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ABSTRACT

ATR, a heavy-water moderated boiling-light-water cooled reactor developed in Japan, is a unique reactor with outstanding flexibility regarding nuclear fuel utilization, because it has superior properties concerning the utilization of plutonium, recovered uranium and depleted uranium.

The development of this type of reactor is expected to contribute both to the stable supply of energy and to the establishment of plutonium utilization in Japan.

Much effort has been and will be made on the development of Plutonium utilization technology in ATR, which is supported by the experience of MOX fuel utilization in the Fugen and by following R & D.

(1) Clarifying characteristics of MOX fueled core on reactor physics and thermohydraulics, especially on reactor physics
(2) Clarifying MOX fuel performance
(3) Development of design, fabrication and inspection of MOX fuel

Fugen, which is the prototype reactor of 165 MWe output using plutonium uranium mixed-oxide(MOX) fuel, has been in commercial operation since March 1979, achieving about 60% of average load factor in more than eight years.

The potential of MOX fuel has been demonstrated successfully by the operation of the Fugen. A total of 334 MOX and 342 UO_2 fuel assemblies were loaded into the core during ten refuelling times. The maximum burn-up of fuel has reached 18,500 MWd/t and no fuel has failed.

CONTENTS

1. INTRODUCTION

ATR, a heavy-water moderated boiling-light-water cooled reactor developed in Japan, is a unique reactor with outstanding flexibility regarding nuclear fuel utilization, because it has superior properties concerning the utilization of plutonium, recovered uranium and depleted uranium.

Fugen, which is the prototype reactor of 165 MWe output using plutonium uranium mixed-oxide(MOX) fuel, has been developed by the Power Reactor & Nuclear Fuel Development Corporation (PNC) with support of the Electric Power Development Company (EPDC), the Government, utilities and other organizations. The Fugen (Fig. 1) has been in commercial operation since March 1979, achieving about 60% of average load factor in more than eighy years.

The potential of MOX fuel has been demonstrated successfully by the operation of the Fugen. A total of 334 MOX and 342 UO_2 fuel assemblies were loaded into the core during ten refuelling times. The maximum burn-up of fuel has reached 18,500 MWd/t and no fuel has failed.

A 606 MWe ATR Demonstration Plant Program is now going on with the target of getting into commercial operation in March 1997. The EPDC is responsible for its design, construction and operation with support of the government, utilities and the PNC. R & D and MOX fuel fabrication are and will be carried out by the PNC.

Table 1 shows brief history of the ATR Development.

2. ROLE OF ATR IN JAPAN

In Japan, 33 light water reactors (LWRs) are now being operated and LWRs will be mainly used in the near future. Plutonium and depleted uranium will then be stored in the form of LWRs' spent fuel or plutonium and depleted uranium themselves by reprocessing.

In principle, plutonium obtained by reprocessing of spent fuel will be utilized in fast breeder reactors (FBRs), but it is presumed that long time will be required before the practical use in FBRs. Under these circumstances, the stepwise development of utilization of plutonium will be realized that the program for the utilization of plutonium in certain scale in LWRs and in ATRs will be promoted as soon as possible for the purpose of consolidating the wide-range technological system related to the utilization of plutonium, which is indispensable in the future era of the FBRs, and of attempting to improve the overall economy of the nuclear fuel cycle.

The ATR is a type of reactor with outstanding flexibility regarding nuclear fuel utilization, because it has superior properties concerning the utilization of plutonium, recovered uranium and depleted uranium. Furthermore MOX fuel could be loaded in full core.
Further development for commercial deployment will be promoted in this connection by attempting to improve the economy in view of the full existence of the technological foundation to consolidate it as an independent nuclear technique of Japan. Moreover, an attempt will be made to sophisticate the heavy water reactor technology of Japan through such development.

Using plutonium in the ATR, at the same time, will contribute to the establishment of plutonium utilization technology whose associated fields are listed in the following.

(a) MOX fuel utilization in reactors
(b) Physical protection and plutonium management in nuclear power plants and other facilities associated
(c) MOX fuel fabrication

(d) MOX fuel reprocessing

(e) MOX fuel transportation

(f) Public acceptance for plutonium utilization

Such fuel utilization is shown in Figure 2.

3. PLUTONIUM UTILIZATION CHARACTERISTICS OF ATR

ATR possesses excellent specific characteristics for using plutonium, such as

(1) Plutonium mixed oxide fuel could be loaded in full core, and the amount of natural uranium required for generating unit electricity would be 1/2 to 1/3 of LWRs;

(2) The nuclear characteristics may not be greatly affected by isotopic composition of plutonium. Then, the Fugen could be rather easily operated with little consideration other than keeping the fissile content (^{235}U + plutonium fissile) of fuels.

The isotope ratio of the fissile Plutonium to the total Plutonium recovered from lighy water reactor's spent fuel is in the range of around 68% to 73%.

Effect of plutonium isotopic composition on fuel burn-up in ATR was analyzed using the WIMS-D code with new library.

The result is shown in Figure 3. The fuel burn-up is affected a little by the plutonium isotopic composition, and is changed within about ±250 MWd/t in the case of using plutonium obtained from LWR's spent fuel.

It is considered that the property originates from the characteristics of cross section and η (neutron regeneration rate) for each plutonium isotope and the neutron spectra of ATR.

Figure 4 shows how η of ^{239}Pu, ^{241}Pu and ^{235}U vary by the neutron energy, and it is seen that

(a) η of ^{239}Pu is lower than that of ^{235}U in the resonance region (∿0.3 eV), however, η of ^{239}Pu is getting to almost the same η value of ^{235}U and ^{241}Pu in the well moderated thermal neutron region,

(b) η of ^{241}Pu is higher than those of ^{239}Pu and ^{235}U in the resonance neutron region,

Figure 5 shows fission cross sections of ^{239}Pu, ^{241}Pu, ^{235}U and absorption cross section of ^{240}Pu as a function of neutron energy, from which followings are derived.

(a) ^{239}Pu and ^{241}Pu have a resonance peak cross section at about 0.3 eV,

(b) ^{240}Pu has a resonance peak cross section at about 1 eV,

(c) their cross sections follow a 1/V law in the thermal the region.

Figure 6 shows the neutron spectra and neutron production rates as a function of neutron energy in ATR.

As neutrons are mainly well slowed down in the heavy water moderator region of about 60°C in ATR, the neutron spectra of ATR is softer than that of LWR.

Therefore, ATR can successfully use the recovered plutonium with almost the same physical value of ^{239}Pu, ^{241}Pu and ^{235}U and a little effect of resonance absorption by plutonium, due to the above plutonium characteristics.

These facts may enable us to specify the plutonium fissile enrichment of ATR MOX fuel in the following form with keeping the fuel burn-up constant.

$$^{239}Pu + ^{241}Pu = \text{constant.}$$

4. R & D FOR PLUTONIUM UTILIZATION IN ATR

One of the most important objects in the ATR Development Program is the establishment of Plutonium Utilization Technology, as written in Chapter 2.

Much effort has been and will be made on the development of Plutonium Utilization Technology in ATR, which is supported by the experience of MOX fuel utilization in the Fugen and by following R & D.

(1) Clarifying characteristics of MOX fueled core on reactor physics and thermohydraulics, especially on reactor physics

(2) Clarifying MOX fuel performance

(3) Development of design, fabrication and inspection of MOX fuel

4-1. REACTOR PHYSICS CHARACTERISTICS OF MOX FUELED CORE

R & D on clarifying the reactor characteristics of MOX fueled core have been done using a deutorium critical assembly (DCA), O-arai Engineering Center, PNC, especially on following items.

(1) Power and neutron flux distributions in the core and fuel assembly

(2) Reactivity coefficients, such as the coolant void reactivity coefficient, etc.

(3) Control rod worth and its effect on the power distribution of adjacent fuel assemblies

Among R & D done in the DCA, Figure 7 shows the relationship between average reaction rate in fuel and its macroscopic cross section (2,200 m/s). The data of MOX fuels, 5s, 8s, and 8r (Table 2), are on a line, which would mean that ^{239}Pu ^{241}Pu have almost the same characteristics of thermal neutron reaction rate against their resonances and ^{240}Pu may have little effect on reaction rate within low enriched MOX fuels.

Design and reactor operation codes have been developed and modified, based on the above experiments and operation data in the Fugen.

4-2. MOX FUEL PERFORMANCE

In order to clarify MOX fuel performance in reactors and to develop design codes of MOX fuel, irradiation tests and post-irradiation tests have been carried out, as shown in Table 3. A spent MOX fuel assembly of the Fugen is now under post-irradiation testing, and two more spent MOX fuel assemblies are planned to be examined.

As far as R & D on MOX fuel assemblies of the 606 MWe Demonstration Plant are concerned, one assembly is now being irradiated at the SGHWR, UKAEA, and three assemblies have been loaded in the Fugen in 1985 and two more assemblies in 1987.

MOX fuel performance would be affected by irradiated conditions in the reactor and quality of MOX fuel. However, based on tests' results obtained until now, it may be said that MOX fuel performance would be within UO_2 fuel performance evaluated by its design codes.

4-3. FABRICATION OF ATR MOX FUEL

MOX fuel assemblies of the Fugen are fabricated in the ATR Line in the plutonium Fuel Fabrication Facility (PFFF) at the Tokai Works whose capacity is 10 t/y. Design of a new ATR Line with the capacity of 40 t/y has been done, based on experiences and R & D obtained in the ATR Line. The new ATR Line will supply MOX fuel assemblies for both the Fugen and ATR demonstration plant. Many systems in the new ATR Line are designed to be automated to cut down the fuel fabrication cost and radiation exposure of operators.

5. EXPERIENCE OF MOX FUEL UTILIZATION IN THE FUGEN

5-1. PLANT DESCRIPTION AND OPERATION EXPERIENCE

The main parameters of the Fugen are listed in Table 4 and the schematic flow diagram is shown in Figure 8. The reactor has two independent coolant circuits, each consisting of a steam drum, an inlet header, two recirculation pumps and associated pipes. Each of 224 cluster-type fuel assemblies is loaded into a vertical Zr-2.5%Nb alloy pressure tube.

Four kinds of standard fuels are loaded in the core: MOX fuel Type A and Type B of different enrichment. Besides these fuels, four special fuel assemblies (UO_2 fuel) are also used, which contain specimens of the pressure tube material for irradiation tests. The fuel assembly, as shown in Figure 9, consists of 28 Zry-2-clad fuel rods which are spaced by 12 Inconel spring-grid-type spacers.

During routine operations, the reactor thermal power is controlled to maintain the rated electric power. The electrohydraulic control system controls the turbine control valves to maintain constant steam pressure and turbine rotational speed. The water level in the steam drum of each loop is controlled by three-element signals, i.e. main steam flow, feedwater flow and the steam drum water level.

Core reactivity is controlled by 49 motor-driven control rods and a control system of liquid poison (^{10}B) concentration in the moderator. Four of the control rods are automatic regulating rods, each of which is installed in the central region of each quadrant of the core. The liquid poison concentration is increased by injecting ^{10}B into the dump tank of the heavy-water circuit, and reduced by passing the heavy-water through the resin beds.

As shown in Figure 10, the Fugen has continued stable fullpower operation except during refuelling and scheduled maintenance shutdown. The Fugen has generated a total of more than ten million megawatt-hours of electricity since it was first synchronized.

Seventy-two per cent of the load factor was achieved in the fiscal year of 1979. The load factors for the fiscal years of 1980 and 1981, however, were 40% and 41%, respectively, due to the repair work for stress corrosion cracking of the piping. Hence, the overall electrical load factor for the past eight years (April 1979 - March 1987) was about 60%.

The Fugen has been operated for more than 43,000 hours, and no trouble has occurred in the main components (turbine generator, recirculation pumps, main isolation valves). No leakage of heavy-water has as yet occurred.

