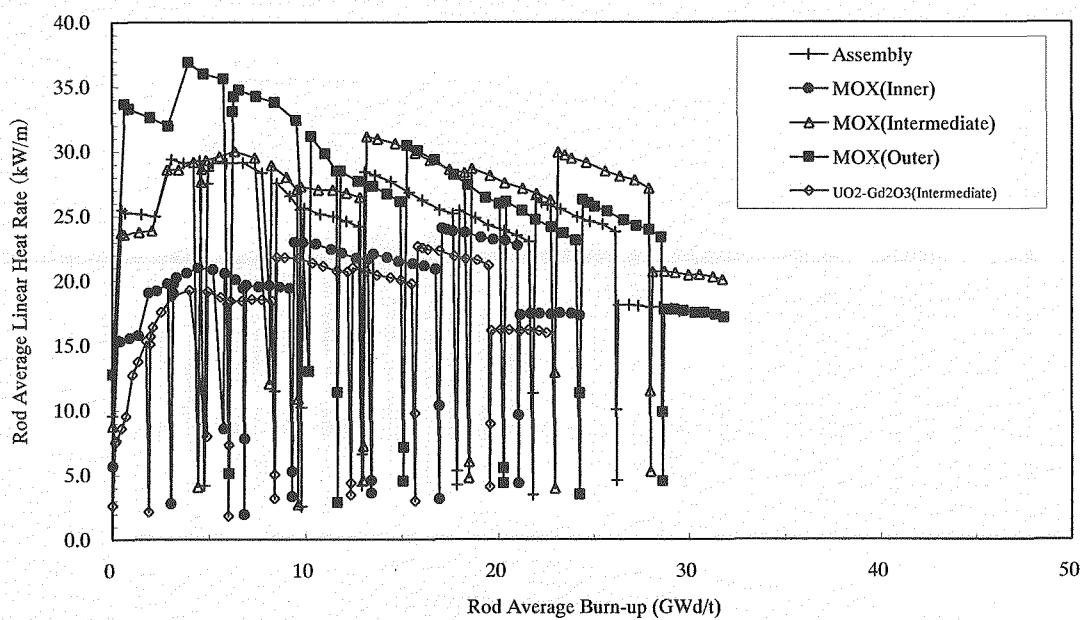


Figure 3-8 History of Rod Average Linear Heat Rate (E08)

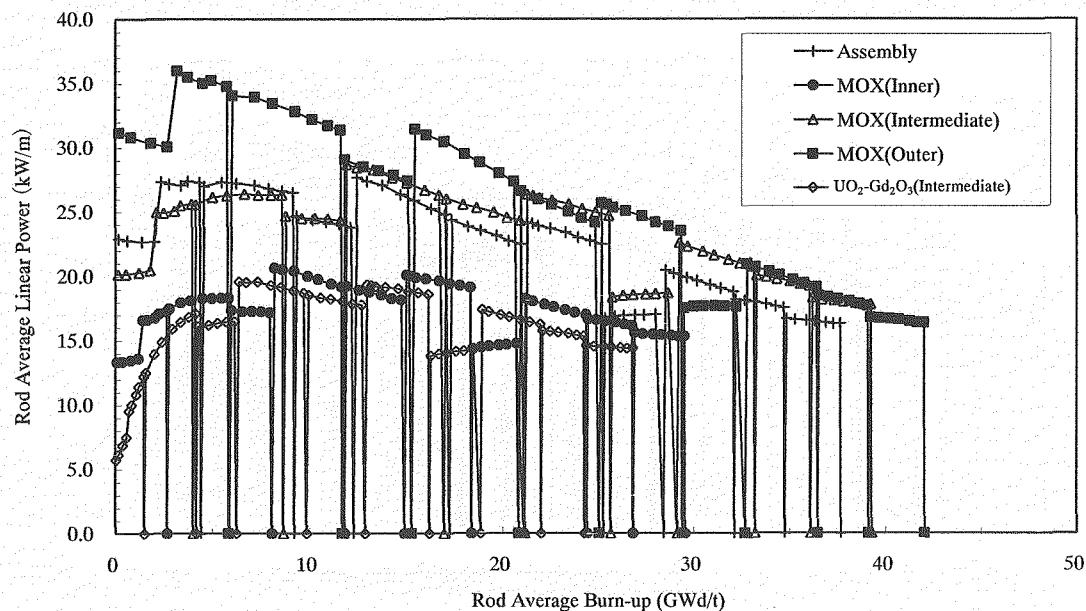
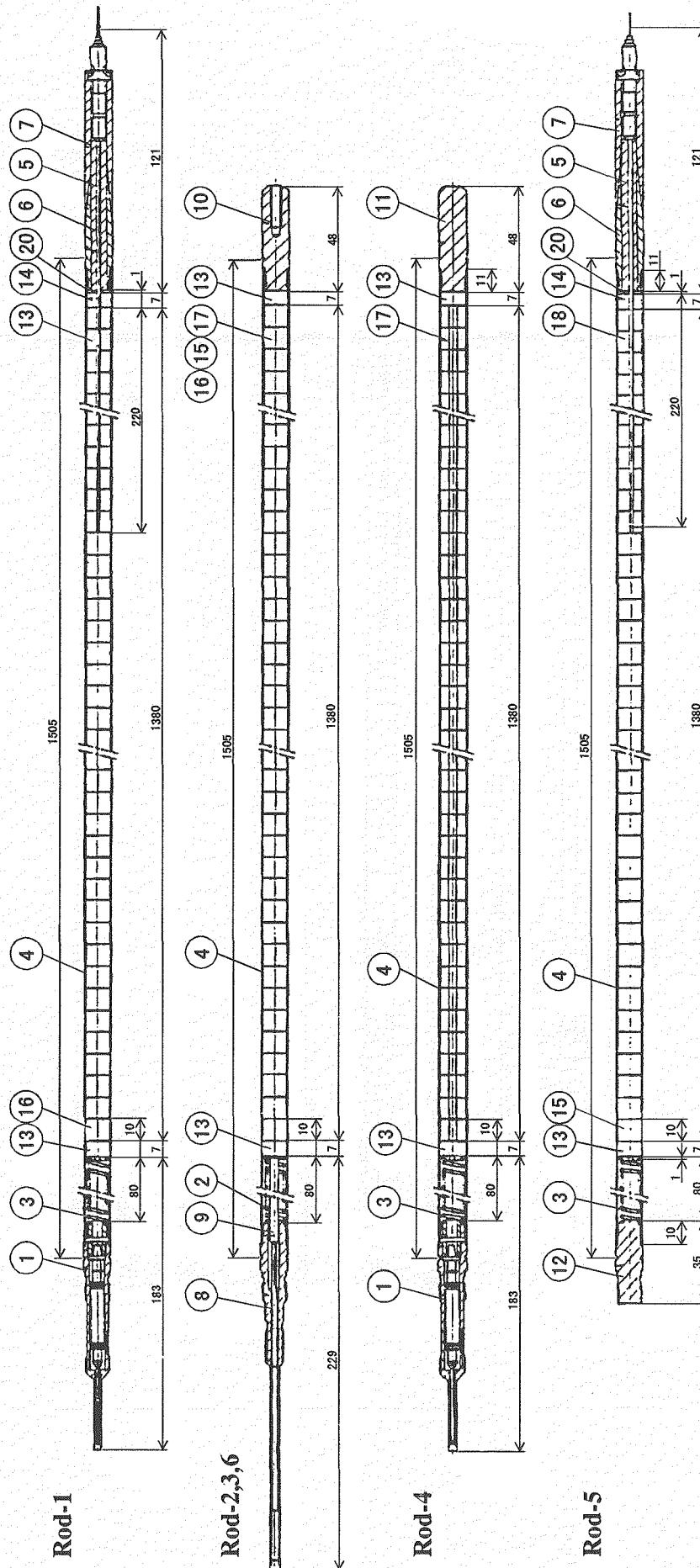


Figure 3-9 History of Rod Average Linear Power (E09)



ITEM No.	NAME	MATERIAL
1	End Plug Assembly	SUS304WPB
2	Spring(A)	SUS304WPB
3	Spring(B)	SUS304WPB
4	Cladding	Zr-2
5	T.F. End Plug	Inconel600
6	Filler Body	Zr-2
7	T.F. End Plug	Zr-2
8	E.F. End Plug Assembly	Zr-2
9	Core Assembly	Zr-2
10	E.C. End Plug	Zr-2
11	Bottom End Plug	Zr-2
12	Top End Plug	Zr-2
13	Thermal Insulator(A)	NiUO ₂
14	Thermal Insulator(B)	NiUO ₂
15	Fuel Pellet(A)	PuO ₂ -UO ₂
16	Fuel Pellet(B)	PuO ₂ -UO ₂
17	Fuel Pellet(C)	PuO ₂ -UO ₂
18	Fuel Pellet(D)	PuO ₂ -UO ₂
19	Fuel Pellet(E)	PuO ₂ -UO ₂
20	Disk Hollow	Zr-2

Figure 4-1 Structure of IFA-514/565

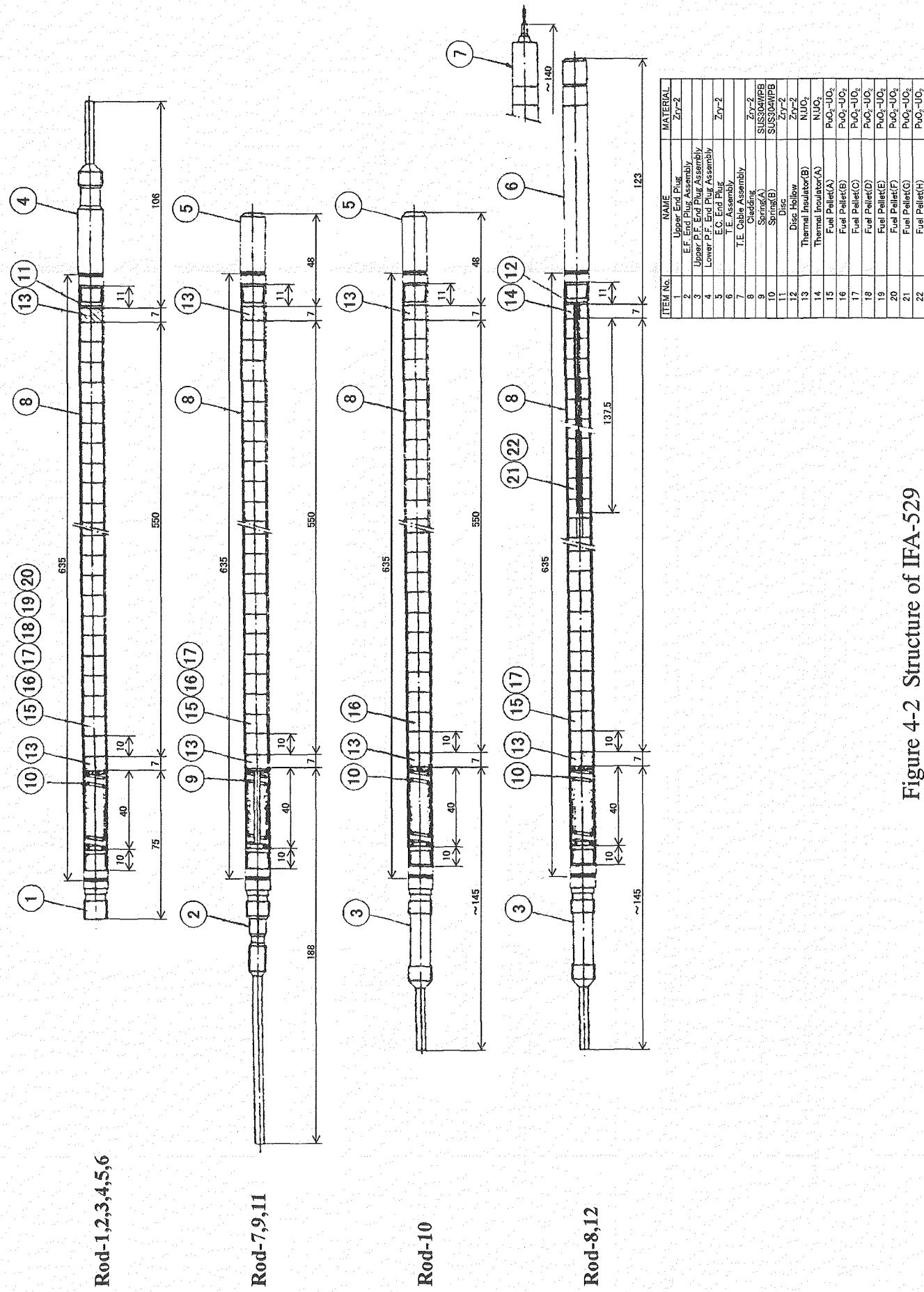
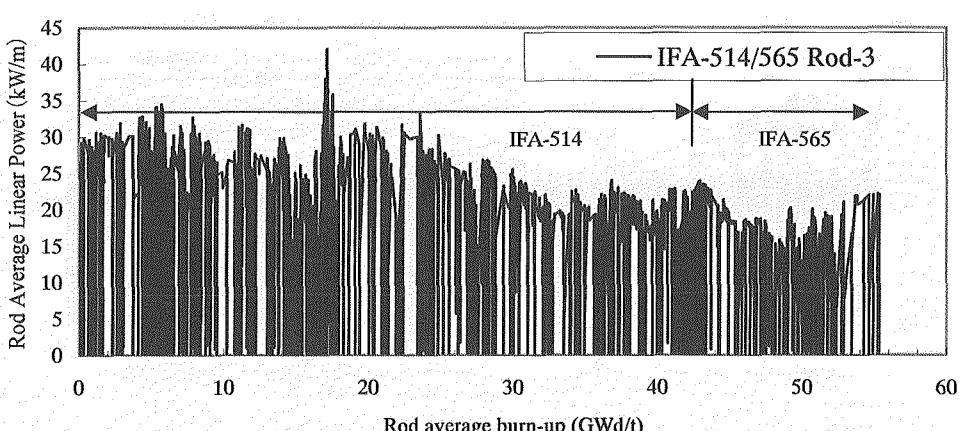
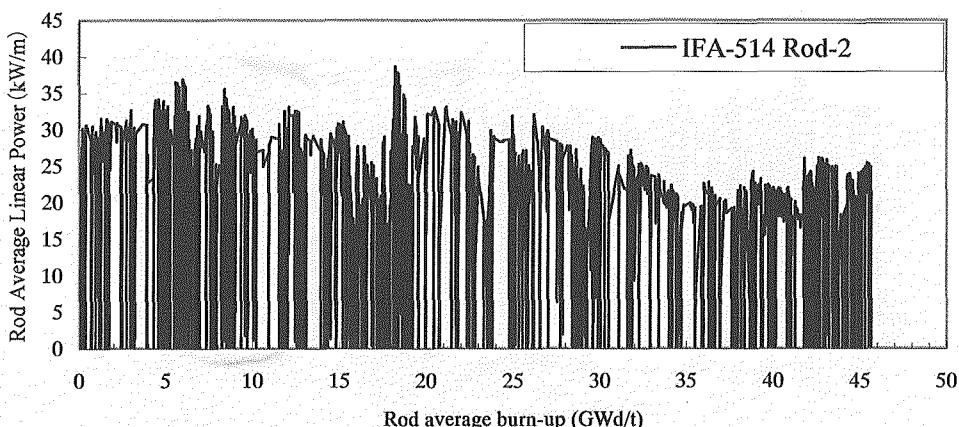
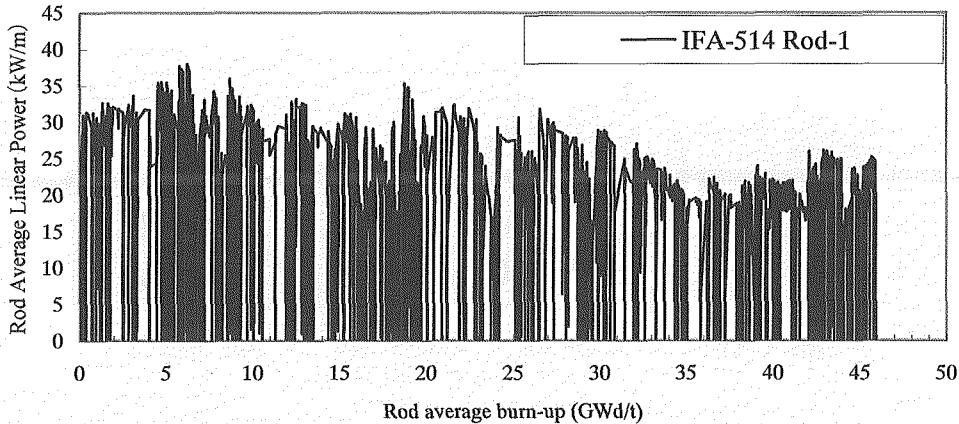


