Annex V: Brazil

An Integral Metallic-Fueled and Lead-Cooled Reactor Concept
for the 4th Generation Reactor

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Abstract

An Integral Lead Reactor (ILR) concept is proposed for the 4th generation reactor to be used in the future. The ILR is loaded with metallic fuel and cooled by lead. It was evaluated in the 300-1500 MWe power range with the Japanese Fast Set 2 cross sections library. This set was tested against several fast benchmarks and the criticality uncertainty was found to be 0.51 % Δk. The reactor is started with U-Zr and changes to the U-TRU-Zr-RE fuel in a stepwise way. In the equilibrium cycle, the burnup reactivity is less than β_{eff} for a core of the order of 300 MWe, pin diameter of 10.4 mm and a pin-pitch to diameter ratio of 1.308. The lead void reactivity is negative for reactor power less than 750 MWe. There is a need to improve the nuclear data for the major actinides.

KEYWORDS: integral lead rector, burnup reactivity, lead void reactivity, equilibrium cycle, liquid metal reactor, metallic fuel, lead coolant

Introduction

The nuclear reactors to be used in the future, after 2030, are being conceived in the developed countries. In order to be commercialized, the main desirable characteristics for these reactors are: (a) efficient utilization of natural resources; (b) safety based on inherent processes and passive systems; (c) adequate waste management as self-confinement and transmutation of the hazardous fission products; (d) proliferation resistance; (e) economic competitiveness with other sources; and (f) public acceptation. A nuclear system concept that satisfies all these requirements may be classified as of 4th generation.

The American Integral Fast Reactor (IFR) [1] concept satisfies several of the requirements mentioned above. Metallic fuel and a dry recycling process performed by the pyroprocess [2] have been chosen as the key characteristics.

Nowadays, the coolant of the fast reactor is sodium. However, operational experience [3,4] with fast reactors has shown that sodium is the weakest point due to its exothermic reaction with water and air humidity.

In the middle 80's, the Russian Kurchatov Institute proposed the Lead-Cooled Reactor - LCR concept [5]. In the 90's renewed interest on hybrid systems, cooled by lead, has been brought about with the advent of Accelerator Driven Systems [6] for electric energy generation.

Currently, lead is an alternative for sodium as a coolant of fast reactor because it improves the safety and the costs of this system. [5] Moreover, its high boiling point (1740 °C) allows one to idealize applications of LCR in others areas such as heat source for industrial applications, although much effort in R&D will be necessary in this case.

Therefore, the combination of the IFR and LCR best characteristics can result in a new concept, hereby named as Integral Lead Reactor (ILR), that is suitable for the 4th generation reactor. The ILR is a self-sustainable energy generation center with all fuel cycle facilities integrated to the reactor site. It uses metallic or nitrate fuel, pool type or top-entry primary circuit, pyroprocess for recycling and lead as coolant. An ILR attractive characteristic is that it may be a cleaner concept, since the pyroprocess recovers the transuranics (TRU) with high efficiency [2] and the fast core burns them. Moreover, the integration of fuel cycle facilities to the reactor site results in a high proliferation resistance concept.

The utilization of metallic fuel and lead has been a subject of interest of the world nuclear community. In 1995, Sekimoto and Zaki [7] studied small reactors - 150MWt, long life core for utilization in remote areas. In the same line, Greenspan [8] - 1998, proposed a 50 MWe reactor loaded with U-Zr to be used in developing countries.

This work evaluates some ILR core characteristics such as: burnup and lead void reactivities, Doppler effect and fast fluence, as function of fuel pin diameter - 6.35/8.12/10.4 mm, pin/diameter (p/d) ratio - 1.308/1.412/1.495, and core power - 300/900/1500 MWe. The ILR is started with U-Zr fuel and changes, in a stepwise way, to the U-TRU-Zr fuel.