5-2. FUEL PERFORMANCE

A total of 334 MOX and 342 UO_2 fuel assemblies, including 12 special fuels were loaded into the core, and 216 MOX and 236 UO_2 fuel assemblies, including eight special fuels, have been discharged. After the third refuelling, the type B fuel assemblies, which have higher fissile content, were loaded to reduce the fuel cycle cost by obtaining higher burn-up. At present, the maximum burn-up of MOX fuel is 18,500 MWd/t, and no leaking fuel has been found for about 2,000 effective full power days of operation up to July 1987.

(1) On-Site Inspection

Visual and dimensional inspection of 120 MOX fuel assemblies discharged, as well as 136 UO_2 ones have been carried out at the Fugen site by the fuel inspection instrument in spent fuel storage pool (FIP).

FIP is composed of the outer fuel rod-rod gap measuring device, the periscope with ITV-monitor system and The associated driving mec-anisms. A schematic drawing of FIP is shown in Figure 11. The outer fuel rod-rod gap is measured by a contact type measuring device, and the range of measurement is 0.9-2.6 mm and its accuracy or precision is ±0.1mm. Measuring point of rod-rod gaps (16 outer rod gaps) is in the middle point of each spacer spans (13 spacer spans), and the number of measuring point of rod-rod gaps is 208 points per fuel assembly.

Results of on-site inspection are as follows:

Fuel rod was covered rather thickly with red-brownish crud, while spacer and tie plate were covered thinly, but no significant change such as break, stricken mark and deformation, was observed at all.

The fuel rod-rod gaps became smaller due to crud adhering. On the other hand, where a measured fuel rod-rod gap was relatively small, adjacent gap was reversely large compared to that before irradiation, which may be caused by fuel rod bowing. Average of rod-rod gaps and their standard deviations at each spacer span were plotted against irradiation time, as shown in Figure 12.

In the result, average rod-rod gaps are getting smaller with the increase of irradiation time. The decrease of average rod-rod gaps is mainly caused by crud adhering amount, which will increase proportional to irradiation time. Standard deviation of rod-rod gaps of whole fuel assembly, as shown in Figure 13, is considered to indicate a degree of fuel rod bowing, and is getting somewhat larger with fuel burn-up. In Figure 12, two peaks in the standard deviation (middle point of each spacer span) are found at the central part and lower part of the fuel assembly.

Crud deposition and rod bowing mentioned above would slightly affect heat removal, because crud is adhering lightly and fuel rod distances are kept wide enough to remove the heat generated in the fuel.

(2) Post-Irradiation Examination

The Post-Irradiation Examination (PIE) for the MOX fuel burned to 13,600 MWd/t has been done at to the Tokai Laboratory of Japan Atomic Energy Research Institute (JAERI) in October 1983. The PIE was finished at the end of December 1985.

Almost all of crud was easily removed by the ultrasonic washing of the fuel assembly to investigate the state of crud prior to PIE. Non-destructive tests such as visual inspection, dimensional inspection and γ-scanning, and destructive tests such as puncture test and metallographical test have been carried out.

The results of γ-scanning, profilometry and fission gas release rate (FGR) are shown in Figures 14, 15 and 16, respectively. Figure 14 shows the axial distribution of γ-ray activity of fuel rod, which depends on local burn-up.

Figure 15 shows the creep down across full length of fuel rod influenced by outer pressure. Figure 16 shows that FGR of MOX feels (Fugen P06 and SGHWR Type-D) depends on the maximum linear heat rate of the fuel and has a similar tendency as that of UO fuels. These phenomena are demonstrated at inpile pressure measurement of Halden IFA-529.

In the puncture test of Fugen P06, the analysis of the collected gas shows that the constituents of the gas in the fuel rod is composed of He which is filled in the fuel rod at the fabrication, Xe and Kr and that the amount of absorbed gases such as N_2, O_2, H_2O is very small.

Henceforth, the PIE of the MOX fuel assembly burned to 18,200 MWd/t is to be made.

5-3. CHARACTERISTICS OF MOX FUELED CORE

In the initial core, 96 MOX fuel assemblies were loaded into the central region, with 124 UO_2 fuel assemblies loaded around them. The scatter loading scheme, with a quadrant symmetry, was selected for refuelling patterns. One-third of the core will be refuelled annually in the equilibrium core.

At present the number of MOX fuel assemblies loaded in the 10th cycle core, is 130 more than 50% of total fuel assemblies in the core.

(1) Reactor Characteristics of Fugen

In Fugen, by adopting the scatter loading scheme or fuel shuffling, it is almost unnecessary to insert the control rods in order to suppress the radical power peaking.

Fuel shuffling has been actively adopted since 10th cycle and the power flattening has been successfully achieved. The maximum linear heat generating rate (MLHGR) was controlled below 495 W/cm throughout all these cycles.

While this type of heavy-water reactor tends to have a large positive void reactivity coefficient, the coolant void reactivity coefficient of the Fugen is very small due to the use of MOX fuel.

The power coefficients, measured in each cycle by reducting the power level by about 5%, are between -4×10^{-5} and -9×10^{-5} k/k% power. These power coefficients are dominated by the negative fuel temperature coefficient, and the coolant void coefficient is too small to contribute to the power coefficient. As the negative power coefficient is almost unchanged with burn-up, the reactor can be controlled satisfactorily by a simple automatic power control system.

(2) Core Management Analysis

Plutonium is produced as the result of neutron capture in ^{238}U and subsequent beta decays to ^{239}Pu. The isotopes ^{240}Pu, ^{241}Pu, ^{242}Pu and ^{243}Pu are formed from successive neutron capture.

^{241}Am, which is the product of the decay of ^{241}Pu with a half-life of 14.4 years, has a large neutron capture cross section in the thermal energy region which is nearly equal to that of ^{10}B. Therefore, the reactor characteristics, especially the burn-up, are influenced by an amount of ^{241}Am in the MOX fuel.

Reactor characteristics of Fugen in consideration of ^{241}Am in MOX fuel have been analyzed using WIMS-D code. Evaluation and adjustment to the WIMS nuclear data library for each plutonium isotope and ^{241}Am have been performed using Fugen operation data, and the results of PIE of Fugen MOX fuel and experiments in the Deuterium Critical Assembly.

① Evaluation of plutonium isotopic composition by PIE

Isotopic composition of irradiated fuel is useful for assessing the nuclear data library of the WIMS-D code.

Owing to the addition of new data files for nuclides ^{238}Pu, ^{243}Pu, ^{244}Pu, ^{241}Am, ^{242m}Am, ^{242}Am, ^{242}Cm etc. to the WIMS nuclear data library as shown in Figure 17 and the adjustment to the ^{239}Pu resonance integral, calculated isotopic composition of plutonium was in good agreement with the experimental result. The result is shown in Table 5. The new data files were prepared from ENDF/B-IV.

② Evaluation of Keff in the start-up tests of the Fugen

The values of K-effective of minimum critical core i.e., a 100 fuel assemblies loaded core and 224 fuel assemblies loaded core in the start-up tests of the Fugen were analyzed in consideration of ^{241}Am in MOX fuel by the WIMS-D code with new library. As shown in Table 6, the calculated values are in good agreement with experimental ones within $\pm$ 0.1% Δk.

③ Evaluation of Keff for each cycle of Fugen

In core management of Fugen, decrease of K-effective caused by ^{241}Pu decay and ^{241}Am accumulation is considered as follows;

a) Elapsed time of newly produced fuel go into service

b) Shutdown period of nuclear reactor due to periodic inspection

c) Formation and annihilation of ^{241}Am during burnup of fuel in service

Analyses of K-effective from 1st cycle core to 8th cycle core of Fugen have been done. The difference of K-effective between calculated values and experimental ones turned out about 0.1% Δk (approximately 0.1 ppm ^{10}B) as shown in Figure 18.

④ Evaluation of Keff in the experiments on DCA

In order to evaluate the effect of ^{241}Am for Keff, the critical experiments have been done using MOX fuel which passed about twelve years after fabrication and contained about 300 ppm of ^{241}Am. The difference of K-effective between calculated values and experimental ones were less than 0.1% Δk.

6. CONCLUSION

The ATR is capable of burning plutonium as well as recovered uranium and depleted uranium. The development of this reactor is expected to contribute both to the stable supply of energy and to the establishment of plutonium utilization in Japan.

The PNC intends to continue Fugen Operations in the future to confirm the design performance of MOX fuel, to accumulate The operating experiences, and to support the ATR demonstration ;lant program.

In parallel with the operations, R & D in order to develop advanced ATR technology are and will be carried out by the PNC.

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Table 1 History of ATR Development

May 1966	Establishment of the National Project for ATR Development (Decision by the JAEC) (Japan Atomic Energy Commission)
Oct. 1967	Establishment of the PNC (Power Reactor and Nuclear Fuel Development Corporation)
Dec. 1970	Construction Commenced at the site of "Fugen"
Mar. 1979	Fugen went into commercial operation at rated power
June 1982	600MWe class ATR Demonstration Plant Program (decided by JAEC)
Aug. 1982	Decision of the Executive Parties (by JAEC) ① Construction and Operation : EPDC (Electric Power Development Co., Ltd.) Supported by the electric Utilities and the PNC ② R & D and Manufacturing of Nuclear Fuel : PNC ③ Cost consultation : Steering Committee on ATR Demonstration Plant Construction Cooperate with Government, Utilities & PNC to make the construction cost and the electricity price down
Aug. 1983	Environmental Survey of the site was Started by the EPDC.
May 1985	ATR Demo. plant Construction Program was Established
Mar. 1986	Fundamental Design of ATR Demo. plant has been Fixed and Siting Negotiation undergoing

Table 2 Pu Content in MOX Fuel for DCA Experiments

	Isotope content, wt%				
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Fuel					
5s, 0.54wt% PuO_2 + UO_2	0.021	90.360	8.640	0.915	0.064
8s, 0.87wt% PuO_2 + UO_2	0.019	90.314	8.682	0.918	0.067
8r, 0.87wt% PuO_2 + UO_2	0.84	64.92	21.77	9.46	3.01

Table 3 MOX Fuel Irradiation Tests by PNC

	Irradiation Plant	Reactor Type	Irradiation Tests	No. of Ass.	Burn-up (MWd/t) Max. Pellet	Burn-up (MWd/t) Ave. Assembly	Max. L.H.R (W/cm)	Pu_f Enrichment (wt %)	Irradiation Period
Test specimens	HBWR	HWR	1FA – 159	1	12,500	9,420	348	2.3	68. 6 – 70. 3
			1FA – 160	1	6,070	5,340	325	2.8	69. 3 – 70. 3
			1FA – 423	1	6,670	5,000	495	0.91	75. 6 – 76.10
			1FA – 514	1	25,600*	22,100*	500	4.64	79. 7 – 85. 3
			1FA – 529	1	22,200*	16,200*	500	6.0	80. 6 – 86. 3
	Saxton	PWR	Saxton	2	8,750	5,340	512	5.0	71.11 – 72. 5
			Saxton	1	6,680	2,830	381	4.0	71.11 – 72. 5
	Saxton–GETR	PWR BWR	Saxton–GETR	–	38,050	25,370	472	4.0, 5.0	71.11 – 76.11
	HBWR	HWR	1FA554/555	1		20,000	492	3.4	85. 7 – 89. 9
Fugen Fuel	SGHWR	HWR	Standard	1	9,860	6,420	489	1.7	75.10 – 77. 4
Demo. Plant Fuel	SGHWR	HWR	Standard	1		15,000	427	1.06	84. 8 – 88. 3
	Fugen	HWR	Standard	3		32,000	492	1.75	85.12 –
	Fugen	HWR	Segment	2		30,000	394	2.25	87. 4 –

Note: Spent fuels of Fugen are under post irradiation testings.