Figure 4-2 Structure of IFA-529



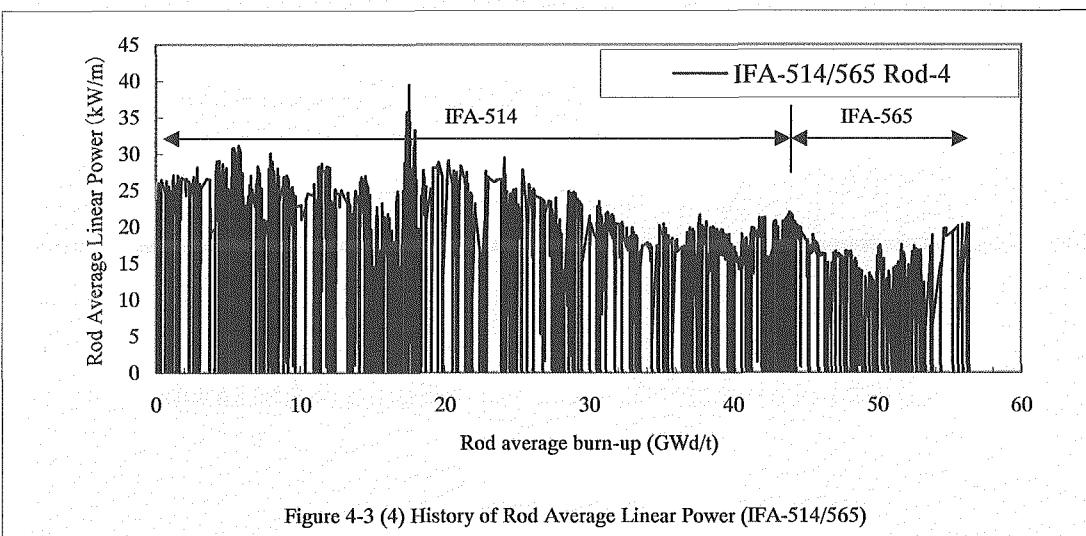


Figure 4-3 (4) History of Rod Average Linear Power (IFA-514/565)

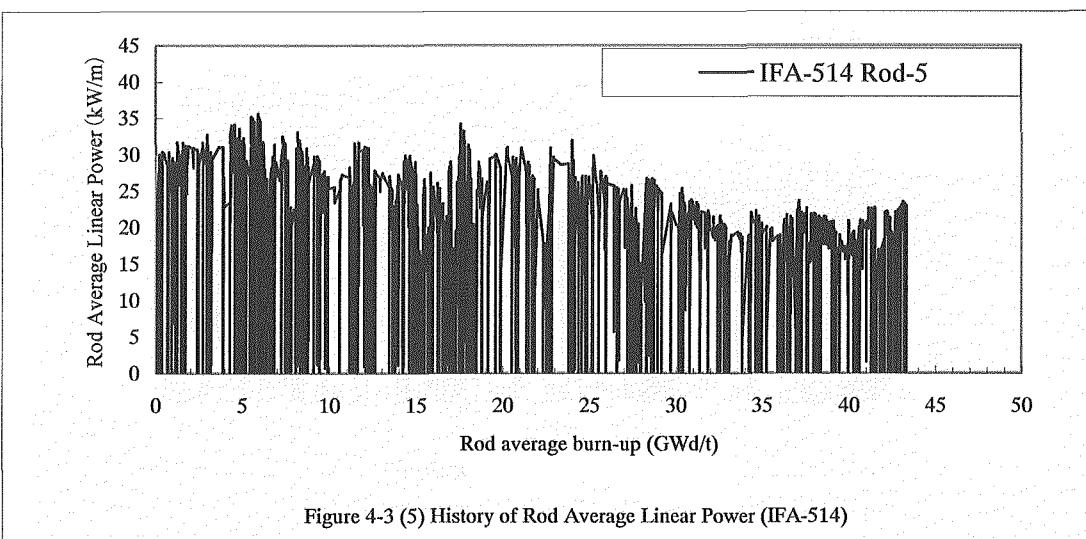


Figure 4-3 (5) History of Rod Average Linear Power (IFA-514)

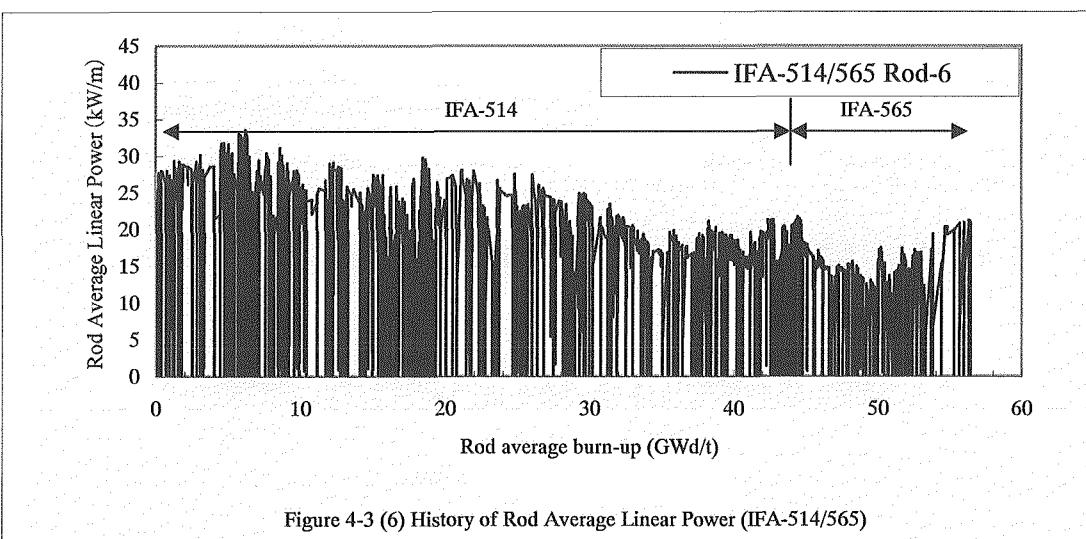


Figure 4-3 (6) History of Rod Average Linear Power (IFA-514/565)

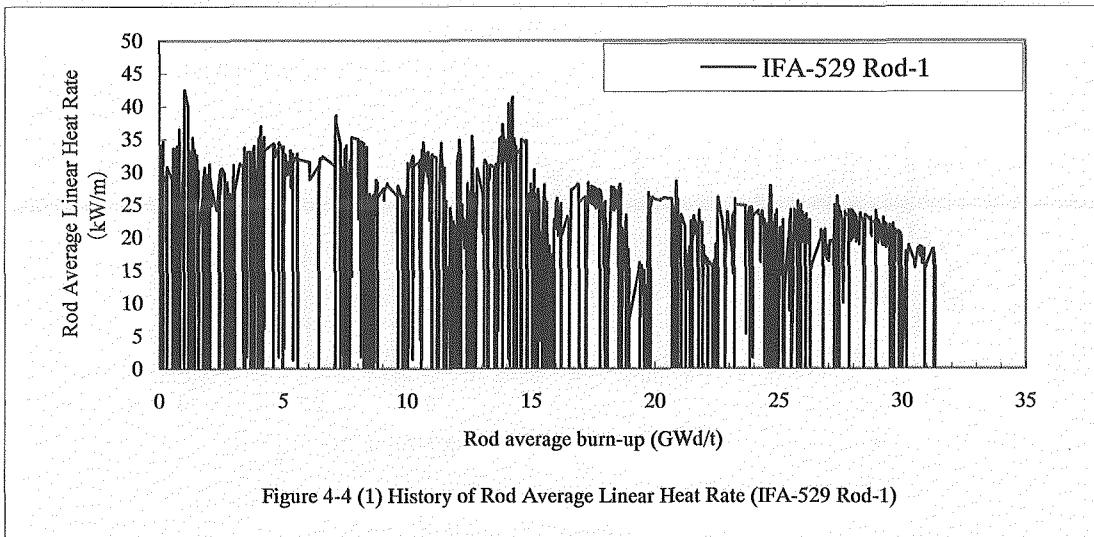


Figure 4-4 (1) History of Rod Average Linear Heat Rate (IF-A-529 Rod-1)

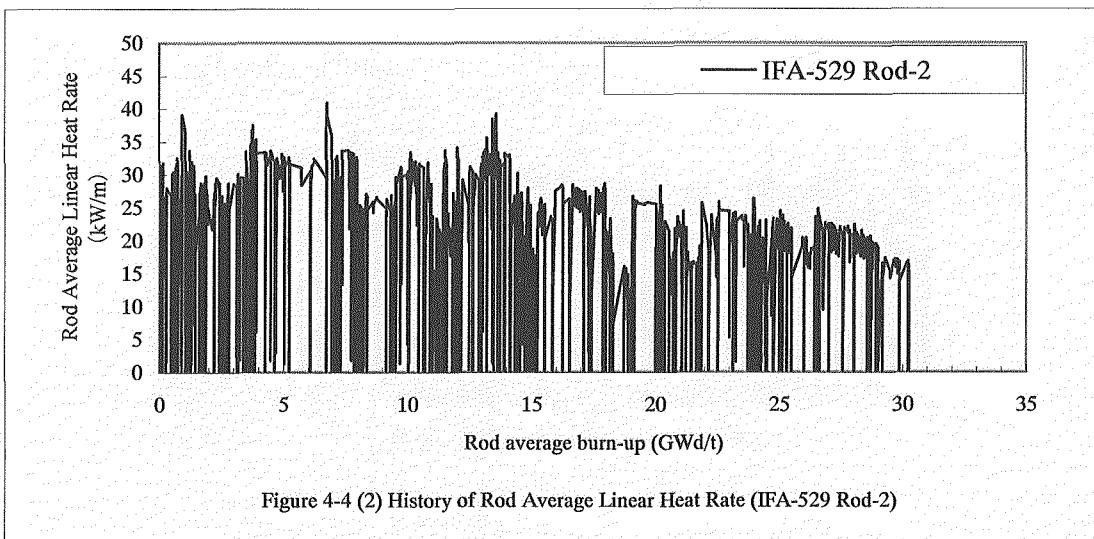


Figure 4-4 (2) History of Rod Average Linear Heat Rate (IF-A-529 Rod-2)