Calculation System - Nuclear Data and Codes

The cross section library used was the Japanese Fast Set 2 - JFS-2 \cite [9] in 70 groups. This study required additional material cross sections, therefore this set had to be completed with data for lead from JENDL-3.1 [10], as well as some structural nuclides and part of minor actinides, both from ENDF/B-VI [11]. The added data were generated by the NJOY [12] system.

The calculation system employs the code EXPANDA [13], which calculates effective cross sections for each case. Then, it performs criticality calculations and collapses the cross sections in a small number of groups to be used by CITATION [14] for the core evaluation. The ORIGEN 2.1 [15] is used in a cycle-by-cycle approach to the equilibrium cycle (EC), using the recycle characteristics of the pyroprocess.

The JFS-2 library and the EXPANDA were evaluated using plutonium and uranium benchmarks. As can be seen in Table 1, the benchmarks' results were better for the plutonium cases. The average criticality uncertainty in these plutonium-uranium systems was 0.43-0.63 %Δk and the total uncertainty due to the JFS-2 was 0.51 % Δk

Table 1 Criticality benchmark results obtained with the EXPANDA code and JFS-2 library

Pu-benchmark	$k_{calc.}$	U-benchmark	$k_{calc.}$
VERA-11A	0.9899	VERA-1B	1.0024
ZEBRA-3	0.9962	ZPR-3-6F	1.0139
SNEAK-7A	1.0036	ZPR-3-12	1.0067
SNEAK-7B	1.0027	ZPR-3-11	1.0061
ZPR-3-48	1.0063	ZEBRA-2	0.9930
ZPR-3-56B	0.9939	ZPR-6-6A	0.9985
ZPPR-2	1.0045		
ZPR-6-7	1.0020		
Aver. $k_{calc.}$	1.0002		1.0014
Aver. $\lvert k - 1. \rvert$	0.0043		0.0063
All cases $\lvert k - 1. \rvert$			0.0051

*Corrected for heterogeneities, transport and dimension effects

The neutronic evaluation of fast cores requires a few neutron energy groups [7,16]. The 9 energy groups used in this work were defined after the benchmark calculations of Table 1 with several structures. Figure 2 shows the average difference between the 70 groups and the several condensed-groups calculations. After 9 groups the difference is constant.

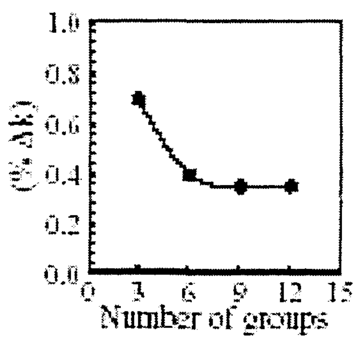

Fig. 1 Average difference between the benchmark criticality calculations with 70 and fewer condensed group structures

ILR Evaluation
Core models

The core models were chosen based on the American and Russian experiences [16,17]. The core power range analyzed was 300/900/1500 MWe. The lower limit is suitable for primary circuit fabrication in factory. The upper limit was selected based on the Super-Phenix 2 project.

A homogeneous core layout was adopted for the ILR. The fuel assembly is of hexagonal type with 271 pins spaced by grid. The core height is 100 cm. The structural material is the HT-9 stainless steel. The lead fusion temperature (327 °C) requires a high inlet temperature, 420 °C. The outlet temperature is 540 °C.

The number of assemblies for the active core was defined using a conservative linear power of 200 W/cm. The equivalent cylindrical (RZ) model radius and the volume fractions can be seen in Table 2. The axial dimensions are shown Figure 2. The active core was split in two radial regions, inner and outer cores, for power flattening. The control assemblies were considered completely withdrawn.