* : at May 1984

Table 4 Reactor data

Reactor type	Heavy water moderated, boiling light water cooled, pressure tube type	
Output	Gross thermal output	557 MWt
	Gross electrical output	165 MWe
Core	Core height	3,700mm
	Core diameter	4,050mm
	Lattice	240mm Square lattice
	Number of fuel channels	224
	Fuel inventory	34 t as metal
Fuel	Fuel material	MOX type A (% Pu fiss.) 0.8/0.8/0.6 MOX type B (% Pu fiss.) 1.6/1.6/1.1 UO_2 type A (% ^{235}U) 1.5/1.5/1.5 UO_2 type B (% ^{235}U) 1.9/1.9/1.9
	Pellet diameter	14.4mm
	Fuel assembly	28 fuel rods, 12 spacers
	Total length of fuel assembly	4,388mm
	Cladding material	Zircaloy - 2
	Cladding thickness (min.)	0.8mm
Pressure tube	Material	Zr - 2.5Wt% Nb alloy
	Inner Inside diameter	117.8mm
	Thickness	4.3mm
	Length	5m
Steam drum	Diameter	2m
	Length	16m
	Material	Low carbon steel clad with stainless steel
Calandria tube	Material	Zircaloy - 2
	Inner Inside diameter	156.4mm
	Thickness	1.9mm
Moderator	Heavy water inventory	160 t
	Heavy water temperature(max.)	70°C
Control rods	Number of control rods	49
	Material	B_4C in stainless steel
	Mechanism	Motor driven wire drum
Primary coolant system	Coolant	H_2O
	Coolant pressure in steam drum	68kg/cm^2
	Coolant temperature in steam drum	284°C
	Coolant flow rate	7,600 t/h
	Steam exit quality (mean)	14%
	Number of cooling loops	2
Primary containment	Configuration	Cylindrical steel
	Diameter	36m
	Height	64m
Turbine System	Steam pressure	63.5kg/cm^2
	Steam temperature	279°C
	Steam flow rate to turbine	910 t/h
	Rotational speed	3,600rev/min.
	Generator rating	200MVA

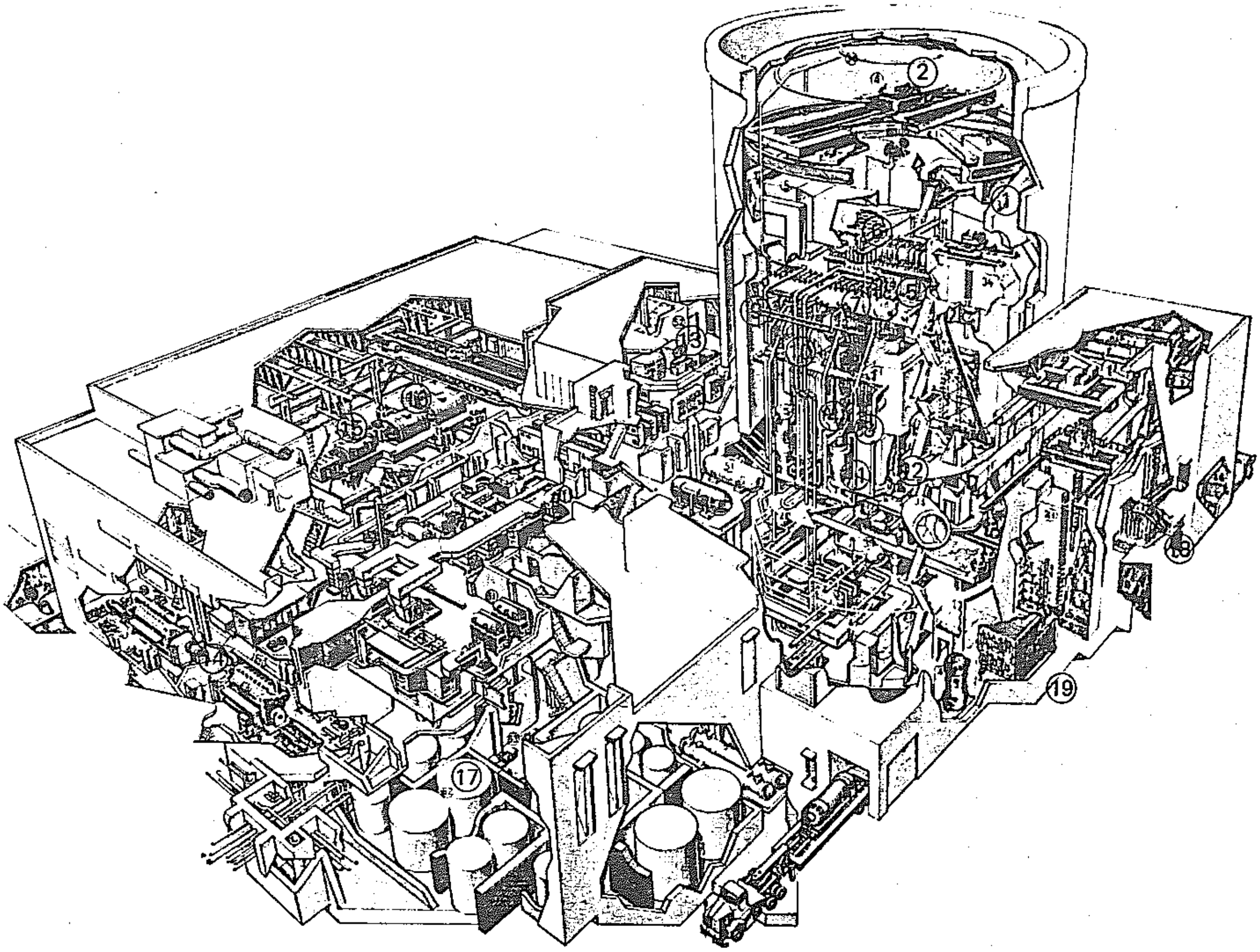
Table 5 Comparison of Isotopic Camposition between Calculation Value and Experiment

Nuclide		$\frac{\text{Exp.} - \text{Cal.}}{\text{Exp.}}$ (%)
U	^{235}U	+2.5
	^{236}U	+1.5
	^{238}U	0.0
Pu	^{238}Pu	−2.5
	^{239}Pu	+2.6
	^{240}Pu	−1.8
	^{241}Pu	−2.0
	^{242}Pu	−2.7

Table 6 Comparison of Keff between Calculation and Experiment of Fugen Start-up Test

Core type	Coolant void fraction (%)	Number of Fuel	$\frac{\text{Cal.} - \text{Exp.}}{\text{Exp.}}$ (%)	Remarks
Minimum critical core	0	MOX : 22	+0.11	^{241}Am : 37ppm
100 channels loading core	0	MOX : 96 SP : 4	−0.04	
Full channels loading core	0	MOX : 96 SP : 4 UO_2 : 124	−0.004	

SP : Special Fuel Assembly (The special fuel assembly contains test specimens of pressure tube material (Zr-2.5%Nb) in its center)



① Containment Vessel
② Polar crane
③ Calandria Tube
④ Inlet Feeder Tube
⑤ Outlet Feeder Tube
⑥ Control Rod Drive Mechanism
⑦ Steam Drum
⑧ Downcomer Pipe
⑨ Feed Water Pipe
⑩ Main Steam Pipe
⑪ Reactor Coolant Pump
⑫ Refueling Machine
⑬ Central Control Room
⑭ Diesel Generator
⑮ 165 MW Generator
⑯ Steam Turbine
⑰ Rad. Waste Storage Tank
⑱ Fresh Fuel Storage Rack
⑲ Spent Fuel Storage Rack

Fig. 1 ATR Prototype Reactor, Fugen (165MWe)