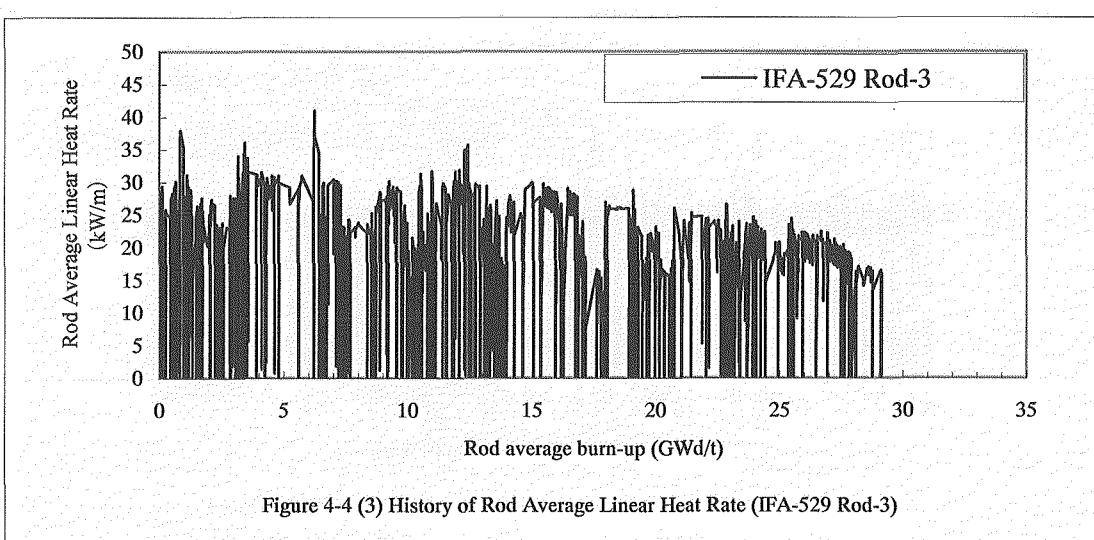


Figure 4-4 (3) History of Rod Average Linear Heat Rate (IF-A-529 Rod-3)

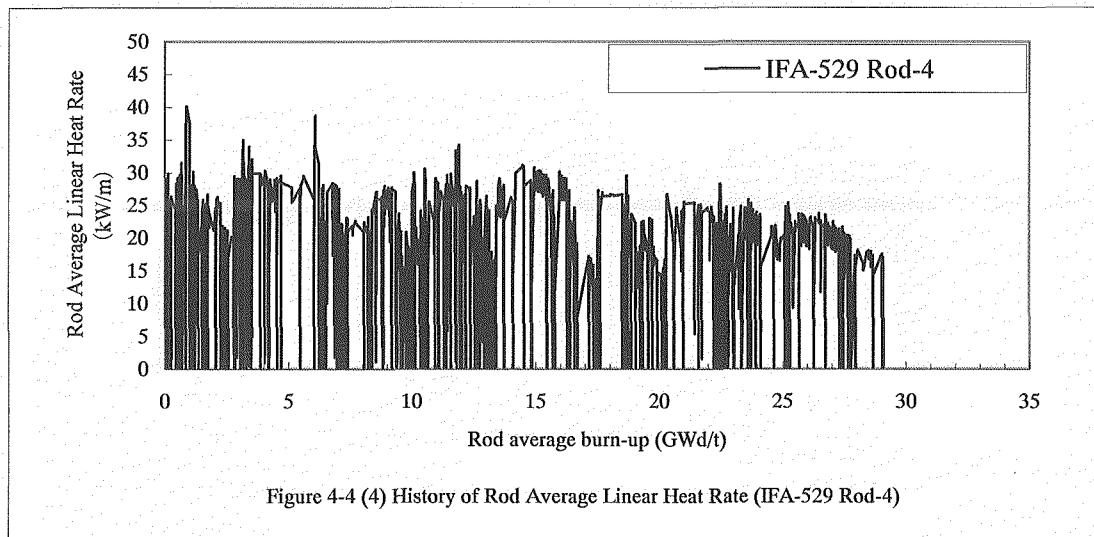


Figure 4-4 (4) History of Rod Average Linear Heat Rate (IF-A-529 Rod-4)

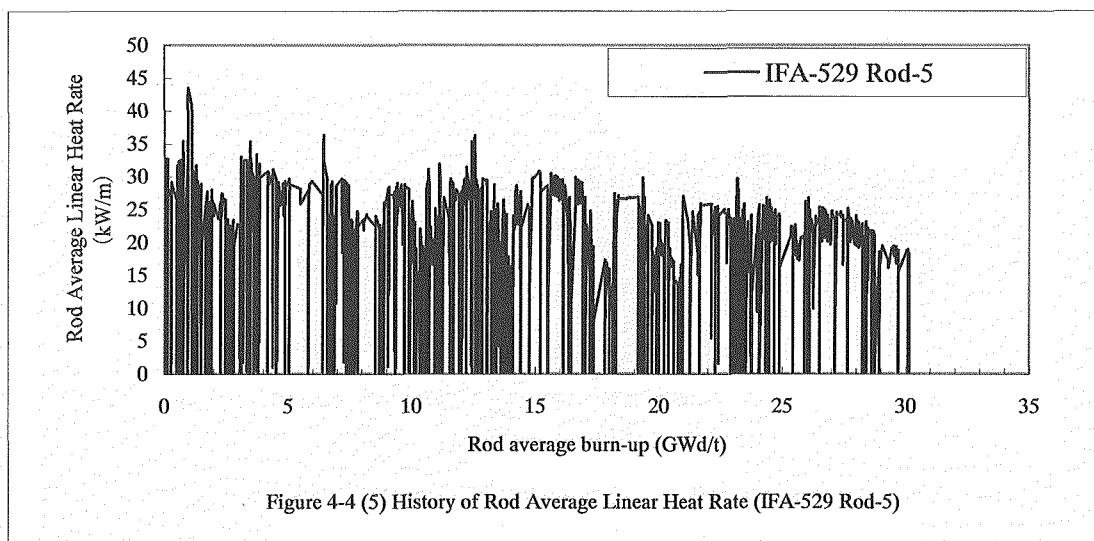


Figure 4-4 (5) History of Rod Average Linear Heat Rate (IF-A-529 Rod-5)

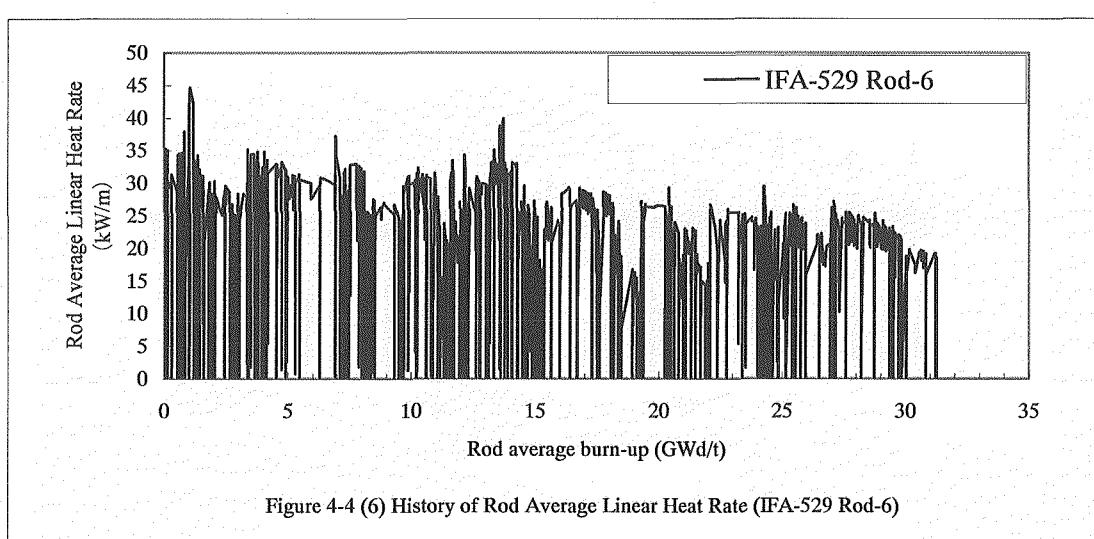


Figure 4-4 (6) History of Rod Average Linear Heat Rate (IF-A-529 Rod-6)

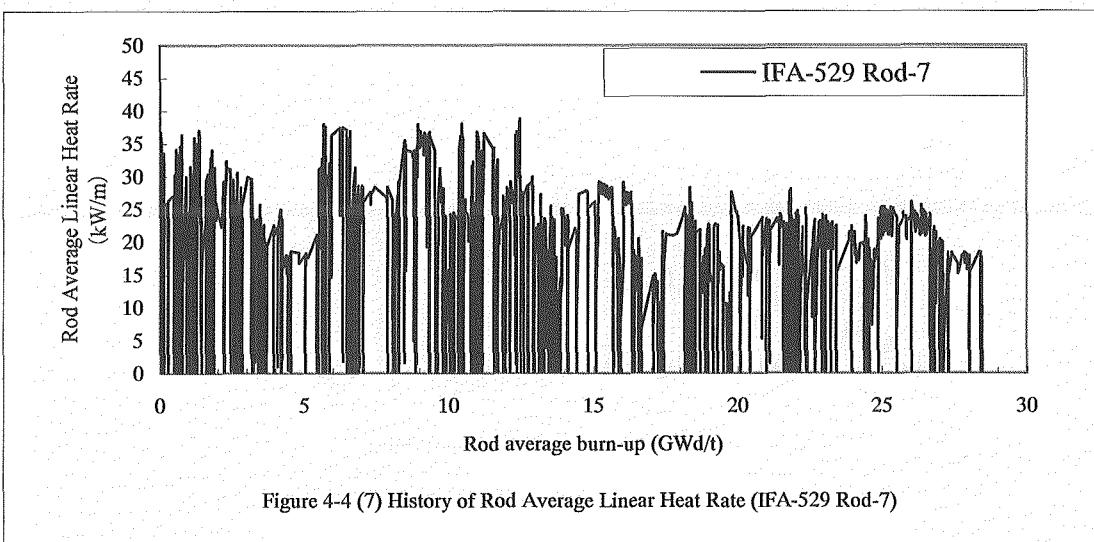


Figure 4-4 (7) History of Rod Average Linear Heat Rate (IF-A529 Rod-7)

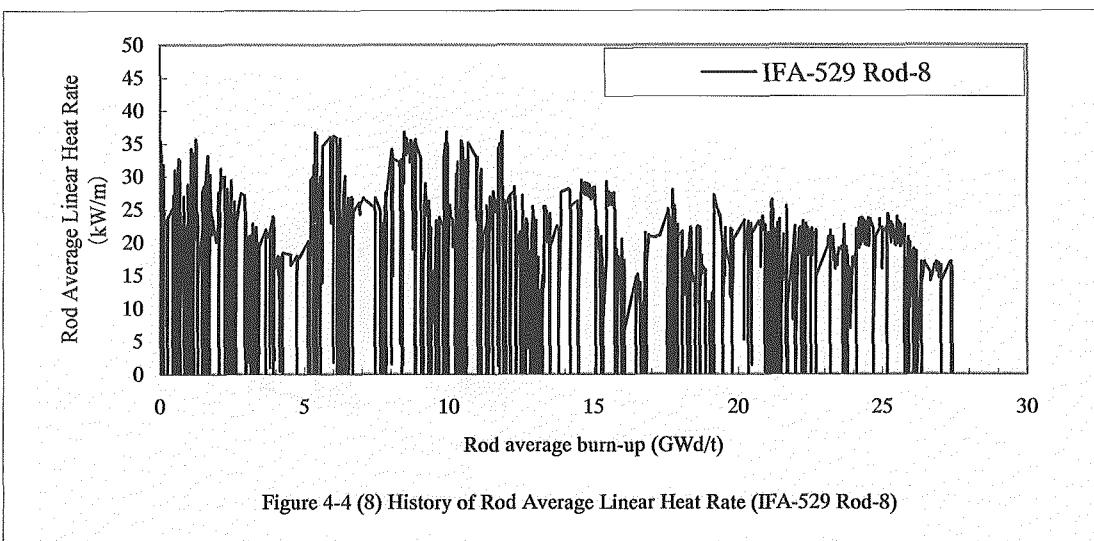


Figure 4-4 (8) History of Rod Average Linear Heat Rate (IF-A529 Rod-8)

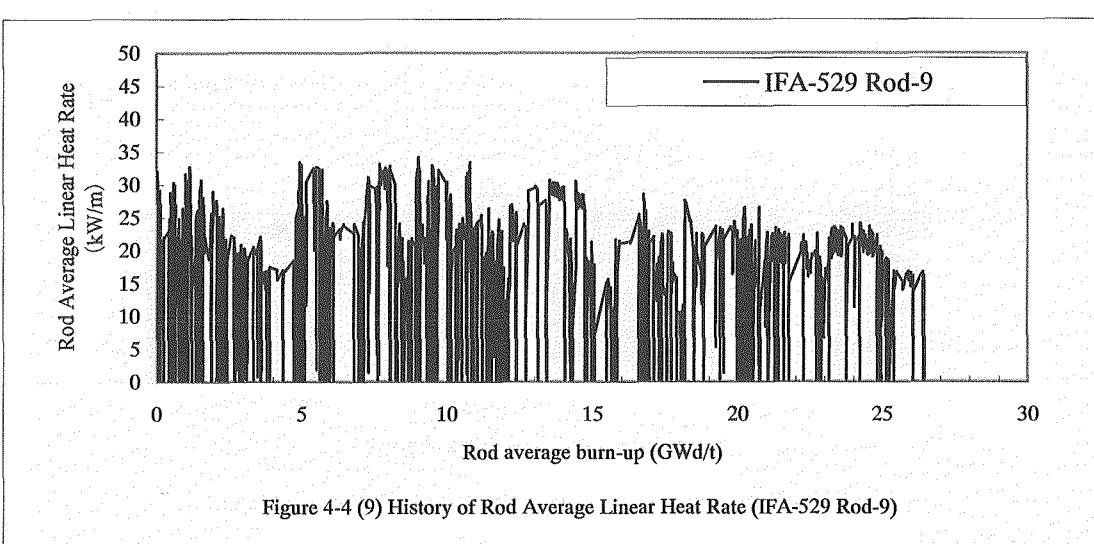


Figure 4-4 (9) History of Rod Average Linear Heat Rate (IF-A529 Rod-9)

