THE USE OF GRAPHITE IN CANDU FUEL WITH RECOVERED URANIUM

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ABSTRACT

Introducing recovered uranium(RU) into CANDU reactors derives double energy output due to the neutronic benefit of RU. However the coolant void reactivity at mid-burnup is somewhat increased due to the use of this RU. Therefore, graphite is introduced into the CANDU fuel of recovered uranium to reduce the coolant void reactivity. The lattice characteristics are calculated and analyzed for both 37-element and 43-element(CANFLEX) fuel bundles. The use of graphite rods in the RU bundle will improve the consequence of LOCA, as well as the power coefficient in CANDU reactors.

1. INTRODUCTION

With the good neutron efficiency of CANDU and the neutronic characteristics of RU, more energy can be extracted from RU than natural uranium. As well, RU offers many of the same benefits as SEU(Slightly Enriched Uranium) in CANDU. Hence, the use of RU has been previously proposed[1] in the past.

Since the CANFLEX(43-element) fuel bundle can significantly reduce the linear power rate and achieve a large burnup, it is considered as a means of introducing RU to CANFLEX bundles. But the coolant void reactivity is increased by using RU in two types of fuel bundles (37-element and 43-element) at mid burnup. Therefore, the use of graphite in RU fuel is considered to reduce the coolant void reactivity.

The use of graphite in fuel bundles has already been proposed to reduce the coolant void reactivity in CANDU reactors[2], based on the understanding of neutronic behavior in the CANDU lattice under nominal and voided conditions. Graphite rods inside the fuel bundle play a role as moderator/reflector under normal conditions, improving neutron economy. When voiding occurs, these graphite rods eliminate the positive void reactivity which can be mainly introduced by increasing the neutron thermal flux in the center region of the fuel bundle. Therefore, coolant void reactivity can be reduced by using graphite in the fuel bundle.

The concepts were evaluated for 37-element and 43-element(CANFLEX) RU(or NU) bundles. The lattice characteristics are calculated for the two types of fuel bundles in this study.

2. WIMS CALCULATIONS

Simulations were carried out using the WIMS-AECL code[3]. The ENDF/B-V library was used for neutron cross sections. The neutron spectrum was calculated in thirty-three energy groups. The PIJ option was used to model the fuel elements discretely in the WIMS calculations.

In order to determine the discharge burnup, the reactivity of the lattice making a critical state of reactor was obtained from a previous analysis of the CANDU 6 reactor. The k-infinity of the critical lattice was 1.045. The excess reactivity of 45 mk is accounted for the reactor leakage, as well as all the absorptions in the reactor, which are not considered in the lattice calculations.

To be compatible with existing CANDU reactors, two types of fuel bundles were used to evaluate the lattice characteristics in CANDU reactors. One is the 37-element fuel bundle and the other is the CANFLEX fuel bundle. WIMS calculations were done for the fuel bundles with NU(Natural Uranium) and RU. When using graphite with RU, the fuel bundles consist of either a central graphite rod and three outer rings containing RU, or 7 ~ 8 graphite rods in the inner and the outer two rings of RU fuels.

3. RESULTS AND DISCUSSIONS

Lattice characteristics are calculated for 37-element and 43-element (CANFLEX) fuel bundles. Figure 1(a) shows the relationship between MLHR(Maximum Linear Heat Rating) and the burnup at outer ring of 37-element fuel bundles, because the value of MLHR in a 37-element fuel bundle is largest at the outer ring. Four types of fuel models consist of NU, RU, RU with one graphite rod and RU with 7 graphite rods. The value of MLHR in the 37-element RU fuel with 7 graphite rods is too large(over 60 kw/m) to be used in CANDU reactors.

Figure 1(b) shows the relationship between MLHR and the burnup for 43-element fuel bundles. The four types of fuel models consist of NU, RU, RU with one graphite rod and RU with 8 graphite rods. The position of MLHR in 43-element fuel bundles with RU is moved from the outer to inner ring at ~ 3700 MWD/T. Aa well, the position of MLHR in 43-element fuel bundles with RU and a graphite rod is moved from the outer to inner ring at ~ 2000 MWD/T. The largest values of MLHR in 43-element fuel bundles with NU and RU are at the inner ring. The value of MLHR in 43-element RU fuel bundles with 8 graphite rods is the largest at the outer ring. The value of MLHR for an RU with 8 graphite rods is the largest, but this value is still smaller than that of a 37-element bundle with NU. Therefore, the use of RU with 8 graphite rods in the CANFLEX bundle is expected to be compatible with CANDU reactors.