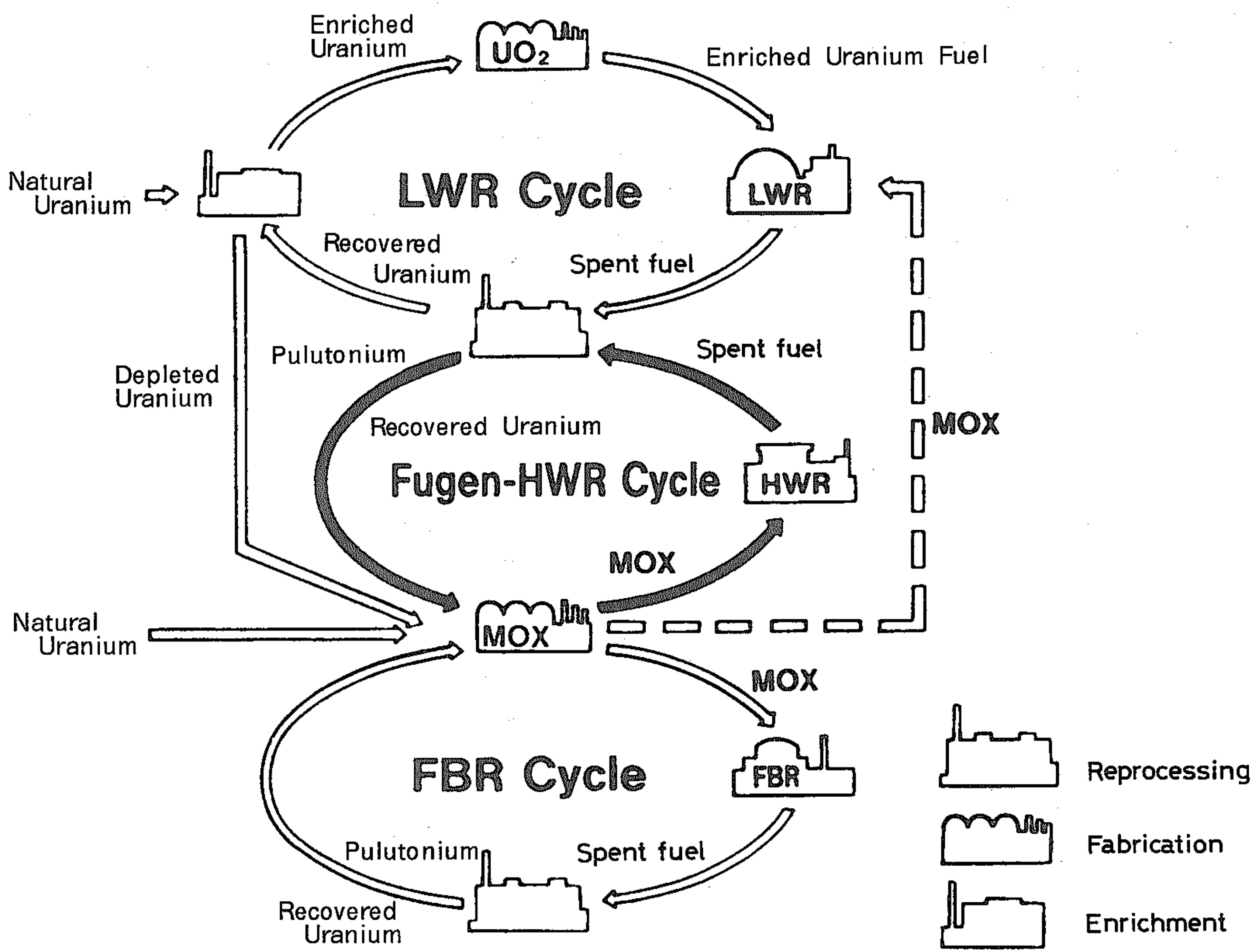


Fig. 2 Nuclear Fuel Cycle in Japan

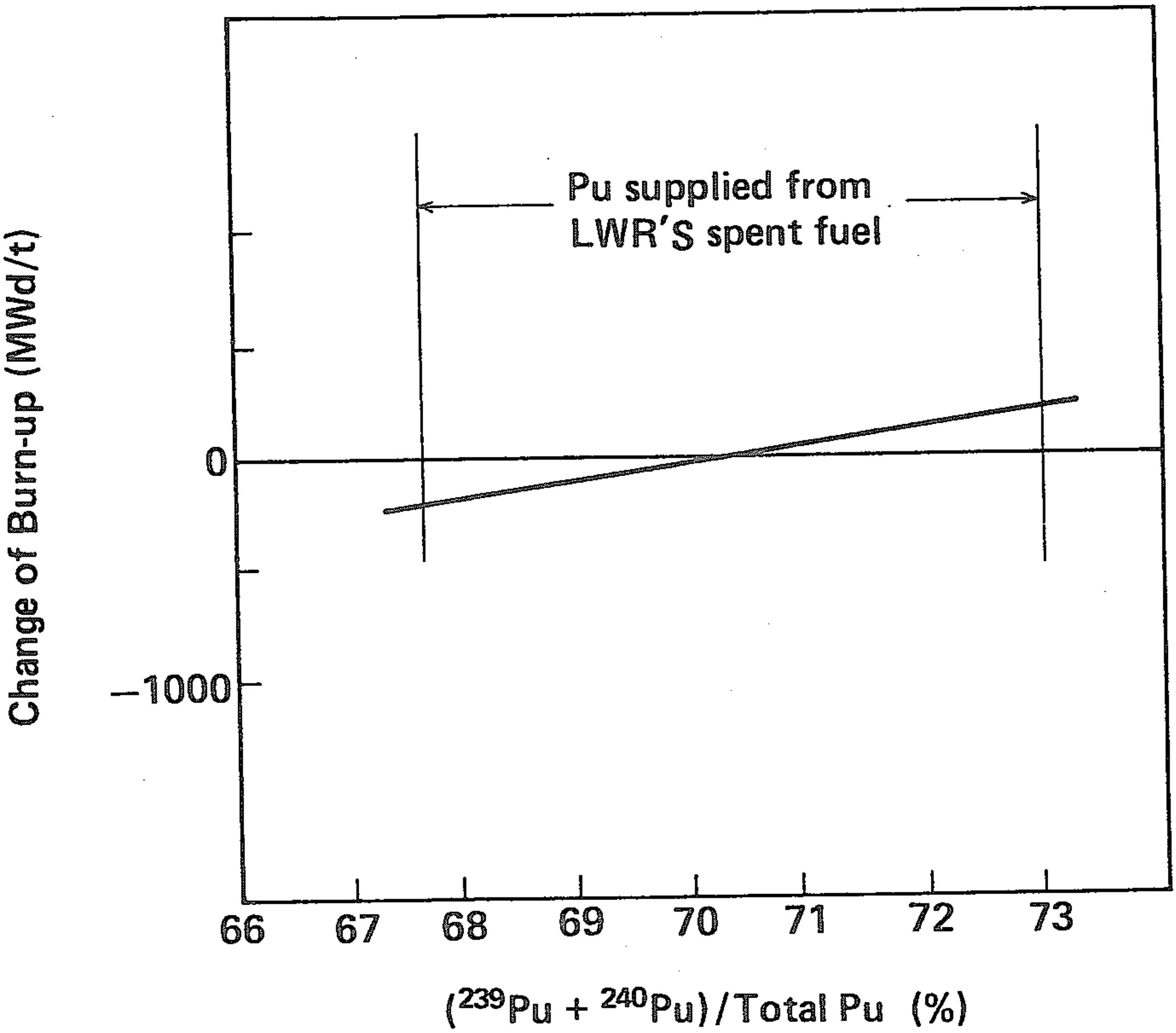


Fig. 3 Effect of Pu Isotopic Composition on Fuel Burn-up (30,000 MWd/t) in ATR

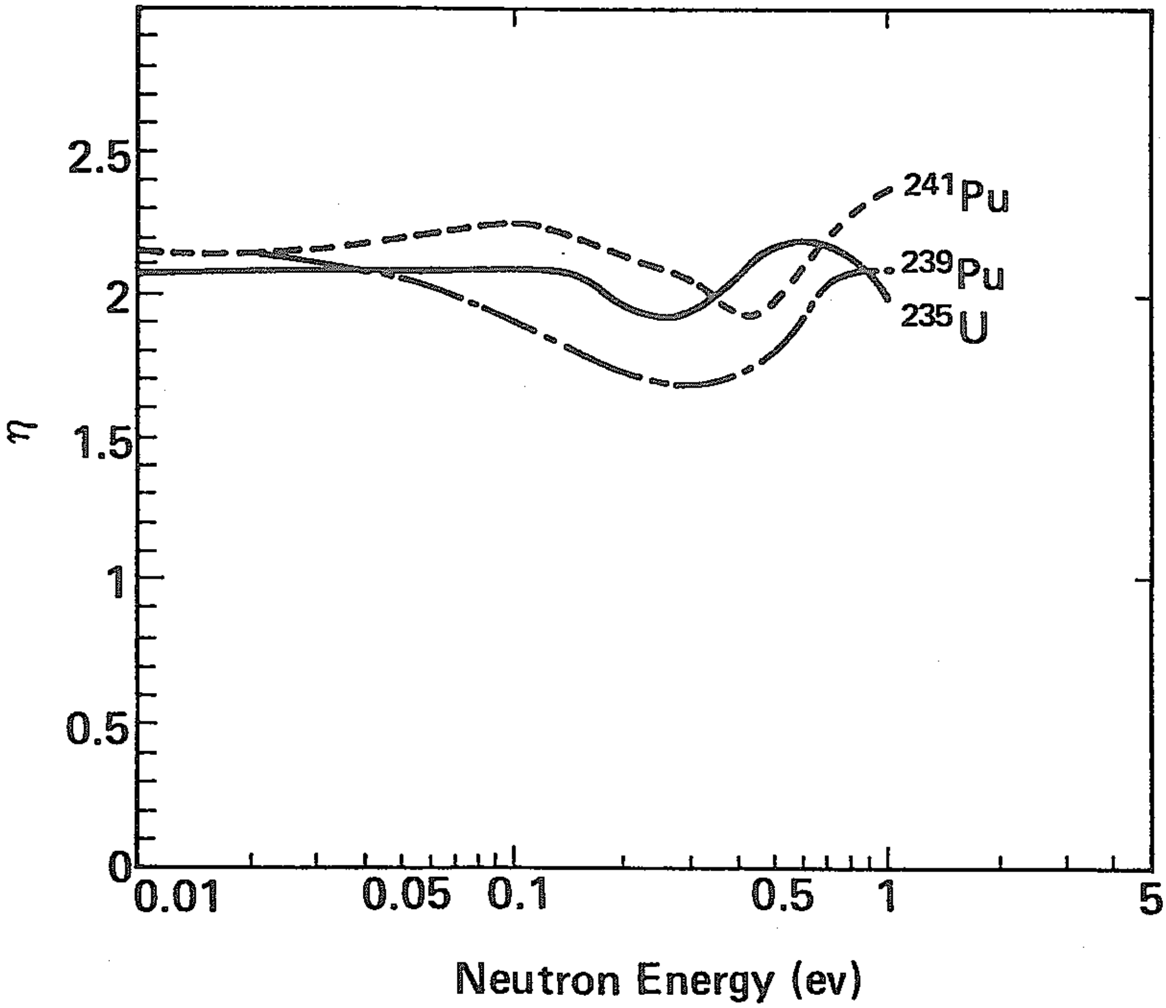


Fig. 4 η of ^{235}U, ^{239}Pu and ^{241}Pu

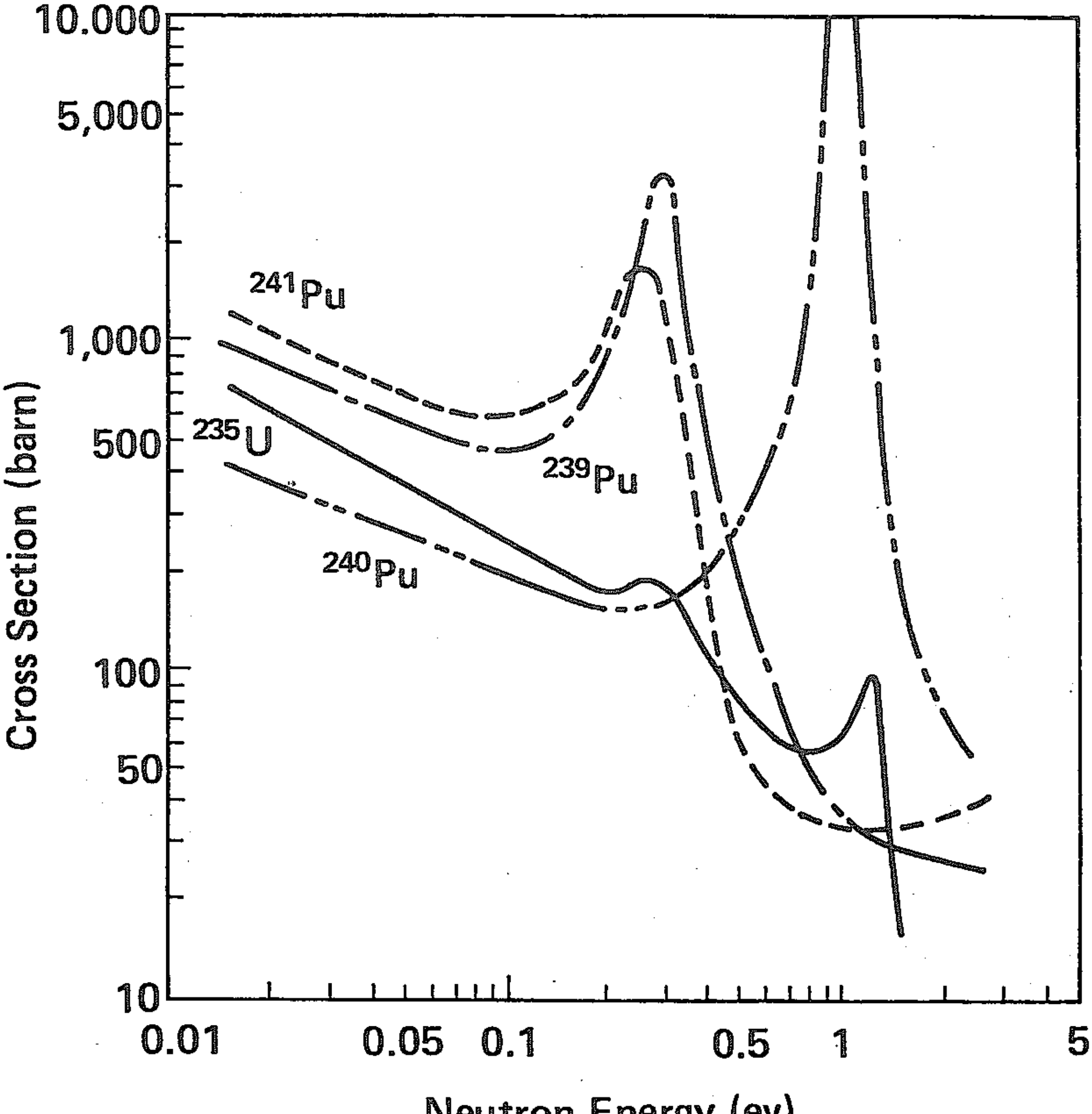


Fig. 5 Fission Cross Sections of ^{235}U, ^{239}Pu, ^{241}Pu and Absorption Cross Section of ^{240}Pu

