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Uses of Plutonium Fuel in Pressure Tube-type, Heavy-Water Moderated Thermal Reactors

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Uses of Plutonium Fuel in Pressure Tube-Type Heavy-Water Moderated Thermal Reactors

Abstract

Since 1962, the feasibility study of the uses of various nuclear fuels has been performed in the JAERI for pressure tube-type heavy water-moderated thermal reactors. This study started with the analysis of the use of uranium in heavy water-moderated thermal reactors such as the CANDU-PHW, CANDU-BLW, SGHW, EL-4, and Ref. 15D and E lattices which are designed in the JAERI, from the standpoint of the core design. Then, the ways of using plutonium fuel in the same type were investigated by using WATCH-TOWER, FLARE, and BOLERO codes, including : (1) direct substitution of the plutonium from light water reactors or magnox reactors, (2) recycle use of the plutonium from heavy water-moderated reactors, (3) plutonium self-sustaining cycle and (4) plutonium phoenix fuel.

From these, the followings are concluded : (1) In direct substitution of plutonium, somewhat depleted plutonium is more suited in the core design than the plutonium from magnox reactors or light water reactors, because the increase in the initial reactivity due to large plutonium absorption cross section must be prevented. (2) In plutonium self-sustaining cycle, the fuel burnup of about 15,000~20,000 MWD/T would be expected from natural uranium, and the positive void reactivity which always happen in the uranium loaded SGHW or CANDU-BLW lattices, is greatly reduced, and the latter property gives some margins to burnout heat flux. (3) Furthermore, it may be concluded from the fuel cycle analysis that the plutonium self-sustaining cycle is equivalent to use slightly enriched uranium (about 1.0 atomic percent).

From the above, it may be concluded that the use of plutonium in heavy water-moderated reactors is feasible technologically and advantageous economically.

December 1967

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要　旨

熱中性子炉でのプルトニウムの利用の仕方には次の5つが考えられる．直接代替利用，専焼炉利用，増殖炉利用，交換系（あるいは連用系），プルトニウム—トリウム利用である．これらの利用方式のうち，主に直接代替利用の研究が日本で行なわれてきた．その場合，対象炉としては軽水炉(1)，重水炉(2)(3)(4)，黒鉛炉(5)が取上げられた．

本論文では，圧力管型重水炉を取上げ，これまで日本原子力研究所で行なつてきた重水炉への種々のプルトニウムの利用方式に関する研究について述べた．第2章では，WATCH-TOWER コードによつて解析された CANDU-PHW, CANDU-BLW, SGHW, EL-4，ならびに日本原子力研究所で設計を試みた Ref・15D, E 格子のプルトニウム装荷下での燃焼特性を，上述の分類に従つて考察した．第3章では，プルトニウム装荷格子とウラン装荷格子の出力分布，DNBR 分布を相互に比較した．ここで解析のために使用されたコードは FLARE, BOLERO コードである．第4章では，プルトニウム自立サイクルでの燃料サイクル費を解析し，それをウラン装荷の場合と比較された．なお，本論文は IAEA 主催の「原子炉燃料としてのプルトニウムの利用」に関する国際会議（ブラッセル，1967年3月）に発表された．

1967 年 12 月

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Contents

目　　次

1. Introduction

The uses of plutonium in a thermal reactor may be divided broadly into the five : direct substitution of plutonium, use in a burner, use in a breeder, use in a cross-over system, and a mixture of plutonium with thorium. Of these, the direct substitution of plutonium is mainly studied in Japan for light water reactors (LWR) [1] and heavy water-moderated reactors (HWR) [2,3,4] and magnox reactors (CHR) [5].

In this paper, descriptions will be given of the feasibility studies carried out at JAERI on various uses of plutonium in pressure tube-type, heavy water-moderated, thermal reactors. In Chapter 2, the burnup characteristics analyzed by WATCH-TOWER code will be reviewed of the plutonium loaded lattices such as the CANDU-PHW, CANDU-BLW, SGHW, EL-4, and Ref. 15D & E designed at JAERI, according to the divisions given above. In Chapter 3, the power distribution analyzed by FLARE code and the DNBR margin analyzed by BOLERO code in the plutonium loaded cores will be compared with those for the uranium loaded cores. In chapter 4, the results of fuel cycle cost analysis in the plutonium self-sustaining cycle will be given.