Figure 2(a) shows the relationship between coolant void reactivity and the burnup for four fuel models of 37-element fuel bundles. The value of the coolant void reactivity of RU fuel is smaller than that of NU fuel at initial burnup but the trend is reversed after ~ 4000 MWD/MTU burnup. The value of the coolant void reactivity of RU is larger than that of NU after ~ 4000 MWD/MTU burnup, but when a graphite rod is used in the fuel bundle, the value of the coolant void reactivity is decreased.

Figure 2(b) shows the relationship between coolant void reactivity and burnup for four fuel models of 43-element fuel bundles. The value of the coolant void reactivity of RU fuel is smaller than that of NU fuel at initial burnup, but the trend is also reversed after ~ 4000 MWD/MTU burnup. The value of coolant void reactivity in the CANFLEX bundle is slightly larger than that of a 37-element fuel bundle, but when a graphite rod is used in the fuel bundle, the value of the coolant void reactivity decreases.

Figures 3(a) and 3(b) show the relationship between fuel temperature coefficients and burnups for four fuel models of 37-element and 43-element fuel bundles. The value of the fuel temperature coefficients of NU fuel is larger than those of others. When using graphite rods, the tendency and magnitude of the coefficients are almost same. Therefore, if the discharge burnup decreases, the fuel temperature coefficient becomes more negative at mid-burnup.

Figures 4(a) and 4(b) show the relationship between coolant temperature coefficients and burnups for four fuel models of 37-element and 43-element fuel bundles. The value of the coolant temperature coefficients of NU fuel is larger than those of others. When using 7 or 8 graphite rods, the coefficient is significantly decreased.

Figure 5(a) and 5(b) show the relationship between moderator temperature coefficients and burnups for four fuel models of 37-element and 43-element fuel bundles. The value of the moderator temperature coefficients of NU fuel is slightly larger than those of others.

The average lattice properties of the reactor core depend on the average fuel burnup of the core. In the CANDU reactor, the mid-burnup can be assumed to be the average fuel burnup. Therefore, the lattice characteristics at mid-burnup may represent reactor core characteristics in the CANDU reactors.

From the above results, the lattice parameters at mid burnup are calculated and summarized in Table 1 and 2. In the tables, all of the reactivity coefficients, except the fuel temperature coefficient, are positive. With the use of RU, as can be seen in Table 1, the absolute value of the fuel temperature coefficient is reduced and the other values are increased. Therefore, the use of RU fuel tends to make the CANDU safety characteristics worse than the use of the current NU fuel.

The use of a central graphite rod within fuel bundles improves the lattice parameters a little and its burnup penalty can be ignored because the amount is less than 0.35 %. As shown in the table, however, this improvement is not enough when considering the power coefficient, which is a function of both the fuel temperature coefficient and the coolant temperature coefficient in CANDU reactors.

The number of graphite rods is increased up to the inner ring in the fuel bundles to improve the safety characteristics. In this case, the value of coolant void reactivity is significantly reduced and the fuel temperature coefficient is also improved. Therefore, the power coefficient becomes better than that of the current fuel. However its burnup penalty is somewhat increased, up to 5.5 %. Also, since the value of MLHR is significantly increased, the fuel performance should be evaluated.

4. CONCLUSIONS

When using RU fuels, the absolute value of fthe uel temperature coefficient is decreased but the values of the coolant and moderator temperature coefficients are increased at mid-burnup. This is not desirable in terms of safety in CANDU reactors. When using graphite rods within RU fuel bundle, however, the value of the coolant temperature coefficient is decreased. In addition, the absolute value of fuel temperature coefficient is increased. This will improve the CANDU safety characteristics of the power coefficient and the consequence of LOCA as well. Therefore, when RU fuel is introduced into CANDU reactors, the use of graphite in the center region of an RU fuel bundle is strongly recommended. These findings will be especilly important in countries where regulations require that power coefficients should be negative. A more extensive study on core calculations will be continued in the future.