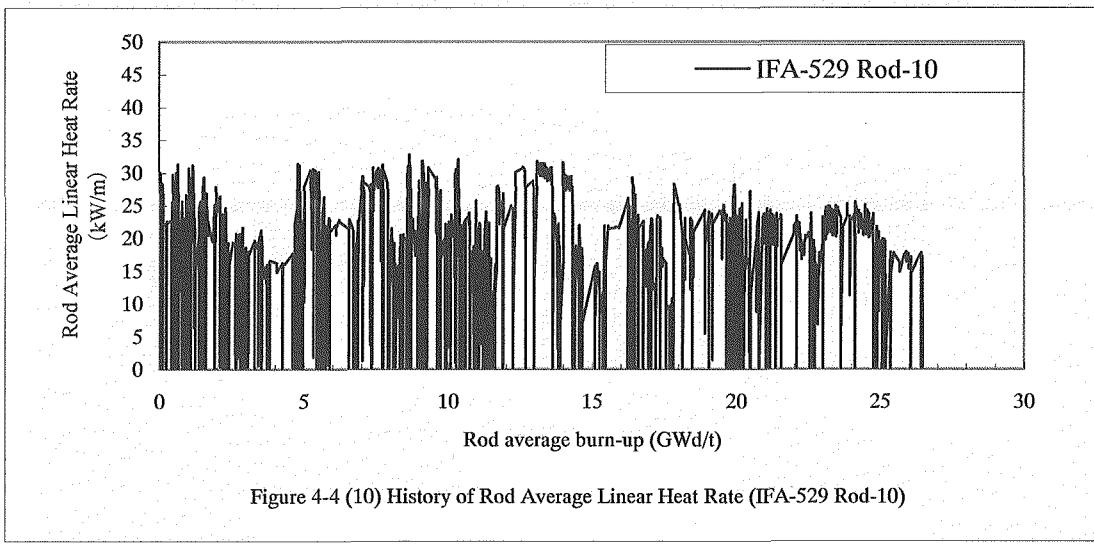


Figure 4-4 (10) History of Rod Average Linear Heat Rate (IFA-529 Rod-10)

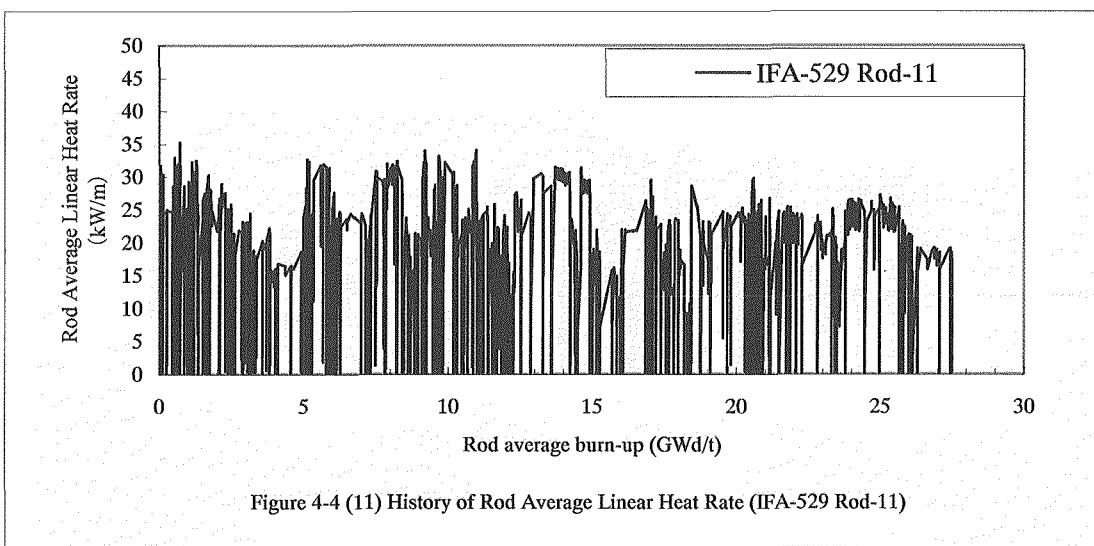


Figure 4-4 (11) History of Rod Average Linear Heat Rate (IFA-529 Rod-11)

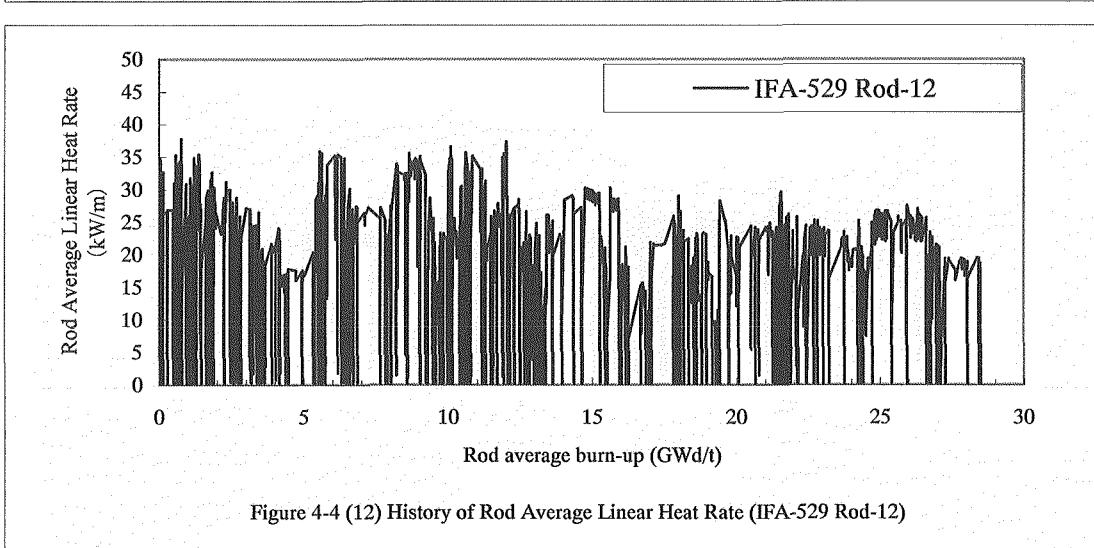


Figure 4-4 (12) History of Rod Average Linear Heat Rate (IFA-529 Rod-12)

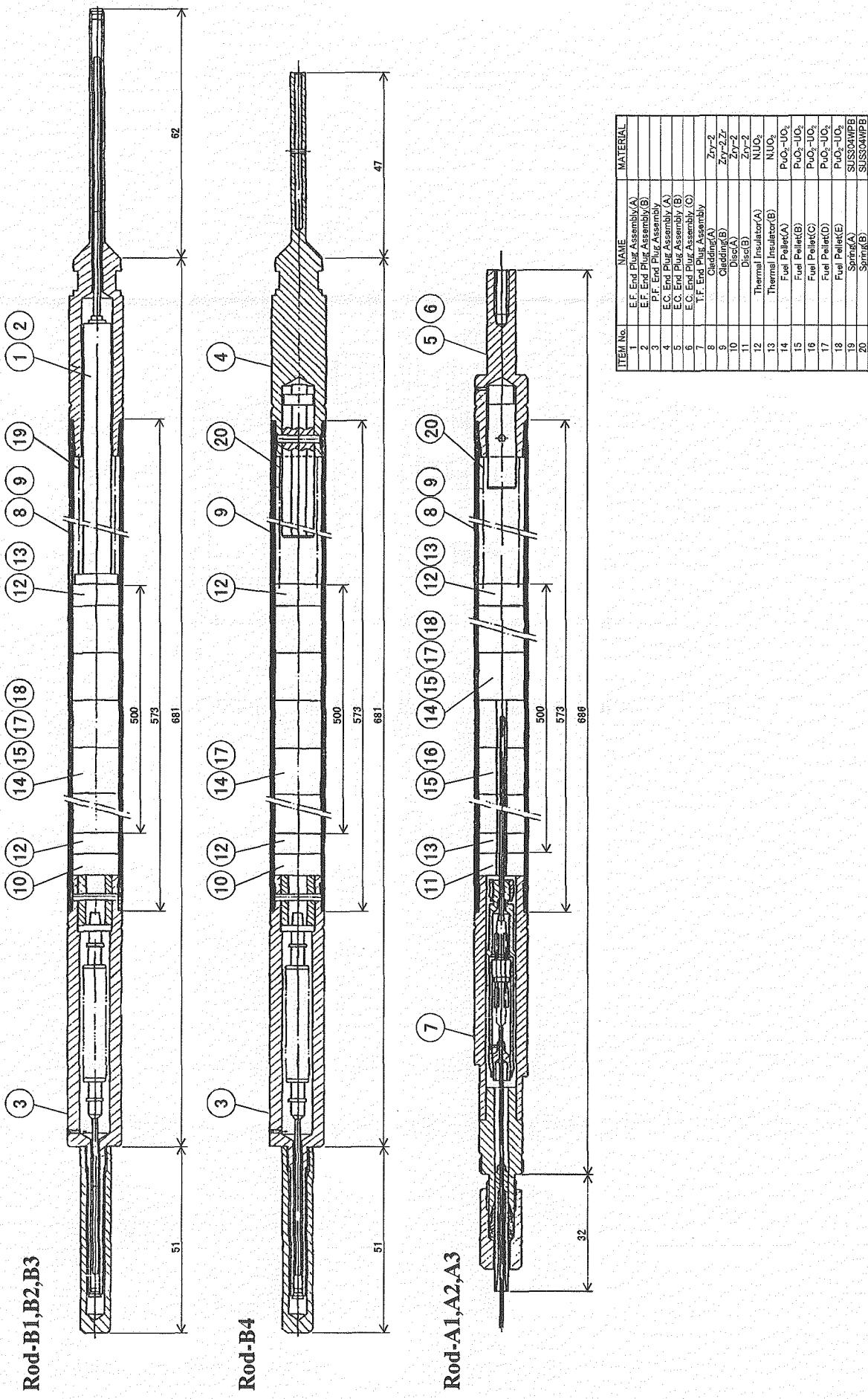


Figure 4-5 Structure of IFA-554/555

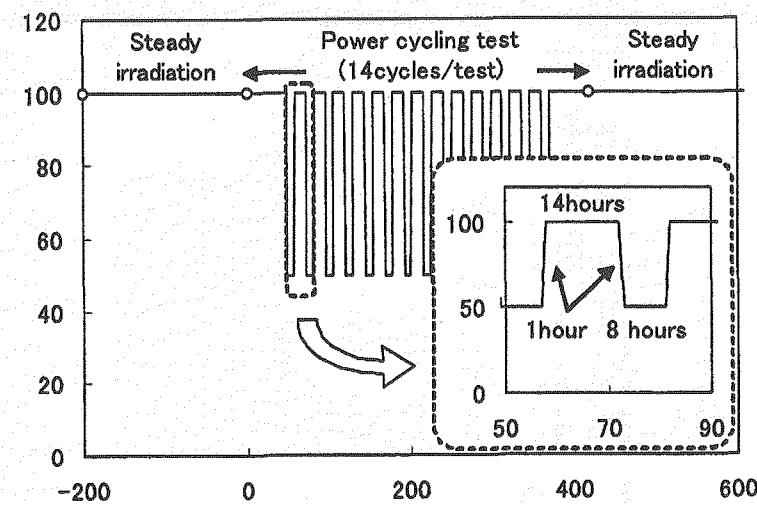


Figure 4-6 Typical Power Pattern during Load-Follow Test

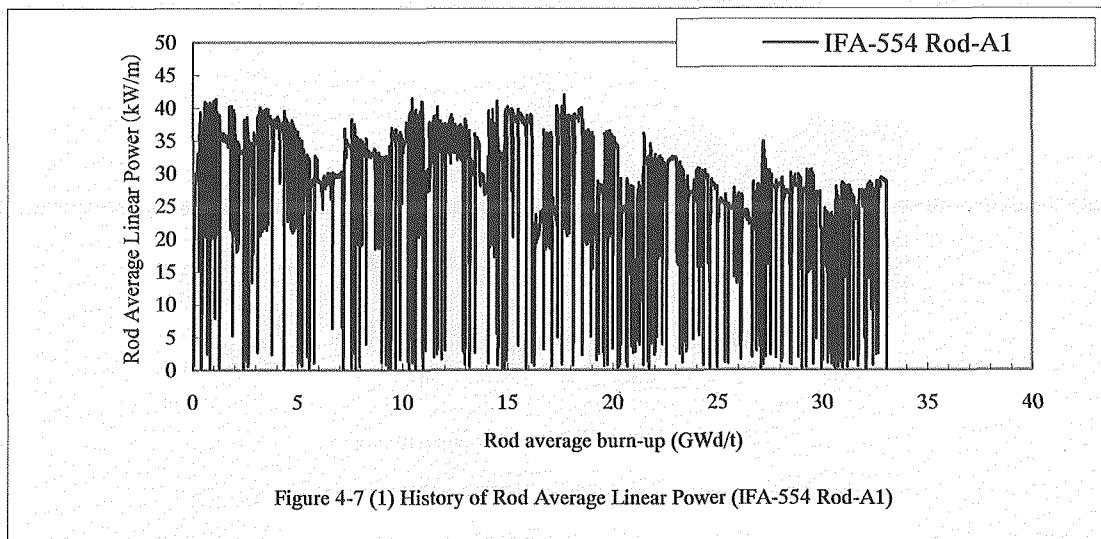


Figure 4-7 (1) History of Rod Average Linear Power (IFA-554 Rod-A1)