2. Burnup Characteristics of Plutonium-Fueled Lattices

Plutonium uses in thermal reactors can be divided into (1) direct substitution [6], (2) burner [7], (3) breeder [8], (4) cross-over system [9,10], and (5) plutonium-thorium system [11]. In (1), the plutonium obtained from HWR's or LWR's is directly used without largely changing the lattice configuration ; this may be subdivided into plutonium recycle and plutonium self-sustaining cycle. In (2), the phoenix effect of plutonium is utilized to obtain a high fuel burnup, with a low excess reactivity. In (3), the development on the plutonium use is still in a stage of feasibility study. In (4), there are two kinds of use : in the first, a fast reactor is combined with a thermal reactor, (the plutonium from the blanket in the former is used in the latter reactor), and in the second, it is the progeny system with a couple of a HWR and a LWR, (the ^{233}U from a HWR, mixed with natural uranium, is used in the LWR, and the plutonium from the LWR is returned to the HWR, mixed with thorium). In (5), the purpose is to use thorium efficiently.

Since 1962, the feasibility study on the plutonium uses has been carried out at JAERI, mainly on the direct substitution of plutonium and the burner use in HWR's. The works on the direct substitution will be divided, for convenience, into a recycle of the plutonium from the LWR's or CHR's, a recycle of the plutonium from the HWR itself, and a self-sustaining cycle of the plutonium from the HWR. In the following, the studies carried out at JAERI on the burnup characteristics will be described. The codes used for these studies are WATCH-TOWER, FLARE, and BOLERO, which are respectively for the generation of two group constants, the calculation of three dimentional power distribution, and the evaluation of burnout margin [12,13].

Prepared for presentation at an IAEA Symposium on "Use of Plutonium as a Reactor Fuel", 13–17 March, 1967.

2. 1. Recycle of the plutonium from BWR's or CHR's

In Fig. 1, the maximum attainable fuel burnups of the plutonium-loaded, CANDU-PHW, and SGHW lattices are compared with those for the same lattices loaded with slightly-enriched uranium.

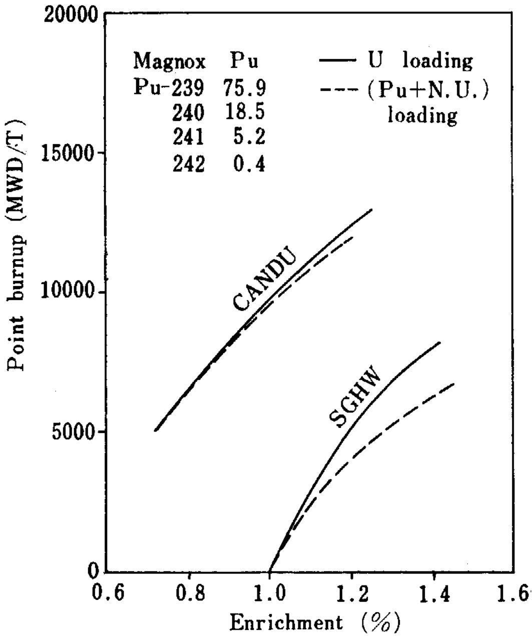

Fig. 1 Burnups in respective lattices fueled with U and Pu.

In the type of plutonium recycle, under consideration, the somewhat well-moderated lattice is more suitable than the undermoderated one. Further, the use of a little depleted plutonium is advantageous in the improvement of fuel burnup and the reactivity control.

2. 2. Recycle of the plutonium from HWR's

In Table 1, the burnups obtainable by recycle of plutonium in the EL-4 lattice (Be cladding) are shown. By this recycle, about 20000 MWD/T of fuel burnup can be obtained with natural uranium, which corresponds to two times that for natural uranium alone. In this recycle, the phoenix plutonium may also be produced. That is to say : the first cycle starts with 0.9% enriched uranium, and the plutonium from this fuel burned about 16,000 MWD/T, is then mixed with natural uranium, which is used in the second cycle. Then, after the 17,000 MWD/T burnup of it, the phoenix fuel is obtained.