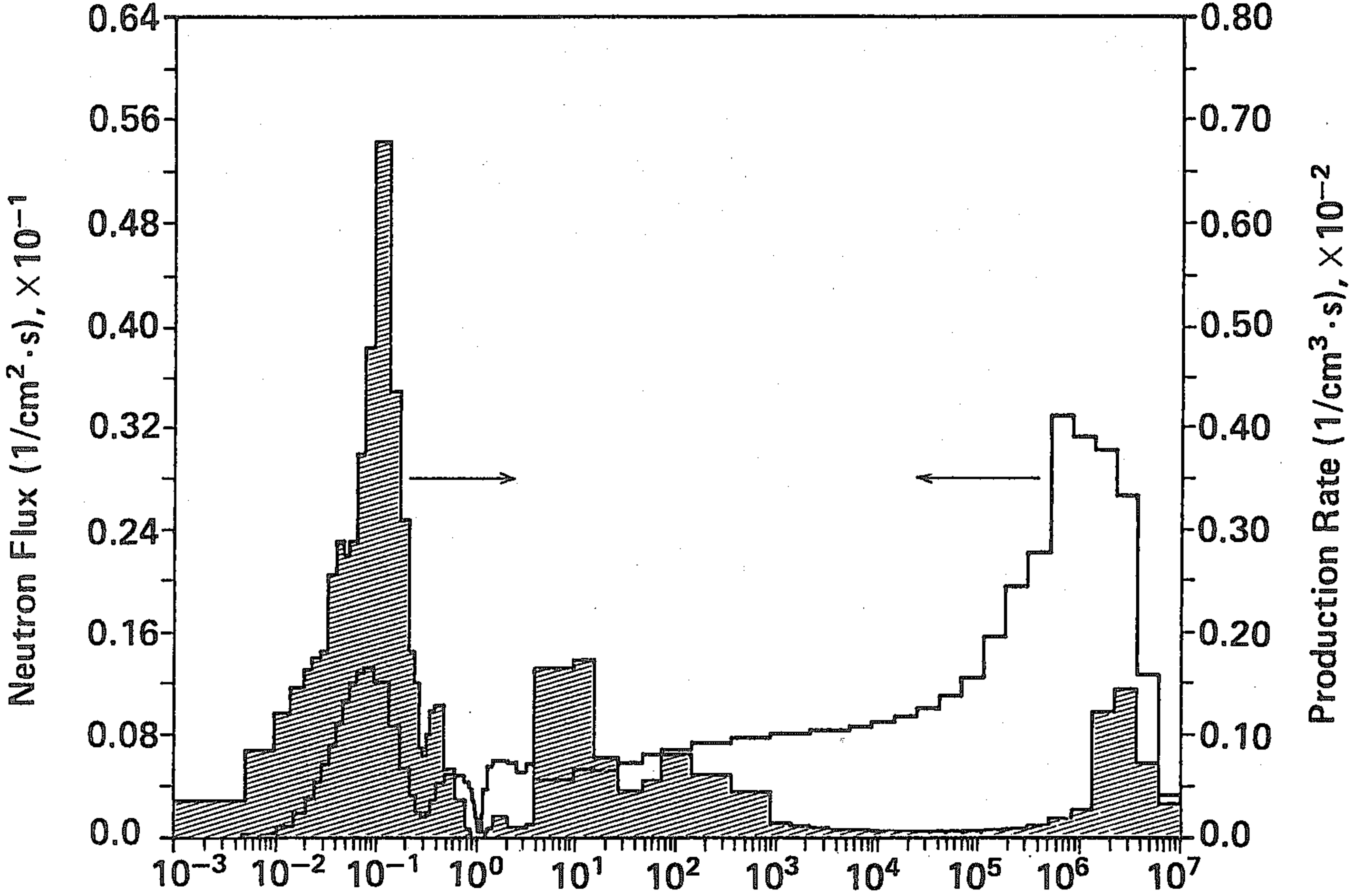


Fig. 6 Neutron Flux and Neutron Production Rate of ATR versus Neutron Energy

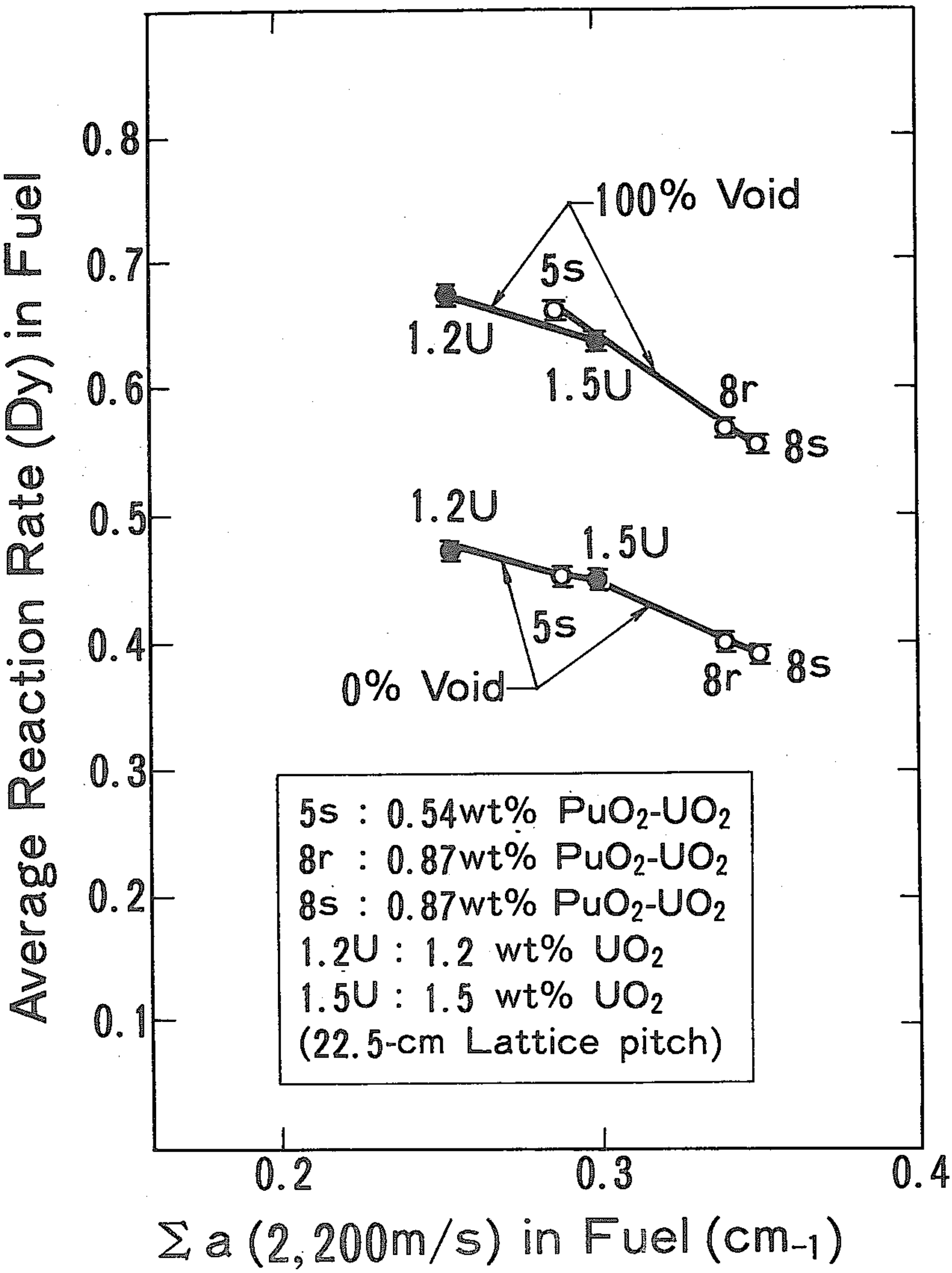


Fig. 7 Relationship between Average Reaction Rate in Fuel and Σa

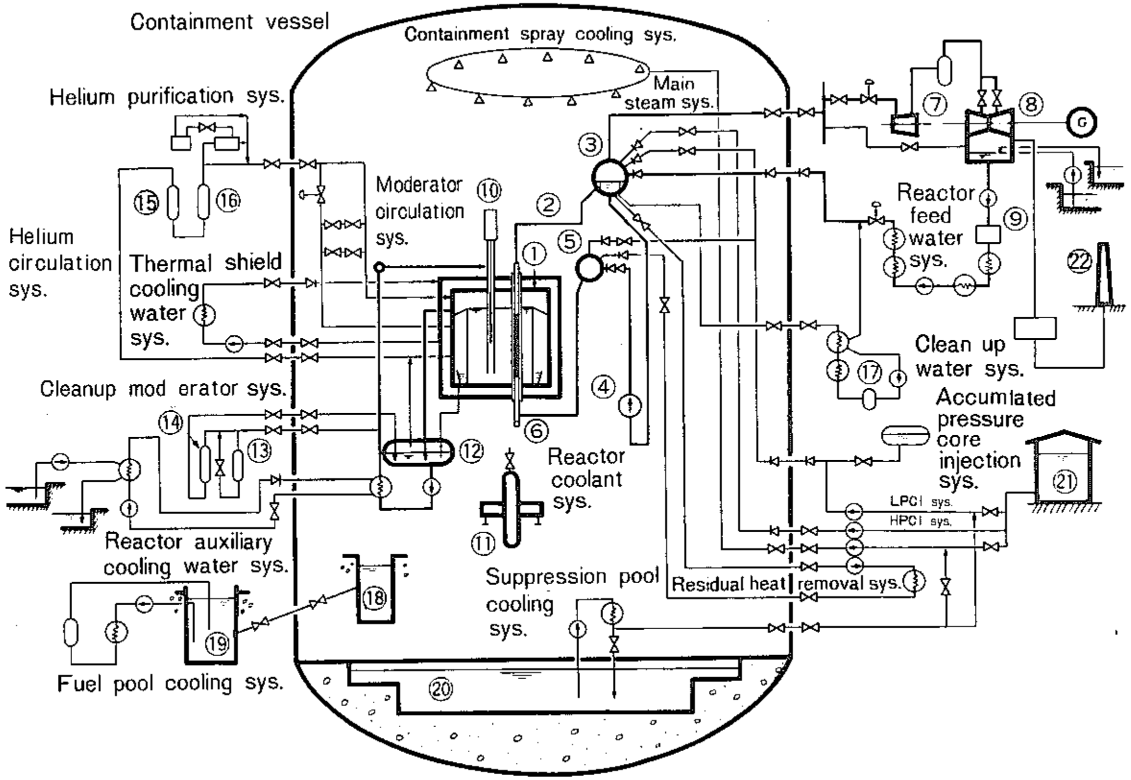
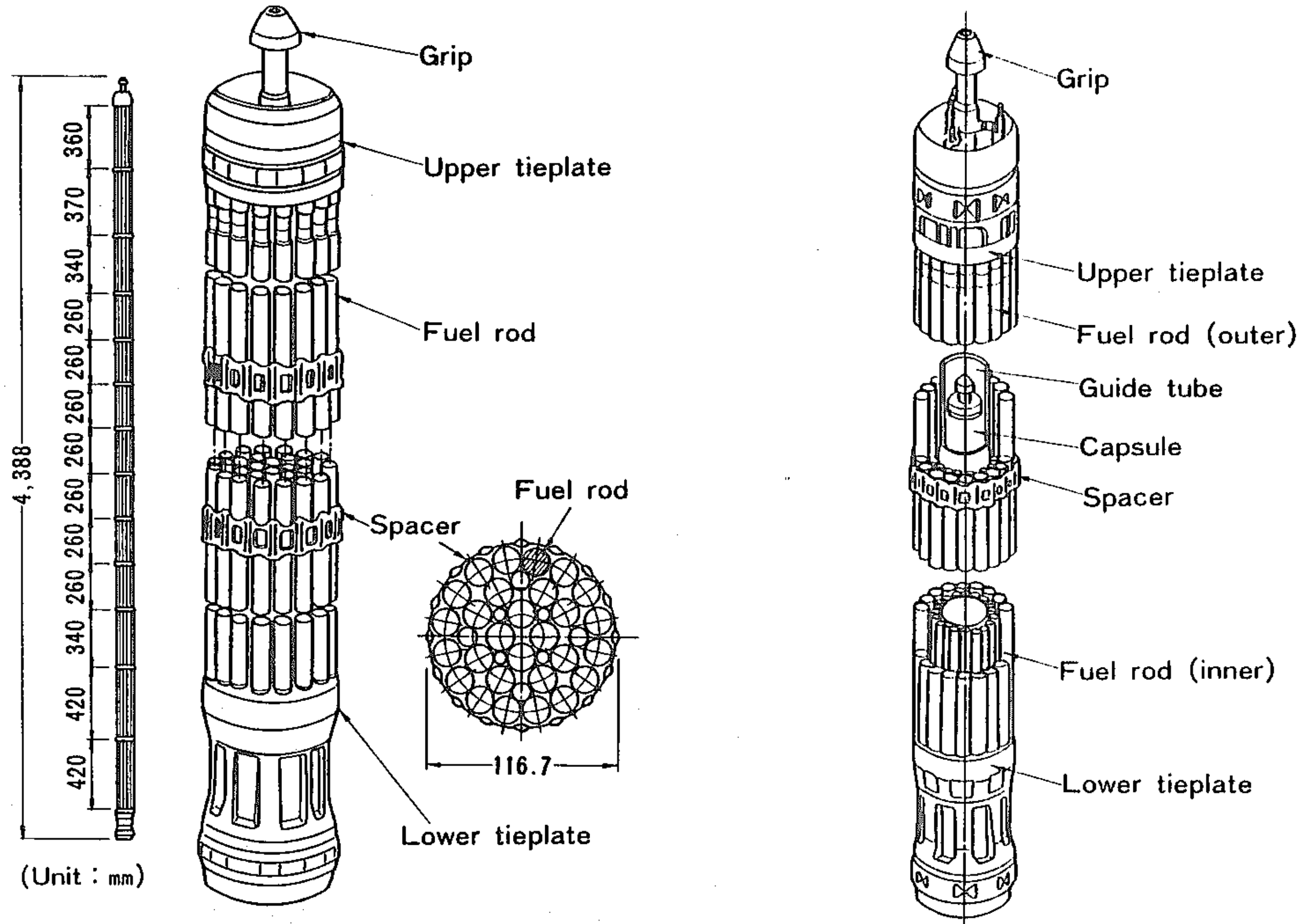