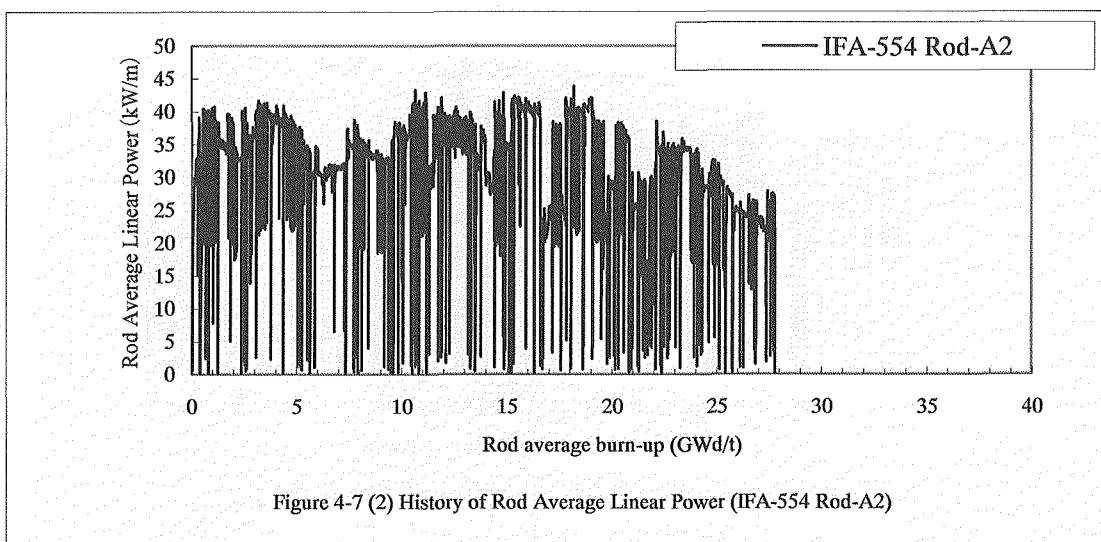


Figure 4-7 (2) History of Rod Average Linear Power (IFA-554 Rod-A2)

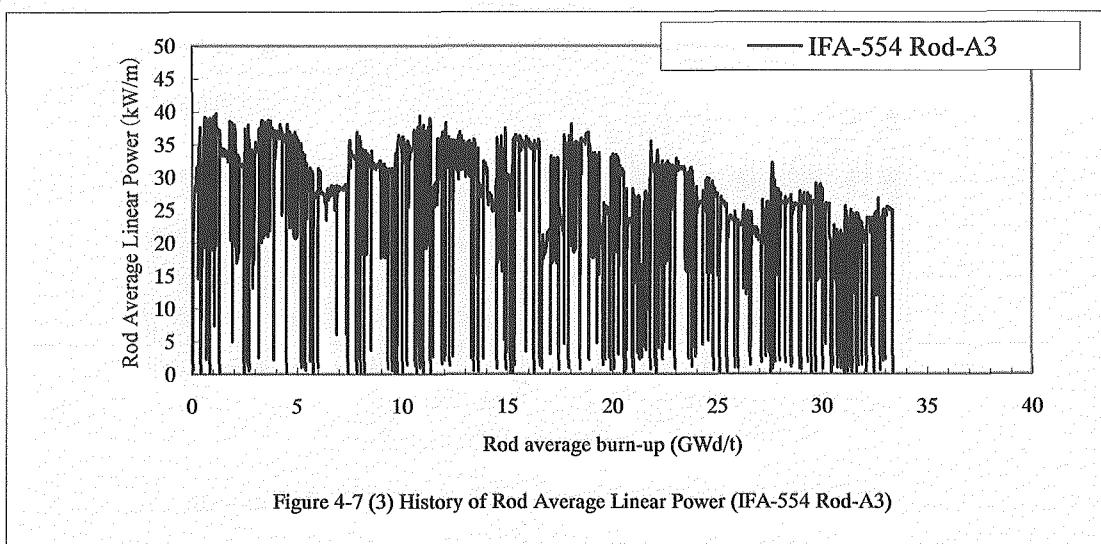


Figure 4-7 (3) History of Rod Average Linear Power (IFA-554 Rod-A3)

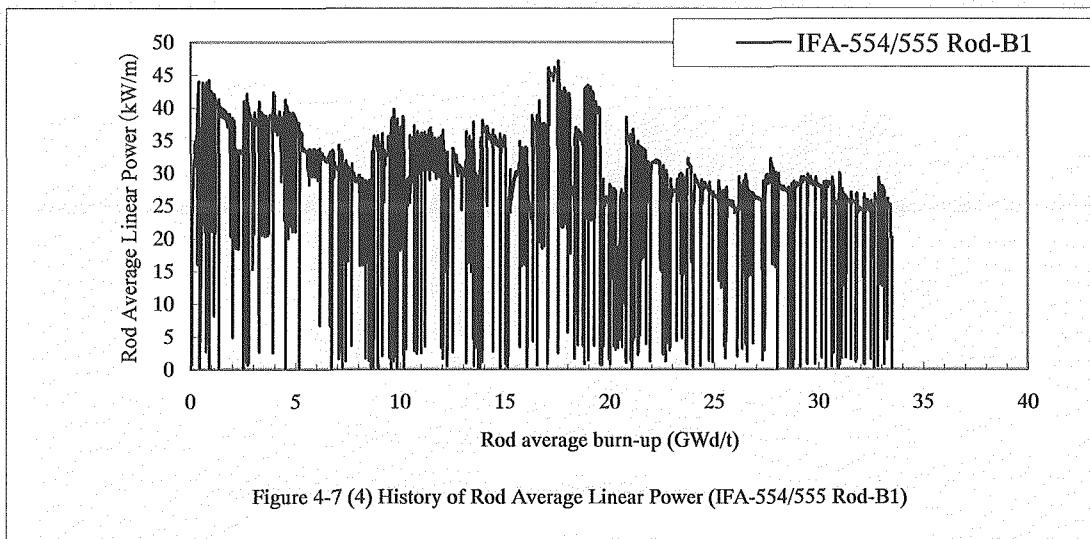


Figure 4-7 (4) History of Rod Average Linear Power (IFA-554/555 Rod-B1)

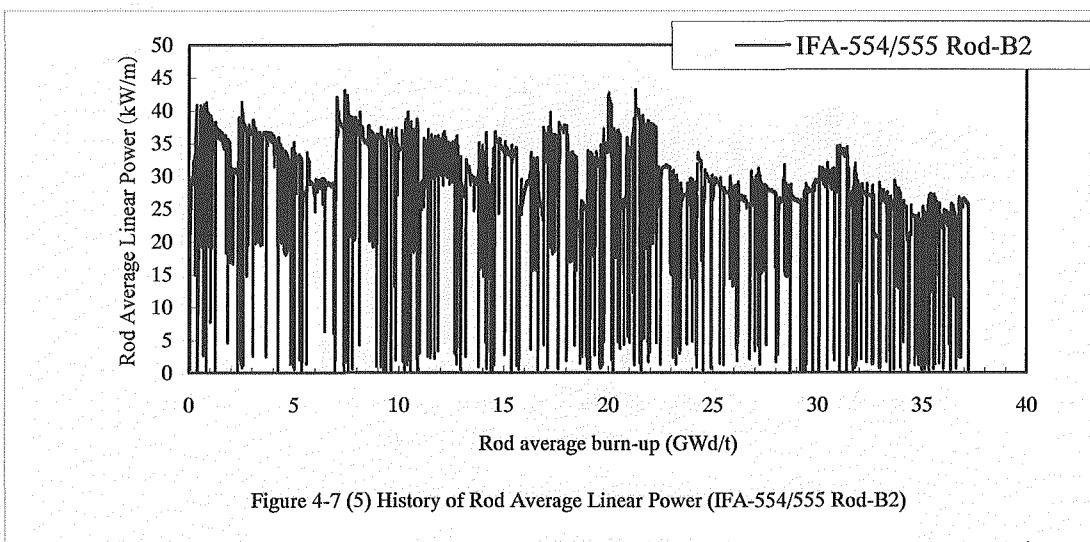


Figure 4-7 (5) History of Rod Average Linear Power (IFA-554/555 Rod-B2)

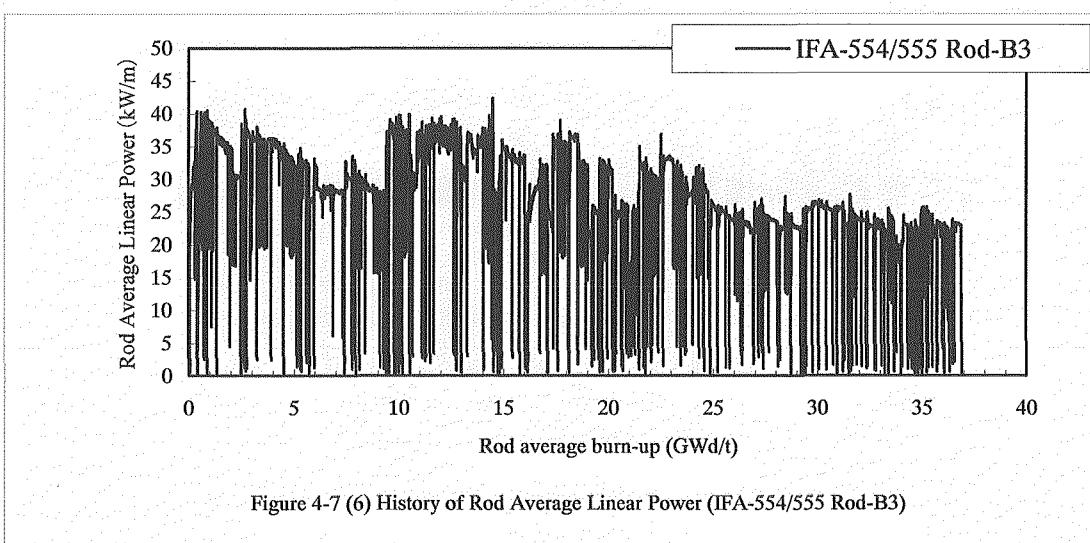
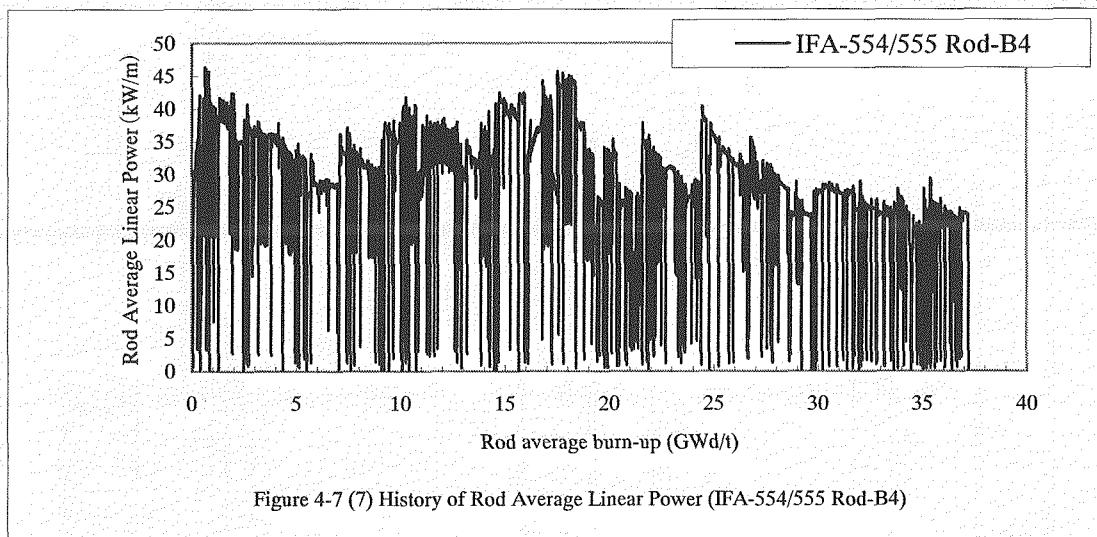


Figure 4-7 (6) History of Rod Average Linear Power (IFA-554/555 Rod-B3)