Table 1 Attainable fuel burnup(1) for EL-4 type lattice (beryllium clad) when plutonium is recycled in use

Cycle	Fuel \ Effective enrichment (%)	0.90	1.10
First	S. E. U.	MWD/T 16000	MWD/T 21330
Second	D. U.(2)+Pu	13500	18540
	N. U.+Pu	16000	20790

(1) (Point burnup)×1.8 (2) Depleted uranium : 0.2% ^{235}U

2.3. Plutonium self-sustaining cycle

This cycle starts with the use of natural or slightly enriched uranium. In the subsequent cycles, natural uranium is always used as the base fuel with which all the plutonium from the preceding cycle is mixed. In Japan, this cycle is attracting much interest for the following reasons : (1) the base fuel is natural uranium, (2) this cycle is equivalent to an slightly enriched system, and consequently gives much flexibility in the core design, and (3) the depleted plutonium from the cycles may be well used in a fast reactor.

Since 1963, the feasibility study of this cycle has been carried out at JAERI from the standpoint of design engineering, for such lattices as CANDU-PHW, CANDU-BLW, SGHW, EL-4 (Be cladding), and Ref. 15D & E designed at JAERI. The results obtained will briefly be given in the following.

(a) When this cycle is used in the non-dual-moderated lattice such as the CANDU and EL-4, about 18,000~20,000 MWD/T fuel burnup can be obtained with natural uranium, and the effective fuel enrichment at the equilibrium cycle becomes from 1.0 to 1.1 atomic percent.

(b) When this cycle is used in the dual-moderated lattices, such as the CANDU-BLW, SGHW, and Ref. 15D and E, it becomes necessary to have the optimum volume ratio of moderator to fuel (V_m/V_f), and of coolant to fuel (V_c/V_f), for obtaining a high fuel burnup and suitable void reactivity ; the latter considerably influences not only the kinetic characteristics but also the distributions of power and DNBR. That is to say, if a selected lattice is an undermoderated one, its excess reactivity then becomes small, and also its fuel burnup may be reduced, even if the conversion ratio may be a little higher. Moreover, the void reactivity takes a larger negative value under plutonium loading, so that the power distribution has its peak near the coolant inlet.

(c) Before attaining an equilibrium cycle, three or four previous cycles are required.

(d) The effective fuel enrichment at the equilibrium cycles is higher, the more lattice is undermoderated.

(e) The plutonium from equilibrium cycles is more depleted than the phoenix one ; its fissile isotope content is about 50 atomic percent.

In TABLE 2, the attainable fuel burnup and the concentration of plutonium higher isotopes, etc., are given for the CANDU-PHW, SGHW lattices, etc., at equilibrium cycle.

TABLE 2 Self-sustaining cycles in various lattices (at equilibrium cycle)

Lattice	CANDU-BLW	Large SGHW	Ref. 15D	Ref. 15E	EL-4	CANDU	SGHW
Lattice pitch (cm)	22.6	26.1	24.0	25.0	27.0	22.8_6	26.1
V_m/V_f	9.06	6.98	5.86	6.64	13.92	13.65	6.98
V_c/V_f	.816	1.068	1.00	.810	1.888	.593	1.068
Enrichment (%)	1.17	1.26	1.29	1.28	1.09	1.07	1.23
I. C. R.*	.692	.715	.742	.739	.675	.633	.688
Burnup** (MWD/T)	14900	11100	13100	15400	18900	18500	5000
Pu composition (%)							
Pu-239	36	42	41	41	31	38	51
Pu-240	28	28	26	27	27	31	27
Pu-241	10	11	12	11	8	9	12
Pu-242	26	19	21	21	34	21	10
Power (MWe)	457	500	300	500	500	200	100

* Initial conversion ratio ** (Point burnup) × 1.8

2.4. Phoenix fuel

Many studies have been reported on the use of phoenix fuel in LWR's, but this is not so for the HWR's. In this section, a description will be made of the results of studies on the burnup characteristics, when phoenix plutonium fuel is used in the EL-4 (Be or 304 SS), CANDU, and SGHW lattices. The different modes for the use of phoenix plutonium are shown in TABLE 3. The following results were obtained:

TABLE 3 The phoenix disposition in various lattices(3)