Table 2 ILR RZ core model characteristics

Power (MWe)	300	900	1500
Inner core radius (cm)	93-168	139-288	204-370
Outer Core radius (cm)	107-195	173-315	218-395
Blanket radius (cm)	136-247	202-367	246-446
Shield radius (cm)	150-273	216-392	270-471
Vol. fraction (%), p/d =	1.308	1.417	1.495
Fuel	32.6	28.1	25.3
Structure	20.4	18.2	16.8
Coolant	47.0	53.7	57.9

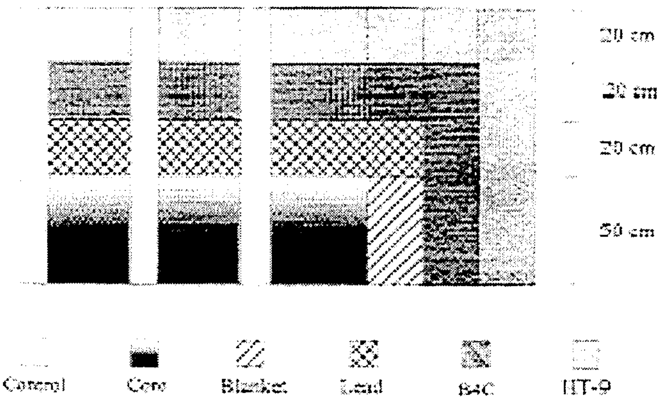

Fig. 2 ILR two-dimensional (RZ) cylindrical model

Calculation methodology

The ILR is started with U-Zr and changed, cycle-by-cycle, to U-TRU-Zr-RE (Rare Earth); the fuel smear density is 75 {%}. The pyroprocess recovers the actinides with a small contamination [2] of RE elements. In this study the RE was simulated by the ^{143}Nd. The ILR target average burnup is 100 MWd/kg and the core reloading was performed in three batches. In this work the burnup reactivity (Δk_{Bu}) is considered as the sum of two components:

$$\Delta k_{Bu} = \Delta k_{Transm} + \Delta k_{Swell}. \qquad (1)$$

where, Δk_{Swell}, is the reactivity due to axial fuel swelling and Δk_{Transm} is the reactivity change resulting from the fuel composition change during the burnup. The U-Zr fuel swells at a higher rate than the U-Pu-Zr fuel [18]. The EC evaluation consideres that the U-TRU-Zr-RE swells at the same rate as U-Pu-Zr. The axial swelling was simulated by uniformly increasing the active height in the beginning of cycle (BOC) and keeping it constant during the burnup calculations.}

The calculational strategy is based on interactive calculations among the EXPANDA, CITATION and ORIGEN codes. First, two enrichments, E_{in} and E_{out}, were adjusted to flat the power distribution, using the criterion that the reactor must be critical at the end-of-cycle. Then, the core was burned using cross sections obtained at the BOC and the nuclide chains shown in Fig 3.

For each reactor, ORIGEN performs the approach to the equilibrium cycle starting from the first cycle. The average fuel composition calculated for the EXPANDA-CITATION equilibrium analyses is shown in Table 3.

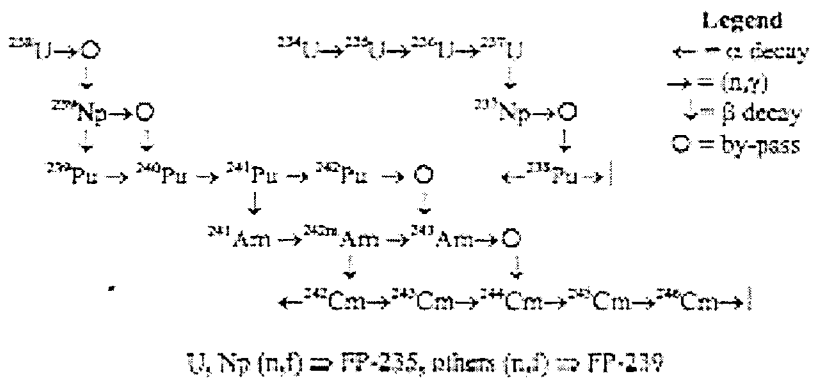

Fig. 3 Burnup chain

Table 3 ILR equilibrium fuel composition

Nuclide	(w/o)	Nuclide	(w/o)	Nuclide	(w/o)
^{237}Np	1.79	^{242}Pu	1.95	^{243}Cm	0.01
^{238}Pu	2.49	^{241}Am	2.22	^{244}Cm	0.23
^{239}Pu	57.12	^{242m}Am	0.10	^{245}Cm	0.06
^{240}Pu	30.05	^{243}Am	0.65	^{246}Cm	0.01
^{241}Pu	3.32	^{242}Cm	0.01		