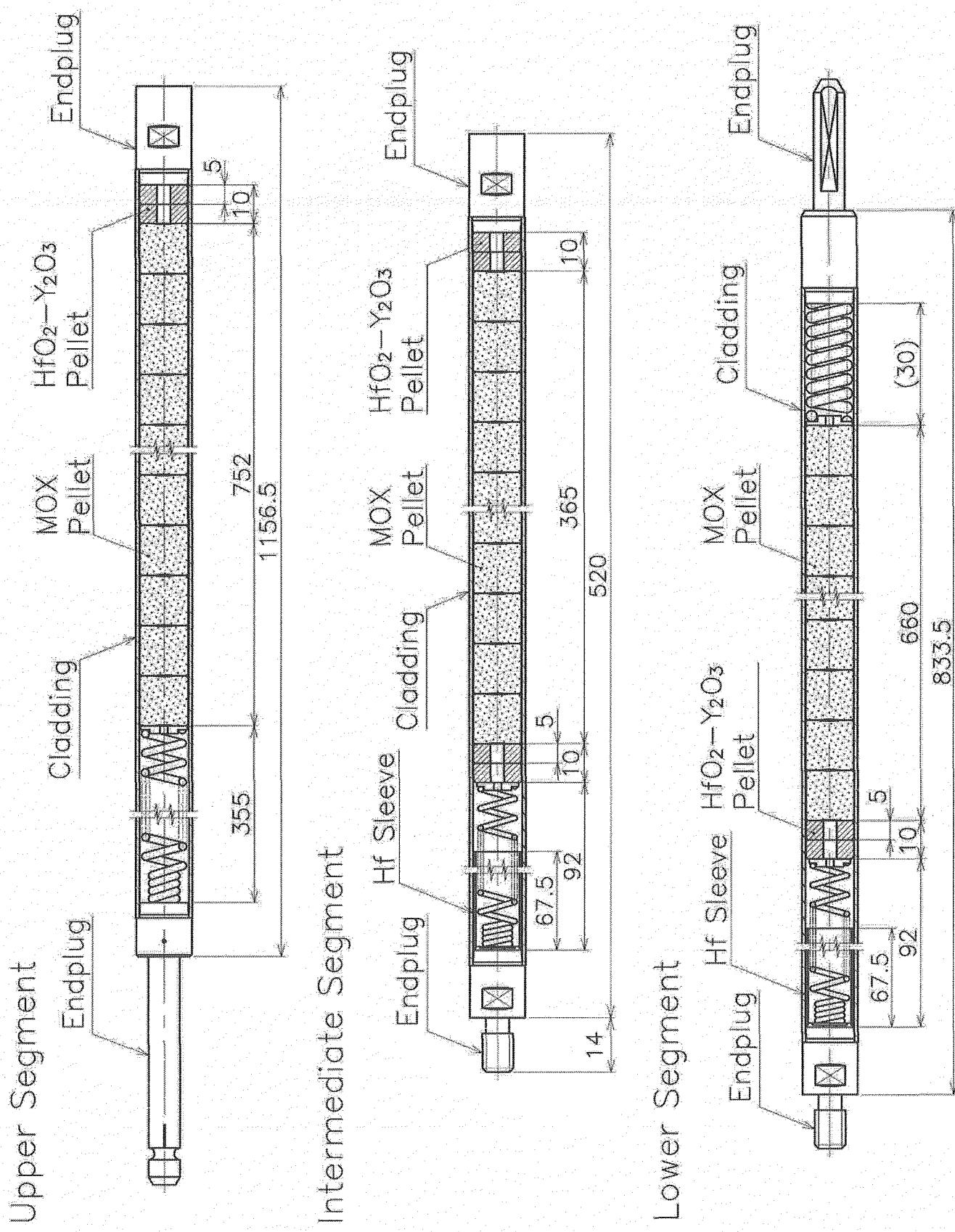


Figure 4-8 Structure of IFA-591

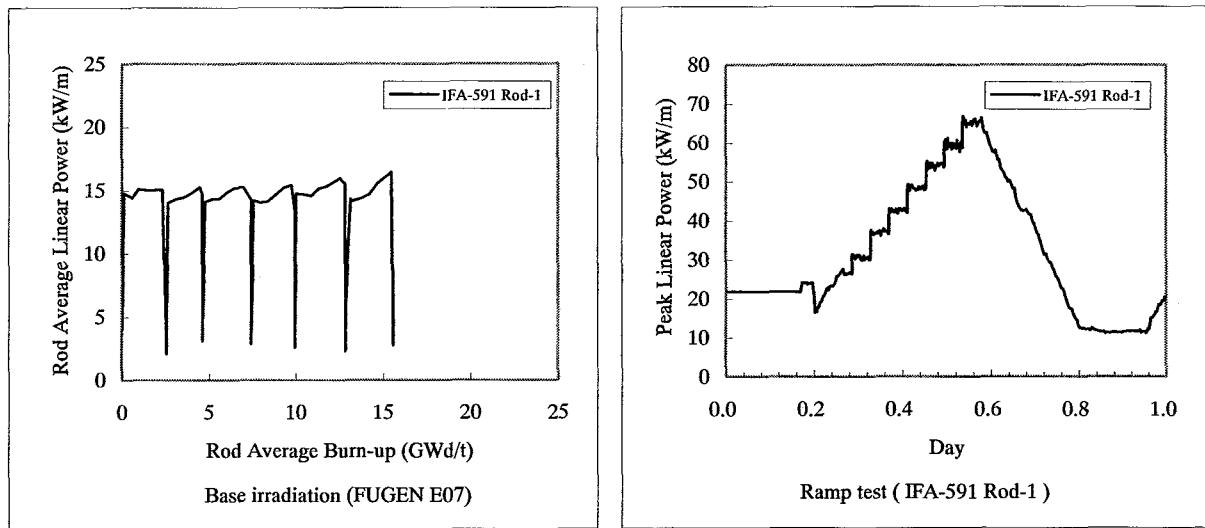


Figure 4-9 (1) History of Rod Average Linear Heat Rate (IFA-591 Rod-1)

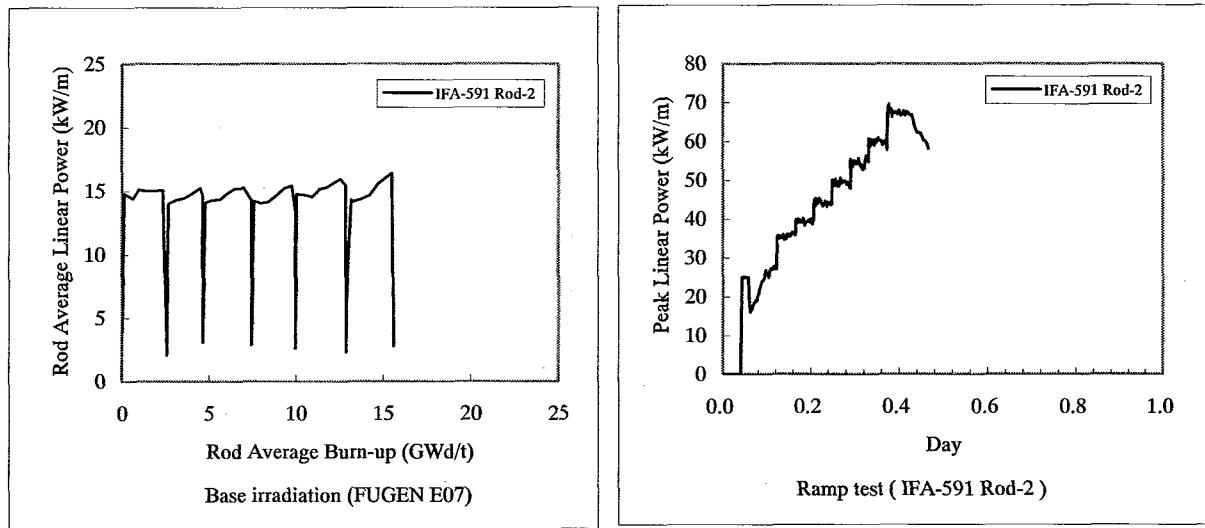


Figure 4-9 (2) History of Rod Average Linear Heat Rate (IFA-591 Rod-2)

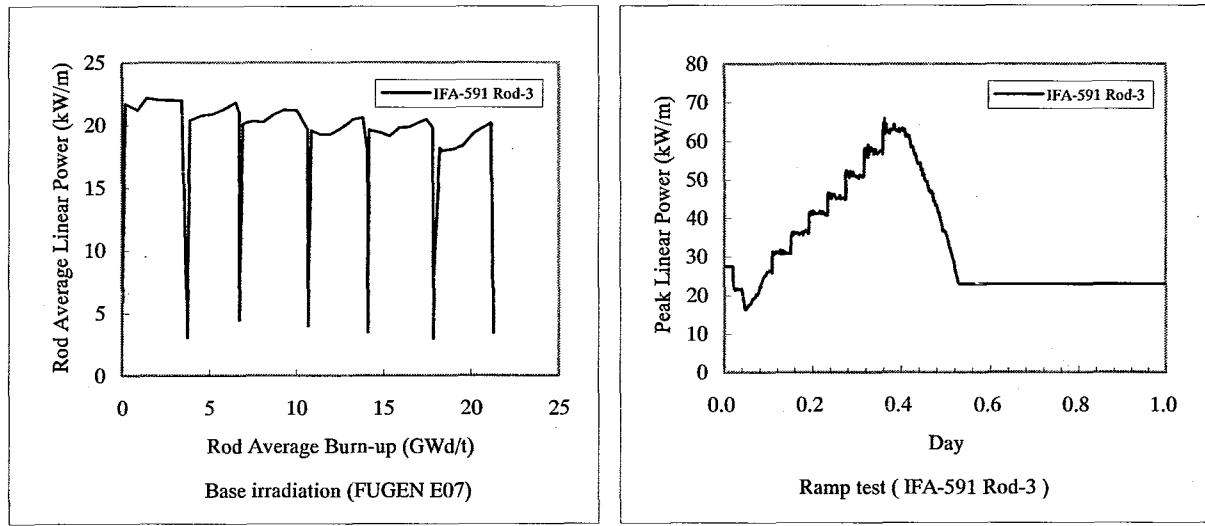


Figure 4-9 (3) History of Rod Average Linear Heat Rate (IFA-591 Rod-3)

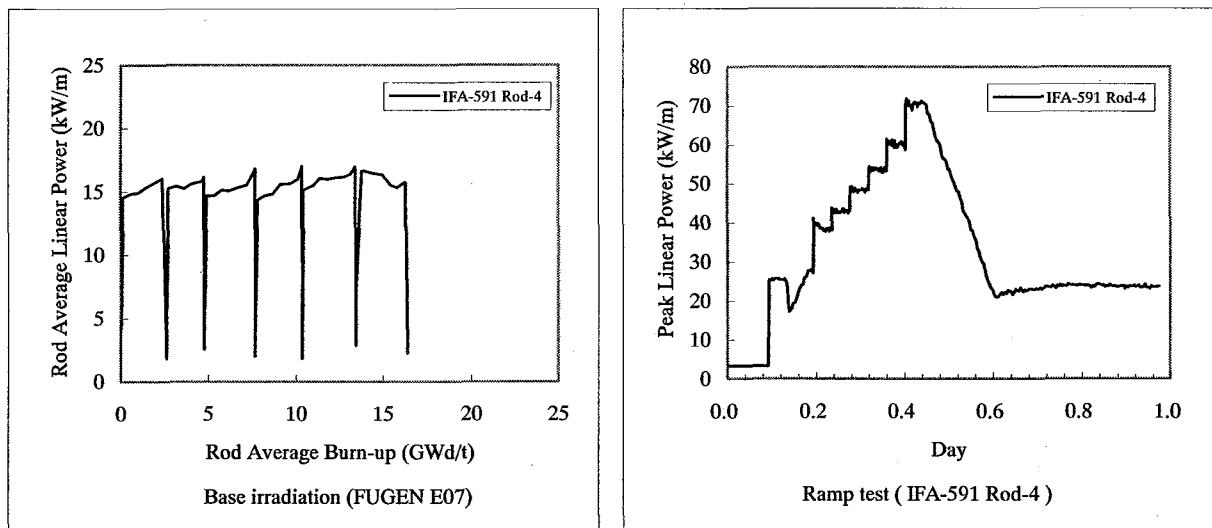


Figure 4-9 (4) History of Rod Average Linear Heat Rate (IF-A591 Rod-4)

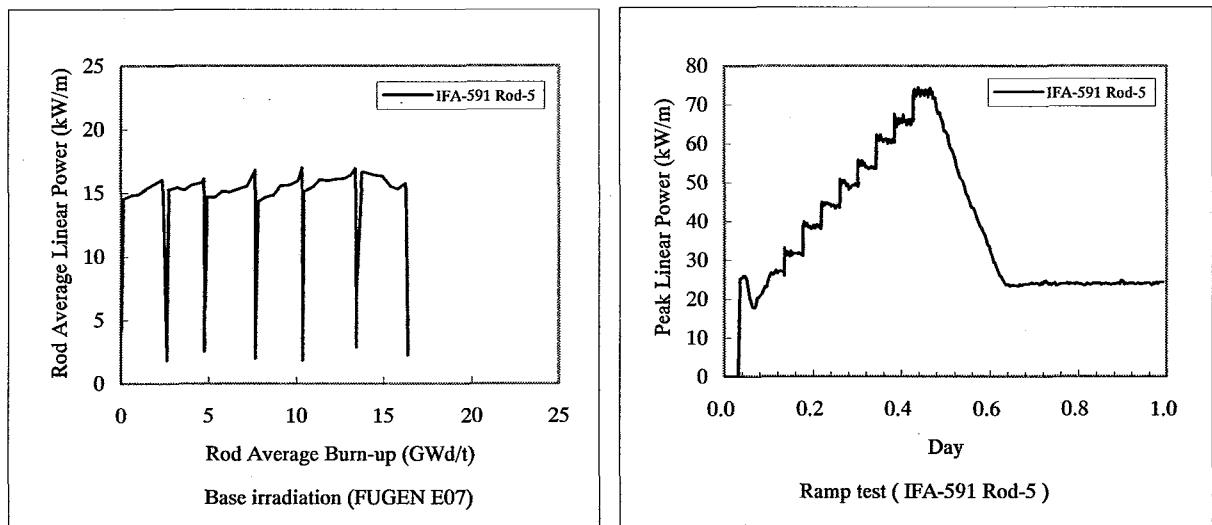


Figure 4-9 (5) History of Rod Average Linear Heat Rate (IF-A591 Rod-5)