Lattice	CANDU	EL-4				SGHW			
Sheath	Zry 2	Be		304SS		Zry-2			
Fuel Pu type(1)	A	A	B	A	B	A	C	D	E
Burnup (MWD/T)	64400	68000	64400	60800	59600	100	52600	40000	25000
I. C. R.(2)	.571	.592	.467	.574	.449	.696	.603	.666	.683
Keff.	1.3041	1.2913	1.5738	1.2768	1.5493	1.0275	1.2394	1.1175	1.0758

(1) The isotope composition of Pu in respective types (%) ^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu ;
A : 43.4/33.1/9.7/13.8 B : 52.0/20.0/20.0/8.0 C : 62.3/24.5/9.2/4.0
D : 51.9/31.6/9.1/7.4 E : 47.7/32.8/9.6/9.9
(2) Initial conversion ratio.
(3) Notice ; Initial enrichment is 6% in all lattices.

(a) The plutonium which exhibits the phoenix effect in the HWR, is generally more depleted than the phoenix plutonium in the LWR, and then the fissile plutonium content is about 55 atomic percent.

(b) However, when this plutonium is used in the considerably undermoderated lattices, such as the SGHW, and Ref. 15D and E lattices, the effective fuel enrichment must then be increased ; this means a higher plutonium inventory for the lattices, not desirable in the core design. Thus, in the case of undermoderated lattices, it is desirable to use a phoenix plutonium whose fissile isotope content is a little higher than 55 atomic percent.

(c) The maximum attainable fuel burnups are from 50,000 to 80,000 MWD/T.

(d) The negative resistance effect of the phoenix plutonium appears at a little high enrichment in the lattices, such as the EL-4 (304 SS cladding), of which neutron economy is not good, compared with that for the lattices with good neutron economy (EL-4 (Be cladding)).

In the above (2.1)~(2.4), the different modes of plutonium use have been reviewed on the basis of the data obtained at JAERI. It may be concluded that the plutonium recycle and the plutonium self-sustaining cycle are considered to be the most feasible from the standpoint of burnup characteristics. Thus, in the next chapter, a discussion will be made on the core characteristics, when the plutonium self-sustaining cycle, for example, is employed.

3. Power Distribution and DNBR Margin

The void reactivity of the SGHW lattice is somewhat positive when uranium is loaded, and it is considerably positive in the CANDU-BLW lattice. This positive value affects not only the kinetic properties but also the power distribution and DNBR margin ; that is the peak in the axial power distribution occurs nears the channel outlet, thereby reducing the burnout margin. In the plutonium self-sustaining cycle, however, this positive void reactivity is fairly reduced, and the power distribution is improved, resulting in an increase of burnout heat-flux margin. In **Fig.** 2, the case of SGHW-500 MWe is shown as an example. From this figure, it is seen that the peak in the power distribution shifts towards the coolant inlet when plutonium is loaded, the value of the peak being reduced at the same time ; the burnout margin is then increased by 0.5. It should be noted here that care must be taken in one point, which is the selection of the proper lattice moderation. If the lattice is considerably undermoderated, its void reactivity becomes highly negative under plutonium loading, so that the power distribution is greatly distorted ; an example is shown in **Fig.** 3, where a large power peak is seen near the coolant inlet, due to the large negative void reactivity. Therefore, it is evident that there exists an optimum lattice moderation for the plutonium self-sustaining cycle. In addition to the above, this cycle has the following advantage : due to the faster start of coolant boiling, the average coolant density in the reactor core becomes low, compared with the case of uranium loading alone, and the fuel burnup is thus increased.

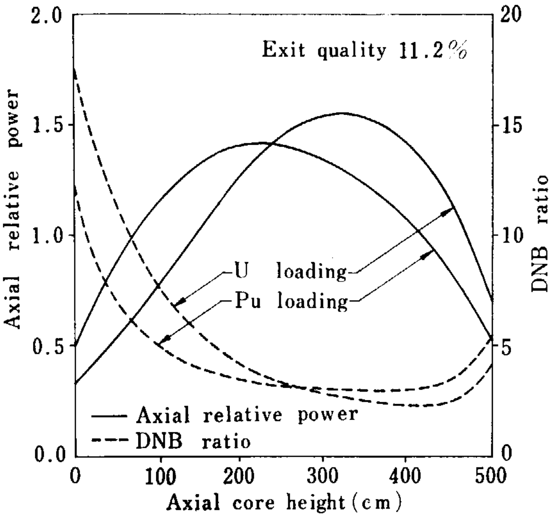

Fig. 2 Power and DNBR distributions in SGHW lattice.