The parameters of interest at the beginning and end-of-cycle were calculated with the nuclide densities obtained in the enrichment adjustment and the burnup calculations. All reactivities were calculated as the difference between the k_{eff} of the perturbed and the reference cases.

Results and Discussion

A main requirement desirable for the ILR is to have $\Delta k_{Bu} < \beta_{eff}$ to mitigate the TOP accident, which is based on the unadvertised withdrawn of the most reactive control assembly. The TOP reactivity is given by:

$$\rho_{TOP} = \frac{\Delta k_{Bu}}{number\ of\ control\ assembly}, \qquad (2)$$

If the core conversion ratio (CR) is close to unit, Δk_{Bu} and ρ_{TOP} can be made as close to zero as possible. The CR is directly proportional to the fertile/fissile (FF) ratio in the core or to the fuel enrichment. A large ^{238}U concentration favors the ^{239}Pu production and, consequently, CR increases. Therefore, a large core has a higher CR than a small one.

The evaluated ILR parameters as a function of the reactor size, pin diameter and the p/d ratio, are show in Table 4 for selected cases. The Doppler coefficient (DC) was calculated as Tdk/dT. The peak fluence calculations considered neutrons with energy > 0.1 MeV.

Table 4 shows that Δk_{Bu} decreases with an increase in power and pin diameter, and with a decrease in the p/d ratio. These changes increase the FF ratio and CR. For a given pin diameter and p/d ratio, a reactor power increase lowers the radial neutron leakage and the enrichment which, by its turn, increases the FF ratio and CR. On the other hand, an increase in the p/d ratio increases the lead volume fraction and its capture and increases the axial neutron leakage, requiring higher enrichment. Consequently, FF is smaller and CR lower.

Table 4 ILR first and equilibrium cycle results

Power (MWe)		300		900	1500
Pin (mm)	6.35	6.35	10.4	10.4	10.4
P/D ratio	1.308	1.495	1.308	1.308	1.308
			First Cycle		
E_{in} (w/o)	16.8	18.8	14.2	13.1	13.1
E_{out} (w/o)	28.2	31.4	20.8	16.5	15.5
Δk_{Bu} (%)	-5.76	-6.07	-4.15	-2.78	-2.52
β_{eff} (10^{-3})	7.10	7.06	6.95	6.81	6.76
CR	0.41	0.36	0.55	0.65	0.68
Fluence(10^{23})	1.26	1.12	1.48	1.62	1.74
DC (10^{-3})	-2.47	-2.25	-3.09	-3.58	-3.70
			Equilibrium Cycle		
E_{in} (w/o)	16.6	18.7	14.1	13.4	13.4
E_{out} (w/o)	25.4	28.6	19.1	16.1	15.2
Δk_{Bu} (%)	-3.39	-4.26	-0.64	+1.12	+1.51
β_{eff} (10^{-3})	3.81	3.61	3.92	3.91	3.91
CR	0.77	0.69	0.96	1.06	1.08
Fluence(10^{23})	1.51	1.34	1.82	2.07	2.39
DC (10^{-3})	-2.28	-2.16	-2.76	2.99	-3.07

An important difference between the first and equilibrium cycles is the fuel change - ^{235}U to TRU - which increases the fuel η. The averaged ηin the ILR spectrum for ^{235}U is 2.32 and for TRU is 2.67. Consequently, the RC increase and the Δk_{Bu} change to the positive direction, Table 4. In the EC, the goal burnup reactivity is obtained in the range of 400-500 MWe cores with thick pin, Fig. 4. This range may be lower if the recharge strategy is changed from 3 to 5 batches. The Δk_{Bu} estimated for 3-5 batches recharge is shown in Fig. 4 for selected cases. For the 5 batches case, a 300 MWe reactor presents a Δk_{Bu} of ~0.28 % < β_{eff}.