Fig. 8 Schematic flow diagram of Fugen

Key to components

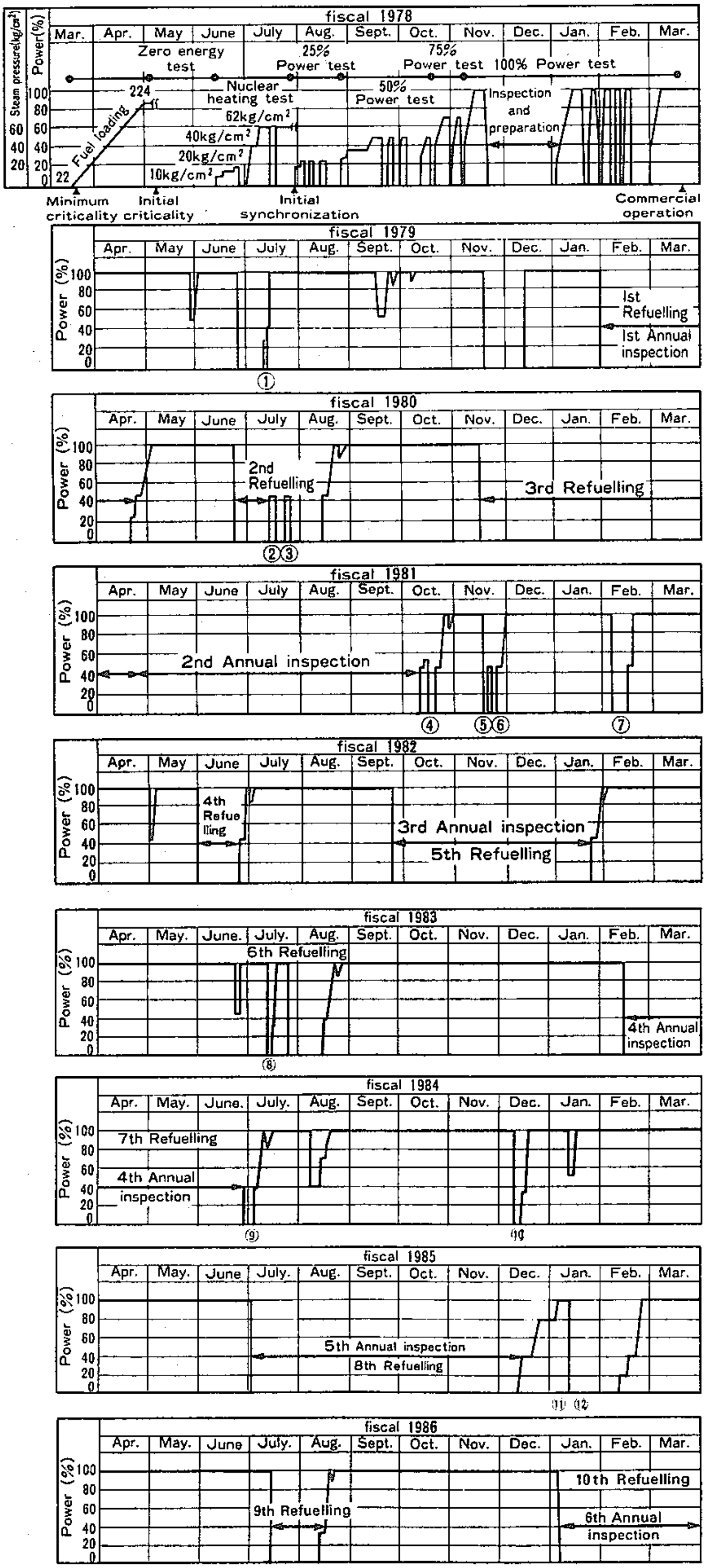
1. Calandria tank
2. Outlet riser tubes (224)
3. Steam drum (2)
4. Recirculation pump (4)
5. Lower header (2)
6. Inlet feeder tubes (224)
7. High pressure steam turbine
8. Low pressure steam turbine
9. Condensate demineralizer
10. Control rod drive mechanism
11. Refuelling machine
12. Heavy water dump tank
13. Liquid poison removal resin bed
14. Heavy water purification resin bed
15. Pre-heater
16. Recombiner
17. Clean up demineralizer
18. Fuel exchange pool
19. Spent fuel storage pool
20. Suppression pool
21. Condensated water storage tank
22. Main stack



Fuel assembly

Special fuel assembly
for irradiating samples

Fig. 9 Schematic view of Fugen fuel assembly



Load Factor

fiscal 1979: 72%

① Scram due to low water level in steam drum

fiscal 1980: 40%

② Scram due to turbine trip
③ Scram due to turbine trip

fiscal 1981: 41%

④ Shut down for repair of the drain vaive in feed water heater
⑤ Scram due to noise of the locai power monitor
⑥ Manual scram due to faiiure in feed water control valve
⑦ Shut down for repair of the drain piping of moisture separator

fiscal 1982: 59%

fiscal 1983: 81%

⑧ Shut down for repair of the make-up water supply system

fiscal 1984: 72%

⑨ Scram due to power excursion -when changing the recirculation pump speed

⑩ Scram due to high temperature of moderator

fiscal 1985: 41%

⑪ Scram due to load ejection

⑫ Scram due to low water level in steam drum

fiscal 1986: 70%

Fig. 10 Operating history in Fugen

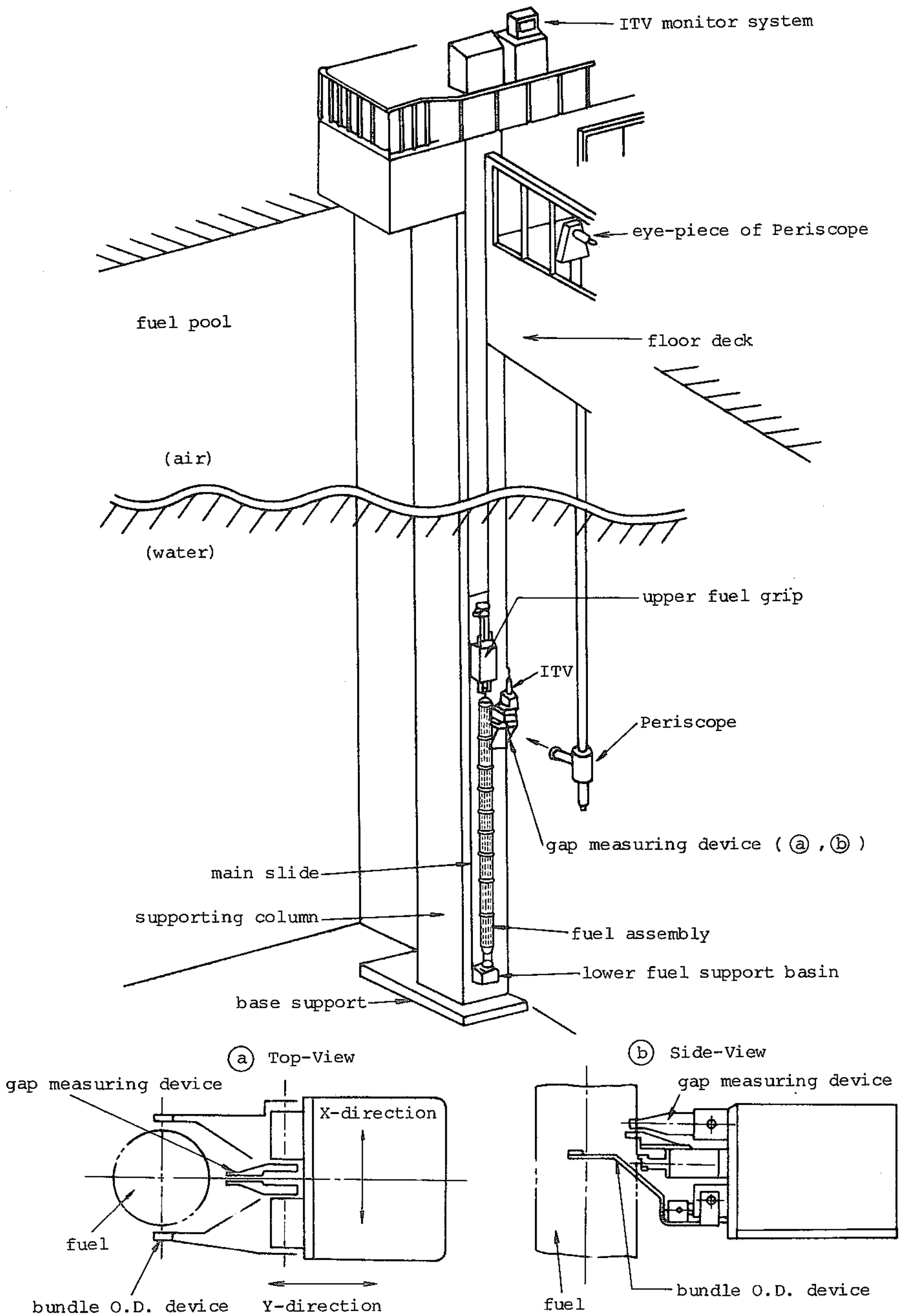


Fig.11 Schematic Drawing of FIP

Mark	Discharge Batch	Irradiation Time (EFPD)
•	New Fuel	
○	1	362
△	2	416
×	3	510
□	4	717
⊙	5	809
■	6	1015