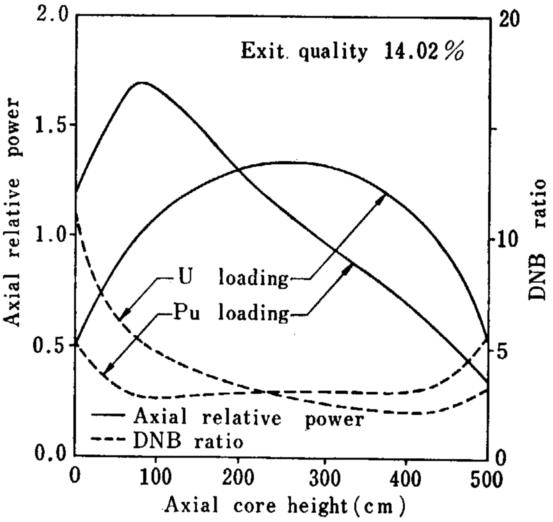

Fig. 3 Power and DNBR distributions in Ref. 15D lattice.

From the above considerations, it may be concluded that this cycle has many posibilities, as well as the flexibility in the core design, and deserves the analysis on the cost of fuel cycle.

4. Fuel Cycle Cost

In this section, the fuel cycle cost of the plutonium self-sustaining cycle will be compared with that of uranium loading. The cost basis is as follows : The prices of uranium are those adopted by US-AEC, and for plutonium it is \$10/g (fissile Pu) ; but this does not affect much the fuel cycle cost because of the self-sustaining. The fabrication cost of fuel is taken to be \$44.3/kg [14] for UO_2, and \$$44.3\times1.1$/kg for UO_2-PuO_2. The evaluation of the reprocessing cost is by the MIT's method [15]. The results of estimate of the fuel cycle cost are shown in **Fig. 4**, with the Ref. 15D lattice as an example. It may be concluded that the polutonium self-sustaining cycle is equivalent to the use of 1.0~1.1% enriched uranium.

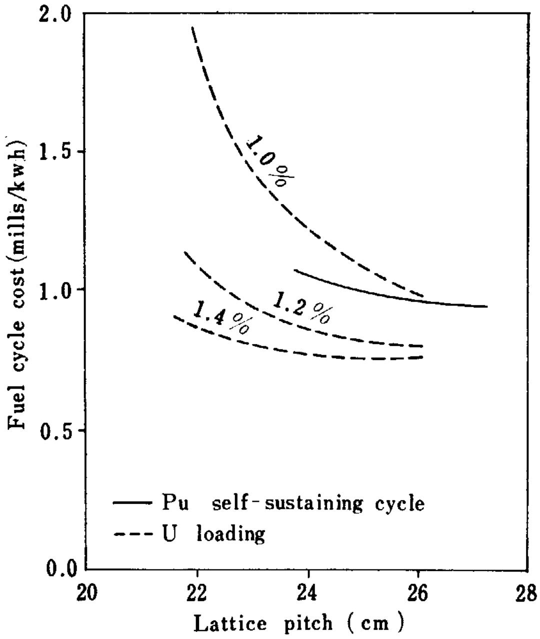

Fig. 4 Fuel cycle cost of the self-sustaining cycle in Ref. 15D lattice.

5. Conclusion

The various modes of use of plutonium in heavy water-moderated reactors have so far been described. More important findings obtained as the results of studies will be summarized below.

(1) The plutonium from either magnox reactors, boiling water reactors, or heavy water-moderated reactors, may sufficiently be used in heavy water-moderated reactors.

(2) When plutonium is used in such dual-moderated lattices as the CANDU-BLW, SGHW, and Ref. 15D and E, the void reactivity becomes fairly negative. And as the result, the power distribution is improved and the DNBR margin is improved, in addition to the advantage in the nuclear safety.

(3) In the plutonium self-sustaining cycle, natural uranium alone is used, furthermore this cycle is equivalent to the use of 1.0~1.1% enriched uranium. This method of plutonium cycle is very attractive for such nations as Japan where uranium resources are scarce and there is no diffusion plant.

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