The ILR requirement of low burnup swing, of the order of β_{eff}, needs an improvement on the nuclear data uncertainty to enable a better prediction of core reactivity, Table 1. Therefore, an effort must be made to improve the uncertainty of the major actinides of the present evaluated data files.

The lead-voiding reactivity (LVR) was evaluated considering a loss of total flowing lead in the active core and adjacent regions. Figure 5 shows the LVR at the end of the equilibrium cycle (EOC) which is the worst condition analised for the selected cases. In the first cycle the LVR is more negative than the corresponding cases in the equilibrium cycle. This behaviour is due to the changes in fuel composition, U $\rightarrow$ TRUs, that increase the fuel η which raises the LVR. An ILR with power less than ~ 750 MWe has a negative LVR in the EC, see Fig. 5. Another result shown in this figure is that the LVR at BOC and EOC are comparable, which reflects the small fuel composition change at these times.

The peak fast fluence limit [19] of 4.0 x10^{23} (n/cm^2) in the cladding material is satisfied only in reactor with thin pin and small power, 300 MWe, at the beginning of life. In this respect, the ILR must be optmized. Some possibilities are: to lower the burnup; to shuffle the peak assemblies during recharge; to adopt axial power flattening.

The Doppler effect is low as expected in fast reactors with metallic fuel. The increase of the FF ratio is the best way to increase this effect. Therefore, not only the increase in the fuel pin diameter but also the reactor power increase contributes in this sense.

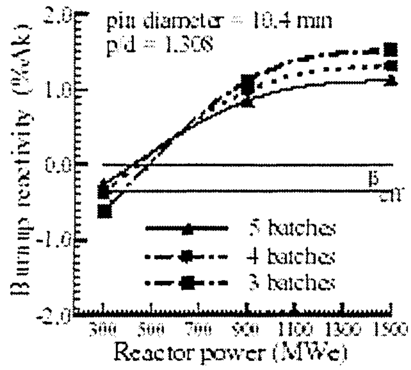

Fig. 4 Equilibrium cycle burnup reactivity versus reactor power and recharge batches number

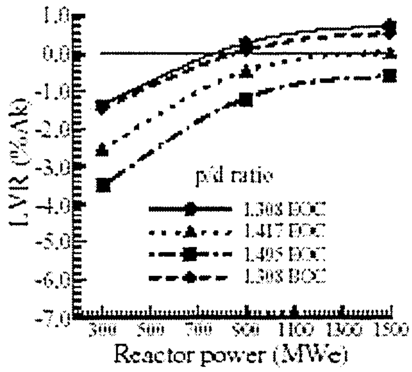

Fig. 5 End of equilibrium cycle, lead void reactivity versus reactor power and p/d ratio for a pin diameter of 10.4 mm

Conclusion

An ILR concept that satifies many requirements of the 4[th] generation reactor is proposed. A key characteristic is that it may be a cleaner concept due the partition/transmutation scheme adopted. The initial enriched uranium must be substituted quickly by the generated TRUs to mitigate the TOP reactivity. In the equilibrium cycle, the TOP accident will be not a concern for rector power of ~ 300 MWe, pin diameter of 10.4 mm and p/d ratio of 1.308 because Δk_{Bu} is < β_{eff} .The ILR must be optimized in respect to fast fluence to satisfy the present HT-9 limit of 4.0 x 10^{23} (n/cm^2). The

Doppler effect is small, as expected in fast reactors loaded with metallic fuel. The LVR is negative for reactor powers less than 750 MWe. The present nuclear data uncertainty must be improved, mainly for major actinides.

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