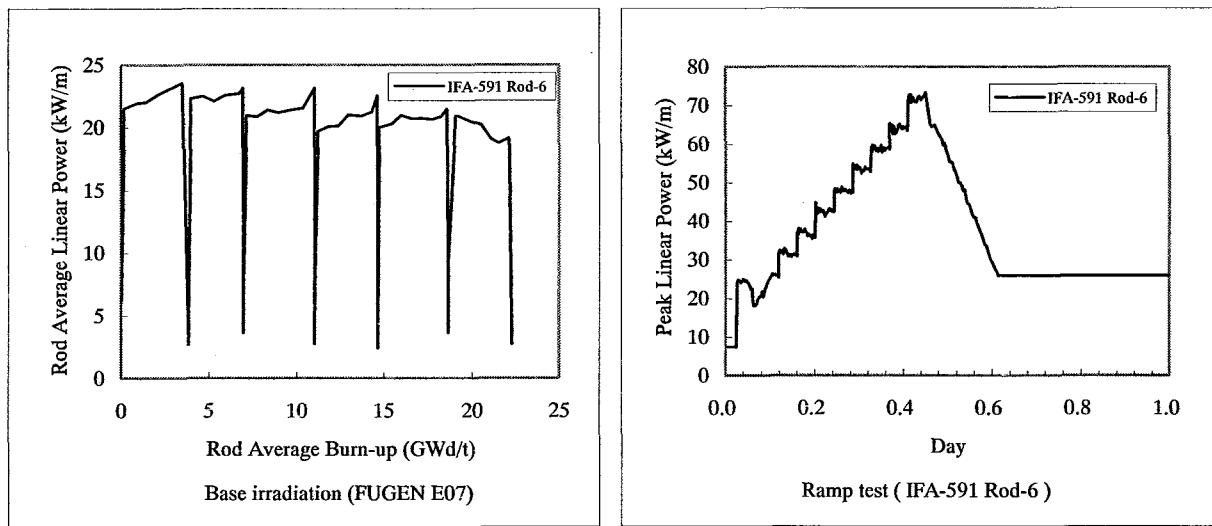


Figure 4-9 (6) History of Rod Average Linear Heat Rate (IF-A591 Rod-6)

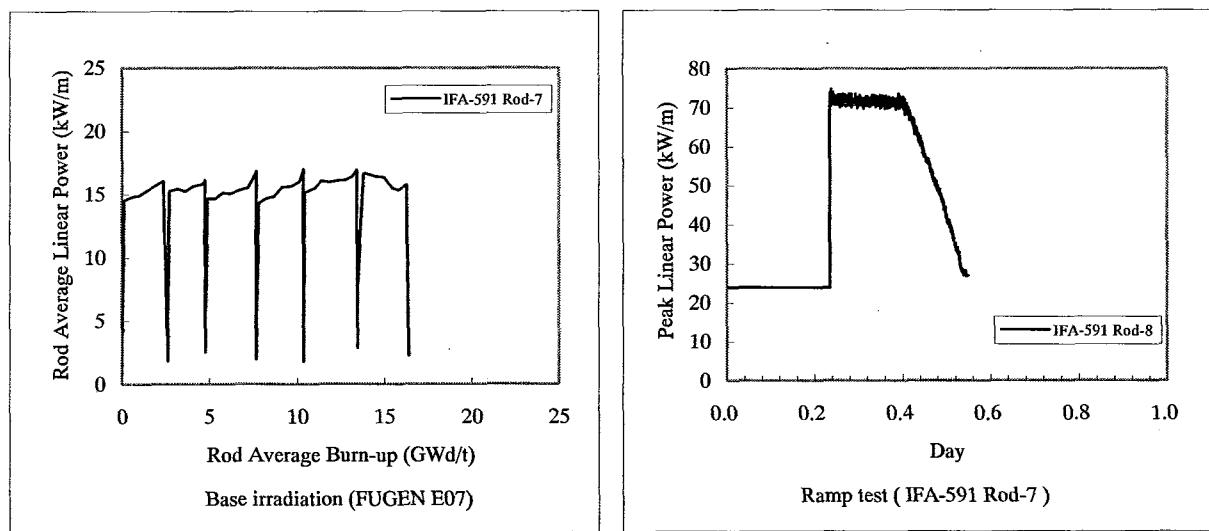


Figure 4-9 (7) History of Rod Average Linear Heat Rate (IFAC-591 Rod-7)

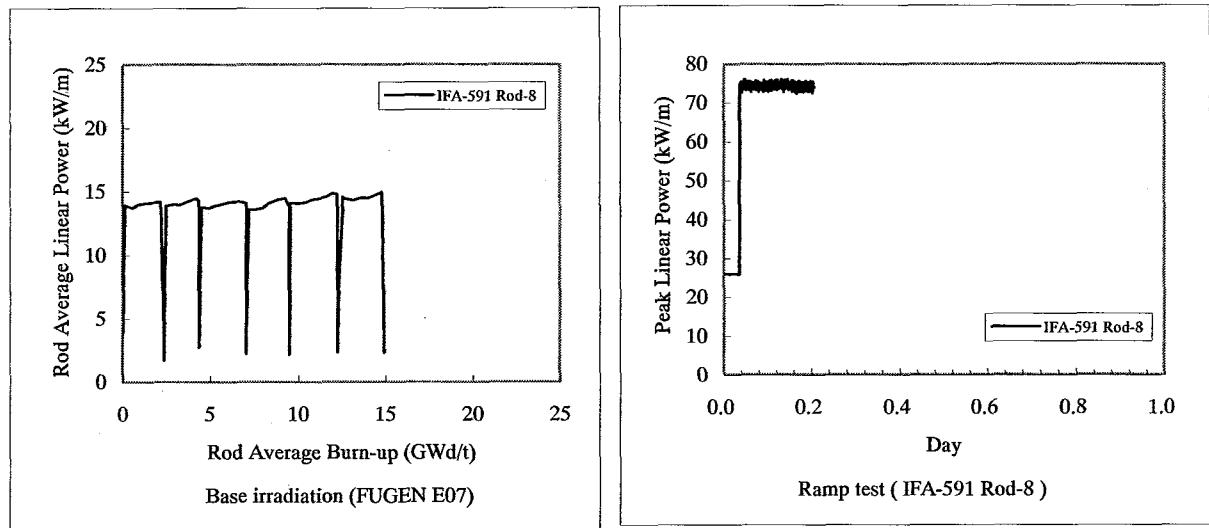


Figure 4-9 (8) History of Rod Average Linear Heat Rate (IFAC-591 Rod-8)

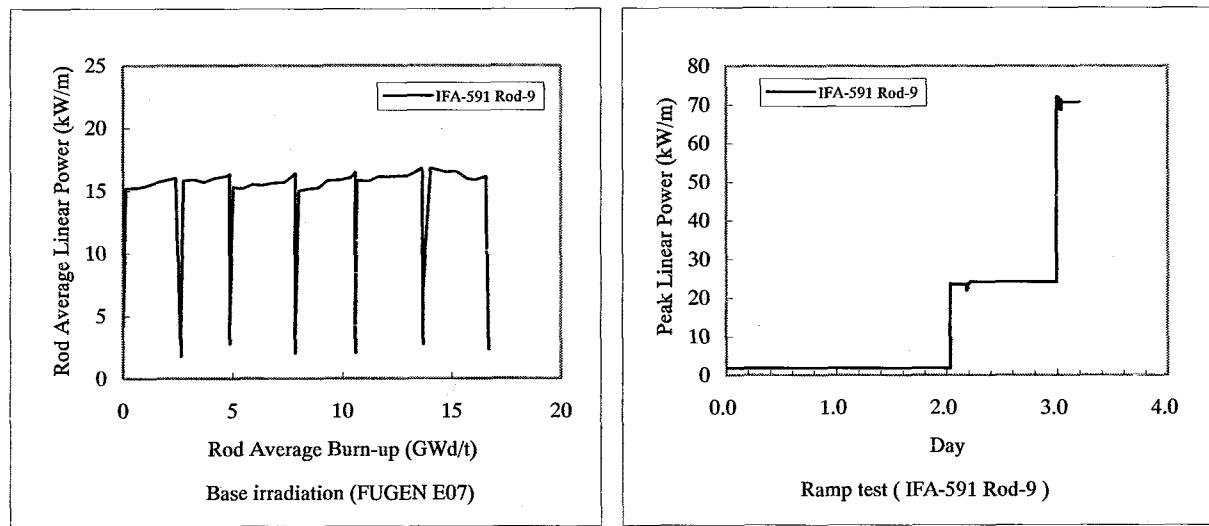


Figure 4-9 (9) History of Rod Average Linear Heat Rate (IFAC-591 Rod-9)

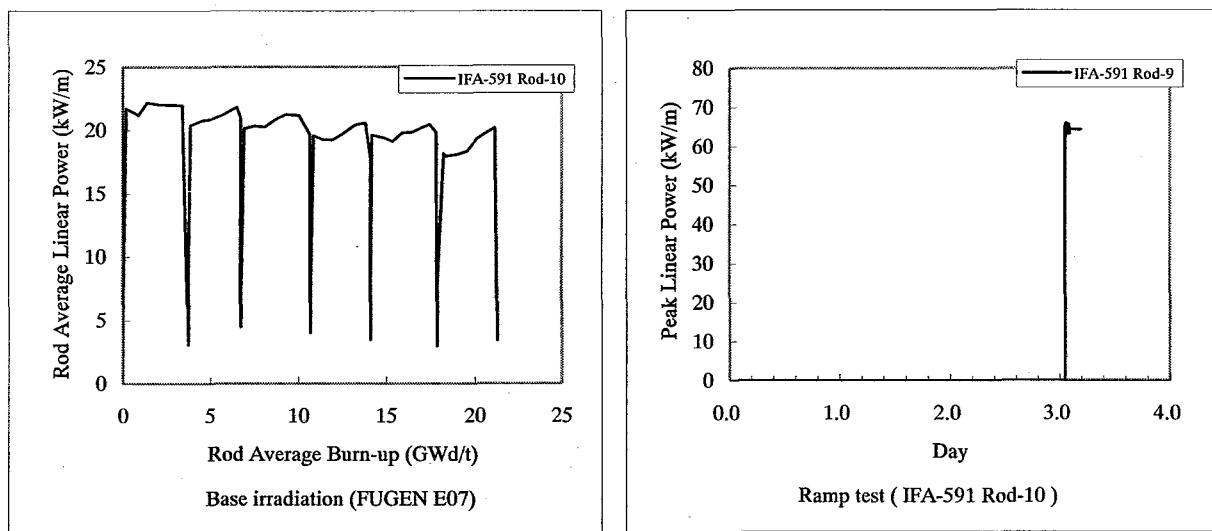


Figure 4-9 (10) History of Rod Average Linear Heat Rate (IF-A591 Rod-10)

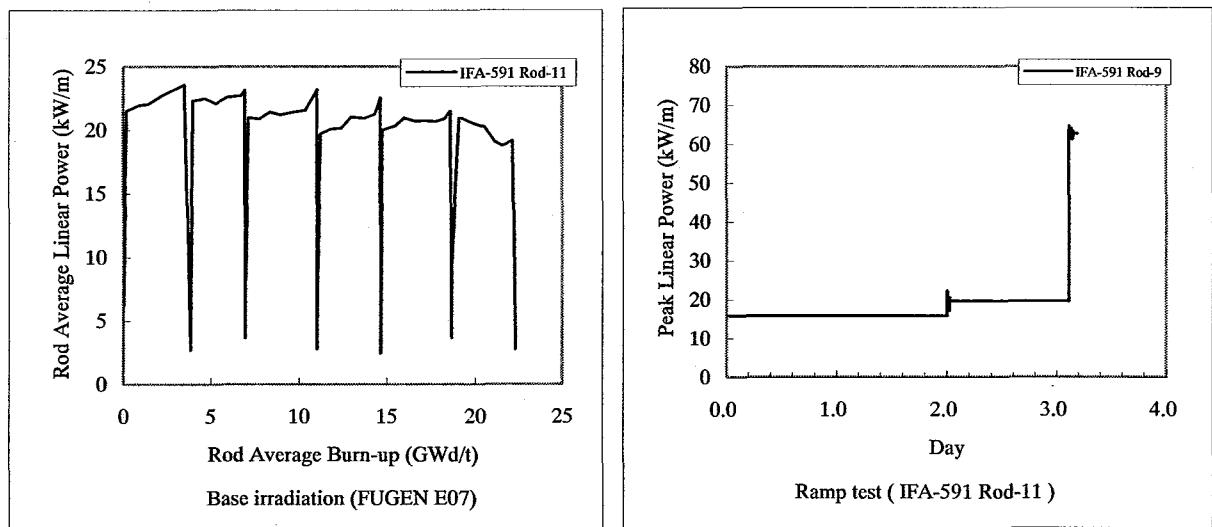


Figure 4-9 (11) History of Rod Average Linear Heat Rate (IF-A591 Rod-11)