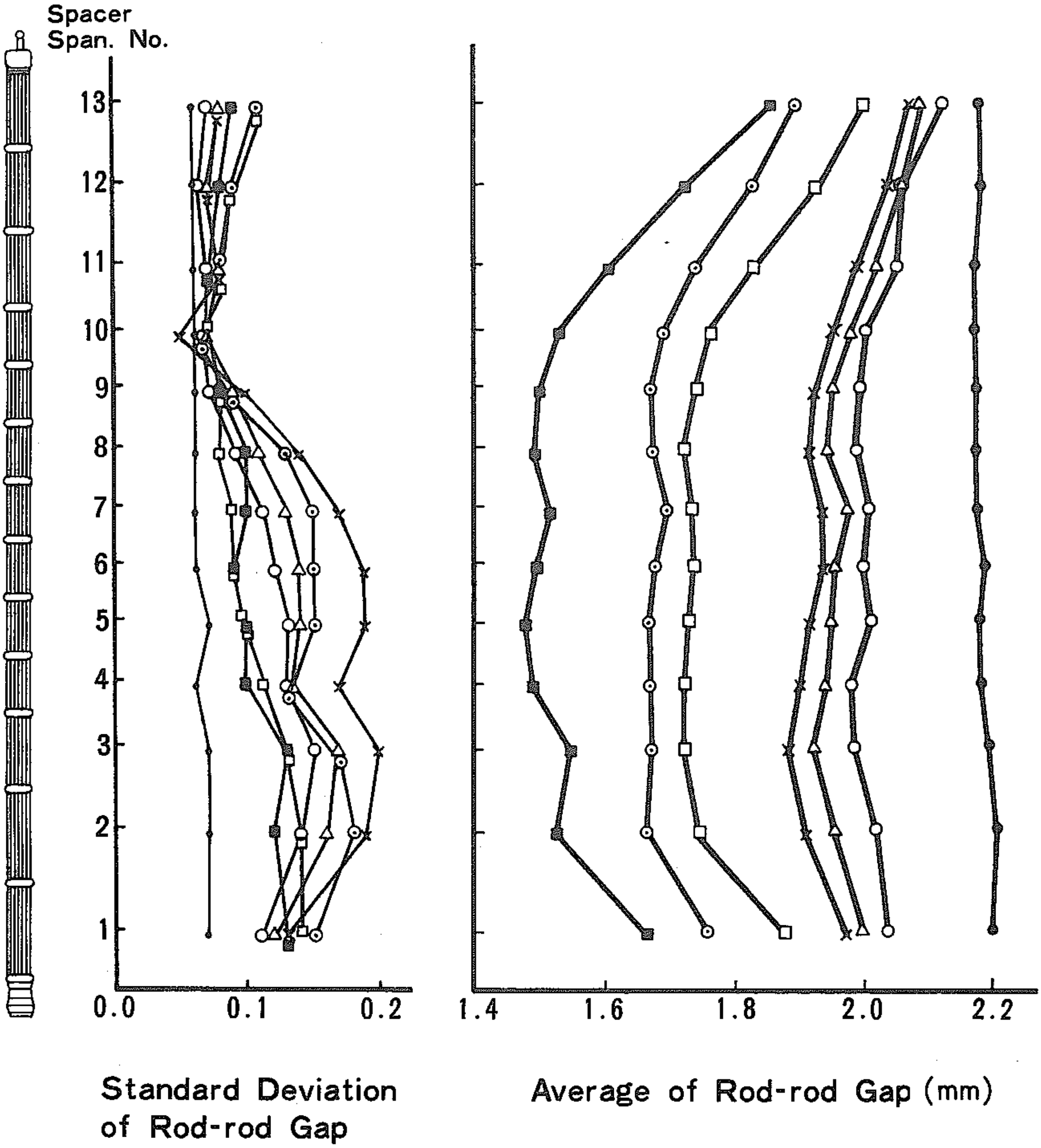


Fig. 12 Rod-rod Gap Measurement of Discharged Fuel Assemblies (On-site Inspection)

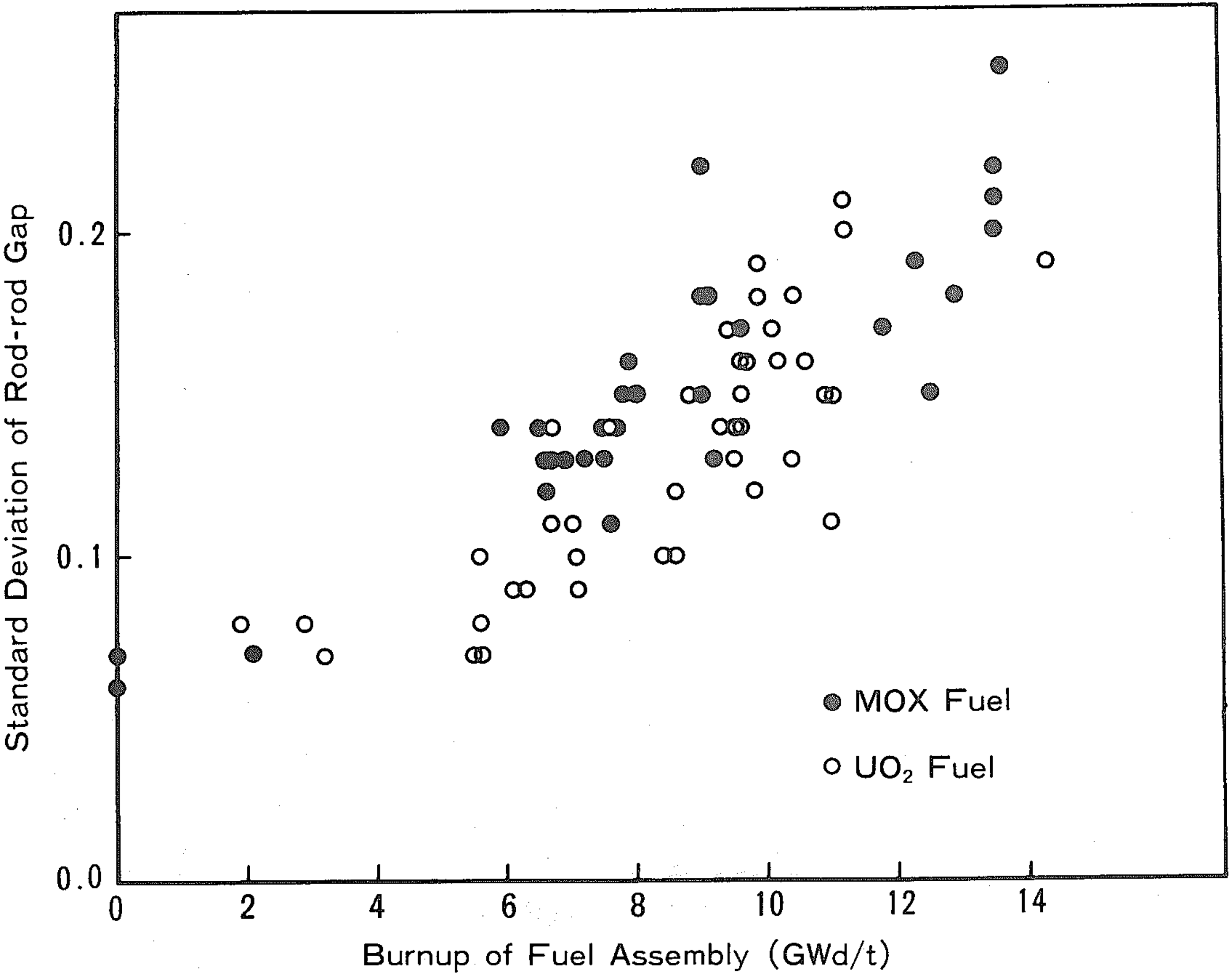


Fig. 13 Standard Deviation of Rod-rod Gap of Discharged Fuel Assemblies (On-site Inspection)

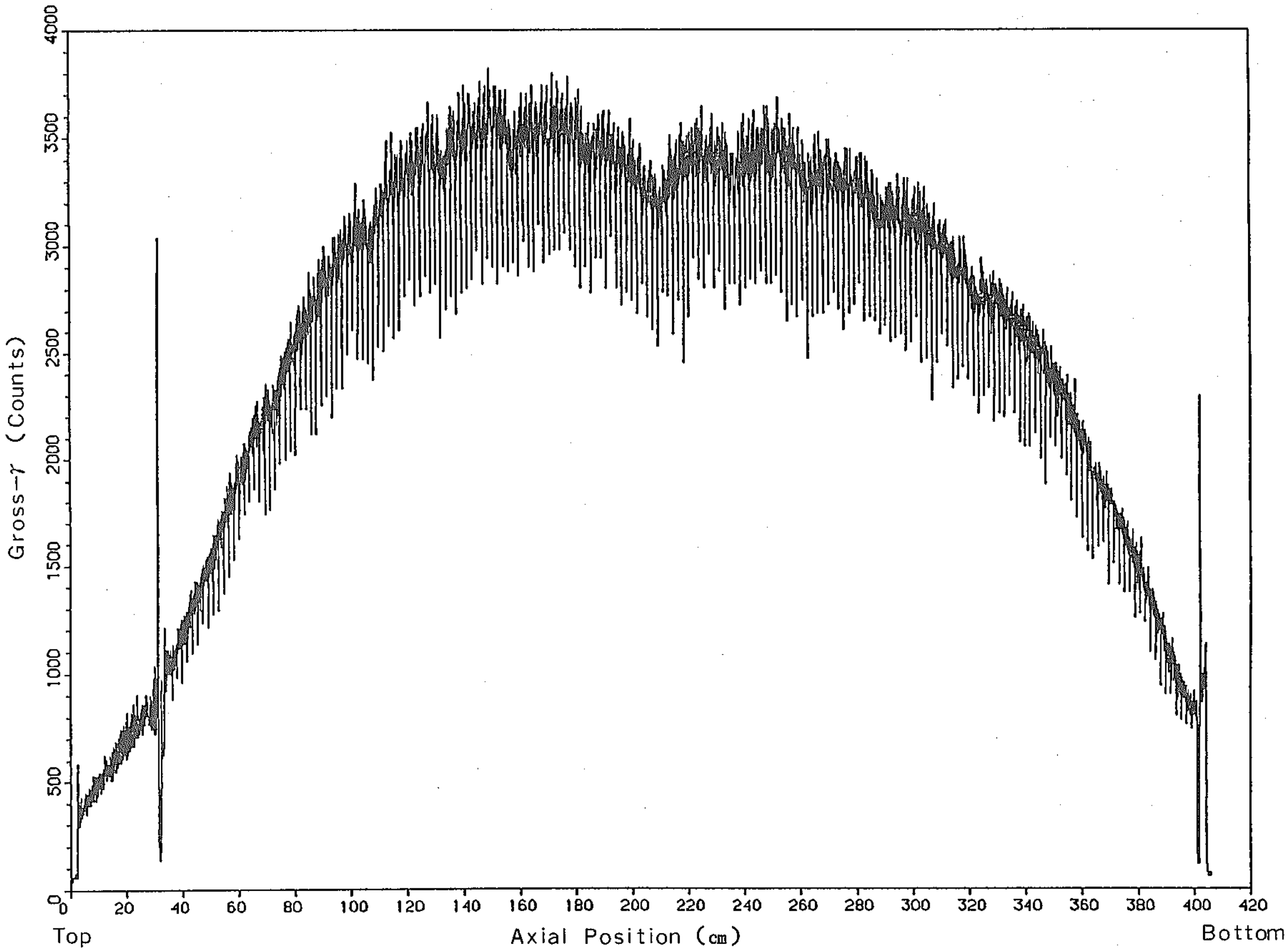


Fig.14 Axial distribution of γ-ray activity of fuel rod.