Appendix 1

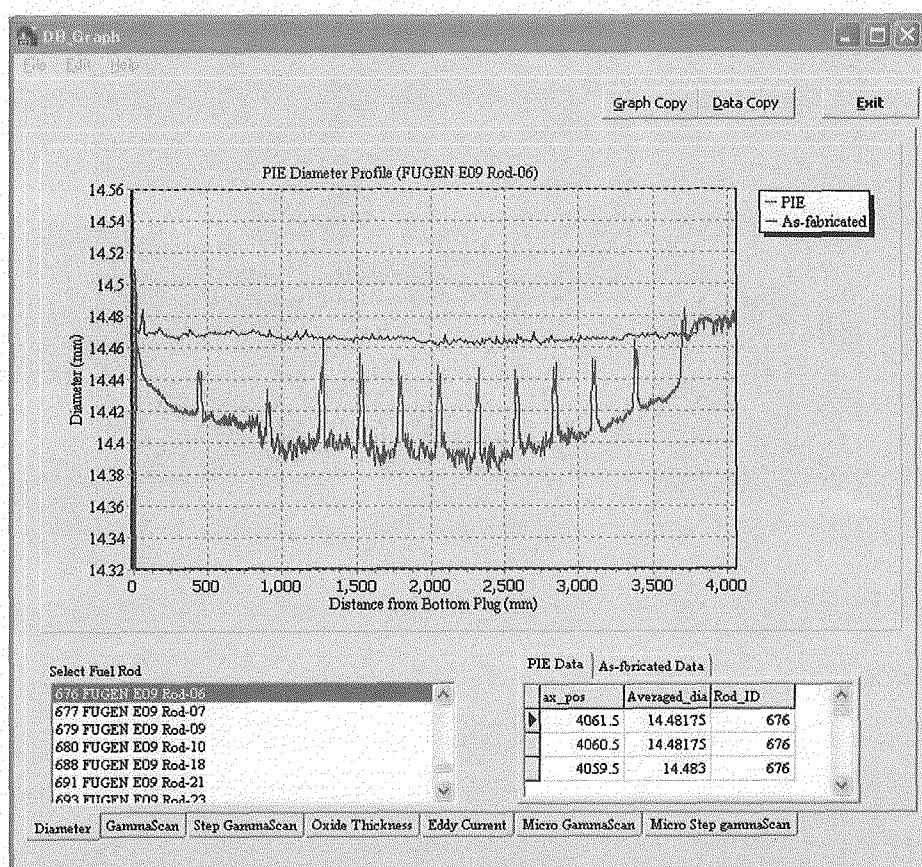
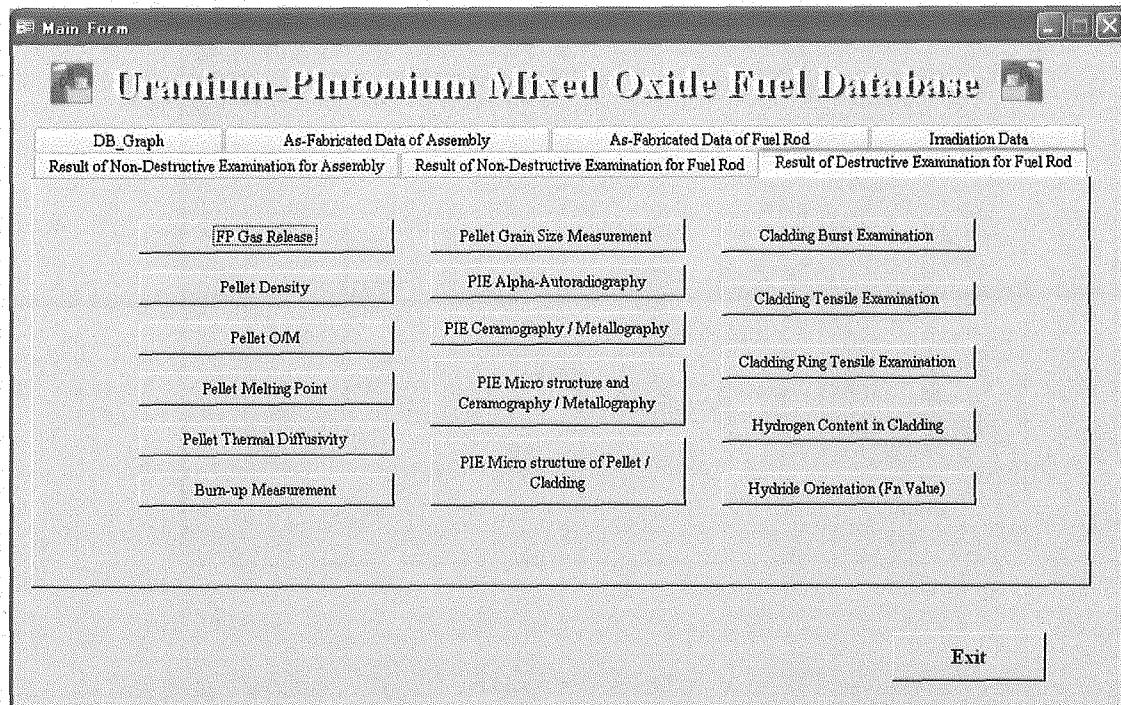


Figure A-1 Typical Image of Uranium-Plutonium Mixed Oxide Fuel Database (1)

Appendix 1

Data of Assembly Dimensions

Reactor Name	Assembly Name	Average Burn-up (GWd/t)	Average Fluence (n/cm ²)	Measurement Angle (Degree)	Overall Length of Assembly (mm)	Bundle Length (mm)	Tie-Plate Length (mm)
FUGEN	E06	26.347	2.822E+21	270		4110.4	
FUGEN	E06	26.347	2.822E+21	0	4409	4109.8	128.3
FUGEN	E06	26.347	2.822E+21	90		4109.7	171
FUGEN	E06	26.347	2.822E+21	180	4409.2	4110.4	128.1
FUGEN	E07	18.266	1.864E+21	180	4405.9	4105.1	170.5
FUGEN	E07	18.266	1.864E+21	90		4105.1	128.8
FUGEN	E07	18.266	1.864E+21	270		4104.9	
FUGEN	E07	18.266	1.864E+21	0	4405.8	4104.9	128.9
FUGEN	E09	37.655	4.400E+21	90		4102.6	
FUGEN	E09	37.655	4.400E+21	270		4103	
FUGEN	E09	37.655	4.400E+21	0	4404.8	4102.8	130.1
							171.9

Select Reactor: FUGEN

Close

PIE Micro structure of Pellet / Cladding

Image copy

Sample No.	Reactor Name	Assembly Name	Rod Name
0101-MMi	FUGEN	E09	Rod-01

Sample ID: 1005

Distance from Upper shoulder of rod Location (mm): 740

Burn-up (GWd/t): 2616

LHR(kW/cm): 1817

Fluence(n/cm²): 4.64E+21

kind: Pellet surface As Etched

Image data Result: Image found and displayed.

Invalidity

PreView

Kind: Invalidity

search

Close

Invalidity

レコード: [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56] [57] [58] [59] [60] [61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74] [75] [76] [77] [78] [79] [80] [81] [82] [83] [84] [85] [86] [87] [88] [89] [90] [91] [92]

Figure A-1 Typical Image of Uranium-Plutonium Mixed Oxide Fuel Database (2)

国際単位系 (SI)

表1. SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表2. 基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m ²
体積	立方メートル	m ³
速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s ²
波数	メートル	m ⁻¹
密度(質量密度)	キログラム毎立方メートル	kg/m ³
質量体積(比体積)	立法メートル毎キログラム	m ³ /kg
電流密度	アンペア毎平方メートル	A/m ²
磁界の強さ	アンペア毎メートル	A/m
(物質量の)濃度	モル毎立方メートル	mol/m ³
輝度	カンデラ毎平方メートル	cd/m ²
屈折率(数の)	1	1

表5. SI接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10 ²⁴	ヨ	Y	10 ⁻¹	デシ	d
10 ²¹	ゼタ	Z	10 ⁻²	センチ	c
10 ¹⁸	エク	E	10 ⁻³	ミリ	m
10 ¹⁵	ペタ	P	10 ⁻⁶	マイクロ	μ
10 ¹²	テラ	T	10 ⁻⁹	ナノ	n
10 ⁹	ギガ	G	10 ⁻¹²	ピコ	p
10 ⁶	メガ	M	10 ⁻¹⁵	フェムト	f
10 ³	キロ	k	10 ⁻¹⁸	アト	a
10 ²	ヘクト	h	10 ⁻²¹	ゼット	z
10 ¹	デカ	da	10 ⁻²⁴	ヨクト	y

表3. 固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位		
	名称	記号	他のSI単位による表し方
平面角	ラジアン ^(a)	rad	$m \cdot m^{-1} = 1^{(b)}$
立体角	ステラジアン ^(a)	sr ^(c)	$m^2 \cdot m^{-2} = 1^{(b)}$
周波数	ヘルツ	Hz	s ⁻¹
力	ニュートン	N	$N \cdot m^2$
圧力, 応力	パスカル	Pa	$N \cdot m^{-1}$
エネルギー, 仕事, 熱量	ジユール	J	$N \cdot m$
功率, 放射束	ワット	W	J/s
電荷, 電気量	クーロン	C	$m^2 \cdot kg \cdot s^{-2}$
電位差(電圧), 起電力	ボルト	V	W/A
静電容量	フアード	F	C/V
電気抵抗	オーム	Ω	$m^2 \cdot kg \cdot s^{-2} \cdot A^2$
コンダクタンス	シemens	S	V/A
磁束密度	テスラ	T	A/V
インダクタンス	ヘンリー	H	Wb/m^2
セルシウス温度	セルシウス度 ^(d)	°C	Wb/A
光束度	ルクス	lx	$kg \cdot s^{-2} \cdot A^{-1}$
(放射性核種の)放射能	ベクレル	Bq	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
吸収線量, 質量エネルギー	グレイ	Gy	J/kg
一分率, カーマ			$m^2 \cdot s^{-2}$
線量当量, 方向性線量当量, 個人線量当量, 組織線量当量	シーベルト	Sv	J/kg

(a)ラジアン及びステラジアンの使用は、同じ次元であっても異なる性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表4に示されている。

(b)実際に、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“1”は明示されない。

(c)測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。

(d)この単位は、例としてミリセルシウス度m°CのようにSI接頭語を伴って用いても良い。

表4. 単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa·s	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	N·m	$m^2 \cdot kg \cdot s^2$
表面張力	ニュートン每メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1} = s^{-1}$
角加速度	ラジアン毎平方秒	rad/s ²	$m \cdot m^{-1} \cdot s^{-2} = s^{-2}$
熱流密度, 放射照度	ワット每平方メートル	W/m ²	$kg \cdot s^{-3}$
熱容量, エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量(比熱容量)	ジュール每キログラム	J/(kg·K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エンントロピー	一		
質量エネルギー(比エネルギー)	ジュール每キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット每メートル毎ケルビン	W/(m·K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール每立方メートル	J/m ³	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト每メートル	V/m	$N \cdot m \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン每立方メートル	C/m ³	$m^{-3} \cdot s \cdot A$
電気変位	クーロン每平方メートル	C/m ²	$m^{-2} \cdot s \cdot A$
誘電率	ファラード每メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー每メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール每モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエンントロピー	ジュール每モル每ケルビン	J/(mol·K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
モル熱容量	ビン		
照射線量(X線及びγ線)	クーロン每キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ每秒	Gy/s	$m^2 \cdot m^{-2}$
放射強度	ワット每ステラジアン	W/(m ² ·sr)	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3} = m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット每平方メートル每ステラジアン	W/(m ² ·sr)	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3} = kg \cdot s^{-3}$

表6. 国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h=60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	$1^\circ = (\pi/180) \text{ rad}$
分	'	$1' = (1/60)^\circ = (\pi/10800) \text{ rad}$
秒	"	$1'' = (1/60)' = (\pi/648000) \text{ rad}$
リットル	L	$1L=1 dm^3=10^{-3} m^3$
トン	t	$1t=10^3 \text{ kg}$
ネーベル	Np	$1Np=1$
ベル	B	$1B=(1/2) \ln 10 (Np)$

表7. 国際単位系と併用されこれに属さないSI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	$1eV=1.60217733(49) \times 10^{-19} J$
統一原子質量単位	u	$1u=1.6605402(10) \times 10^{-27} kg$
天文単位	ua	$1ua=1.49597870691(30) \times 10^{11} m$

表8. 国際単位系に属さないが国際単位系と併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里	mi	1海里=1852m
ノット	kn	1ノット=1海里毎時=(1852/3600)m/s
アーチル	a	$1a=1 dm^2=10^{-2} m^2$
ヘクタール	ha	$1ha=1 hm^2=10^4 m^2$
バール	bar	$1bar=0.1 MPa=100kPa=1000hPa=10^5 Pa$
オングストローム	Å	$1 Å=0.1 nm=10^{-10} m$
バーン	b	$1b=100 fm^2=10^{-28} m^2$

表9. 固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	$1 erg=10^{-7} J$
ダイナ	dyn	$1 dyn=10^{-5} N$
ボアズ	P	$1 P=1 dyn \cdot s/cm^2=0.1 Pa \cdot s$
ストークス	St	$1 St=1 cm^2/s=10^{-4} m^2/s$
ガウス	G	$1 G=10^{-4} T$
エルステッド	Oe	$1 Oe=(1000/4\pi) A/m$
マクスウェル	Mx	$1 Mx=10^{-8} Wb$
スチル	sb	$1 sb=1 cd/cm^2=10^4 cd/m^2$
ホルト	ph	$1 ph=10^4 lx$
ガル	Gal	$1 Gal=1 cm/s^2=10^{-2} m/s^2$

表10. 国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリ	Ci	$1 Ci=3.7 \times 10^{10} Bq$
レントゲン	R	$1 R=2.58 \times 10^{-4} C/kg$
ラド	rad	$1 rad=1 cGy=10^{-2} Gy$
レム	rem	$1 rem=1 cSv=10^{-2} Sv$
X線単位	IX unit	$1 IX unit=1.002 \times 10^{-4} nm$
ガンマ	γ	$1 \gamma=1 nT=10^{-9} T$
ジャンスキー	Jy	$1 Jy=10^{-26} W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ	fermi	$1 fermi=1 fm=10^{-15} m$
メートル系カラット	Torr	$1 metric carat=200 mg=2 \times 10^{-4} kg$
トーラ	atm	$1 Torr=(101325/760) Pa$
標準大気圧	cal	$1 atm=101325 Pa$
カリ	μ	$1 μ=1 μm=10^{-6} m$