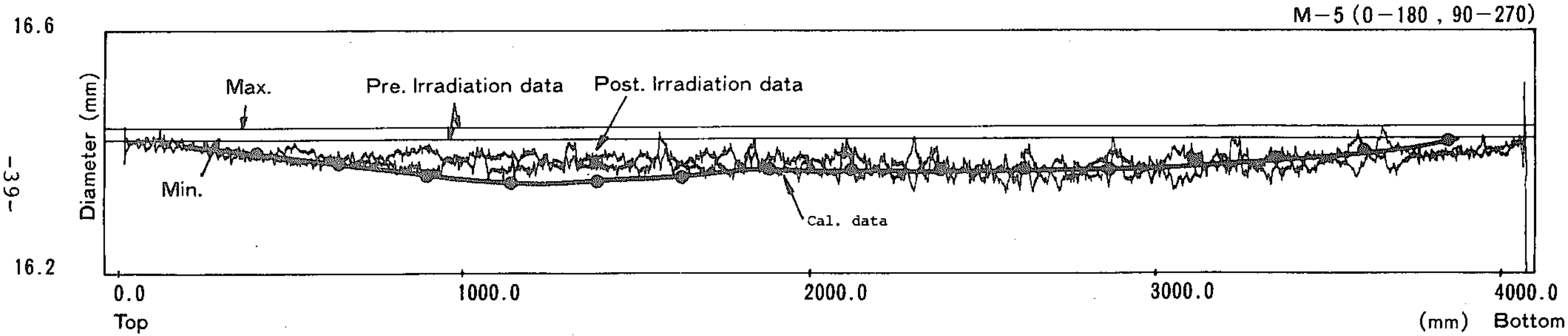


Fig.15 Outer Diameter Profile of Intermediate Fuel Rod

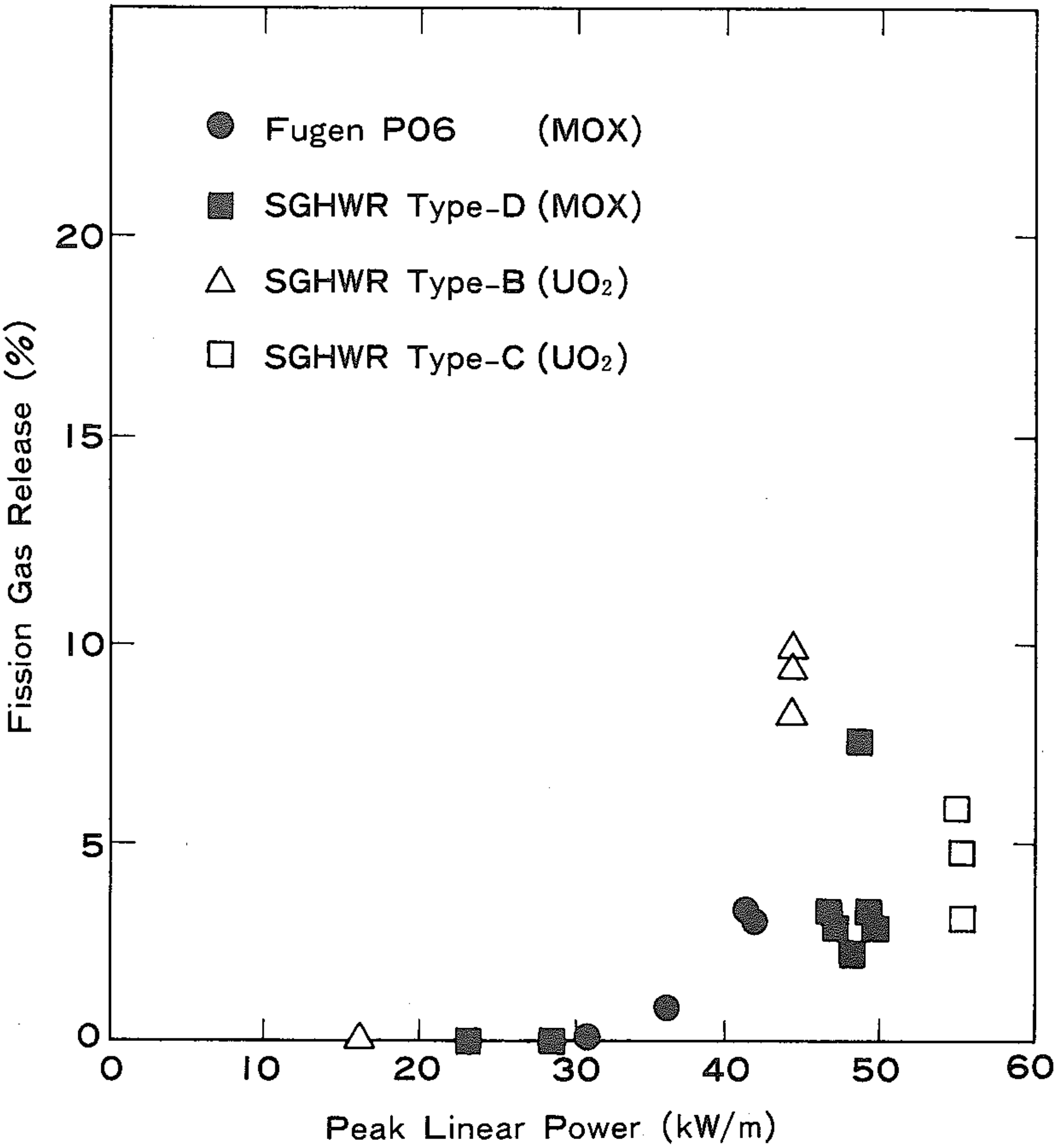


Fig.16 Dependence of fission gas release on peak linear power

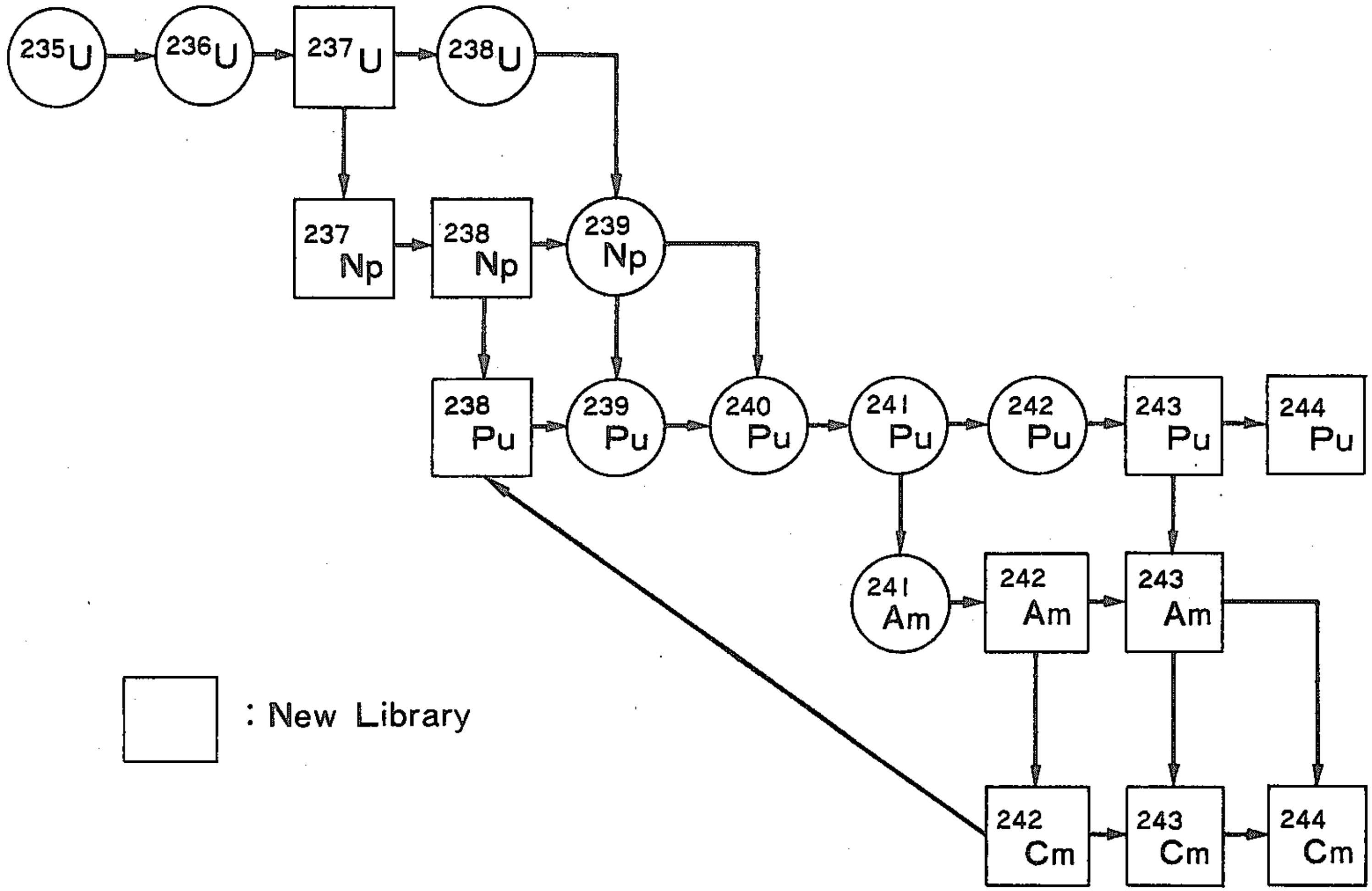


Fig.17 WIMS−D Nuclear Data Library

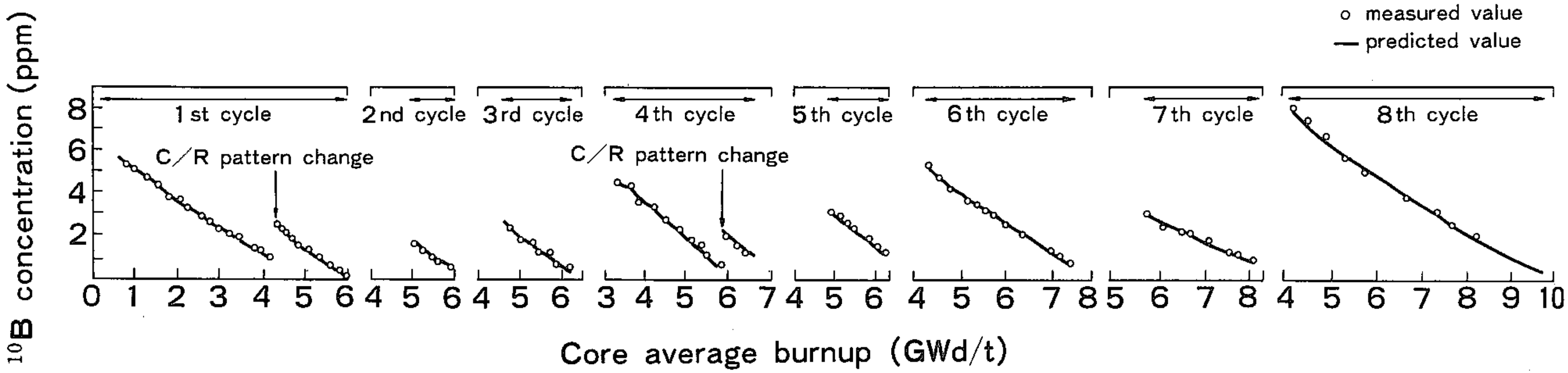


Fig. 18 History of ^{10}B concentration during rated power operation.