REFERENCE

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2. MIN B.J., KIM B.G., SIM K-S. and SUK H.C., "The Use of Graphite for the Reduction of void reactivity in CANDU Reactors", Proceedings of the 4th International Conference on CANDU Fuel, Pembroke, October (1995)
3. DONNELLY J.V., "WIMS-CRNL : A User's Manual for the Chalk River Version of WIMS", AECL-8955, January (1986)

TABLE 1. THE VALUES FOR VARIOUS FUEL TYPES BASED ON K_{inf}

Fuel Types	MLHR (kW/m)	Coolant Void Reactivity (mk)	Fuel Temp. Coeff. (mk/℃)	Coolant Temp. Coeff. (mk/℃)	Moderator Temp. Coeff. (mk/℃)	Discharge Burnup (MWD/MTU)
37-elm. (NU37)	58.044	14.44756	-.00126	.05254	.02751	6988
37-elm. (RU37)	58.884	14.73053	-.00080	.05599	.03744	12548
CANFLEX (NU43)	48.821	15.46555	-.00147	.05619	.02893	6939
CANFLEX (RU43)	49.288	15.76631	-.00091	.05866	.03831	12485

TABLE 2. THE VALUES FOR VARIOUS TYPES OF RU FUEL WITH GRAPHITE RODS

Fuel Types	MLHR (kW/m)	Coolant Void Reactivity (mk)	Fuel Temp. Coeff. (mk/℃)	Coolant Temp. Coeff. (mk/℃)	Moderator Temp. Coeff. (mk/℃)	Discharge Burnup (MWD/MTU)
37-elm. (C1+RU36)	59.768	14.34245	-.00085	.05468	.03705	12507
37-elm. (C7+RU30)	67.438	12.17765	-.00108	.04878	.03954	12103
CANFLEX (C1+RU42)	51.256	15.30020	-.00106	.05780	.03861	12445
CANFLEX (C8+RU35)	57.249	12.56472	-.00149	.05084	.04186	11833

* NU : Natural Uranium
* RU : Recovered Uranium
* C : Graphite in Center or Inner Ring
* N# : Number of Rods
* All Temperature coefficients and coolant void reactivity at Mid Burnup

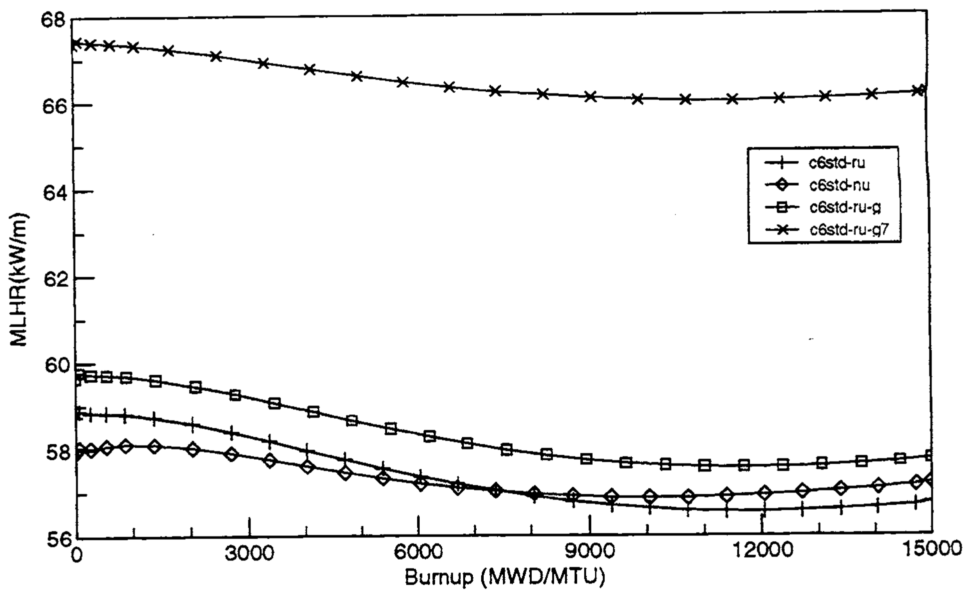

FIGURE. 1(a) MLHR FOR 37-ELEMENT BUNDLE

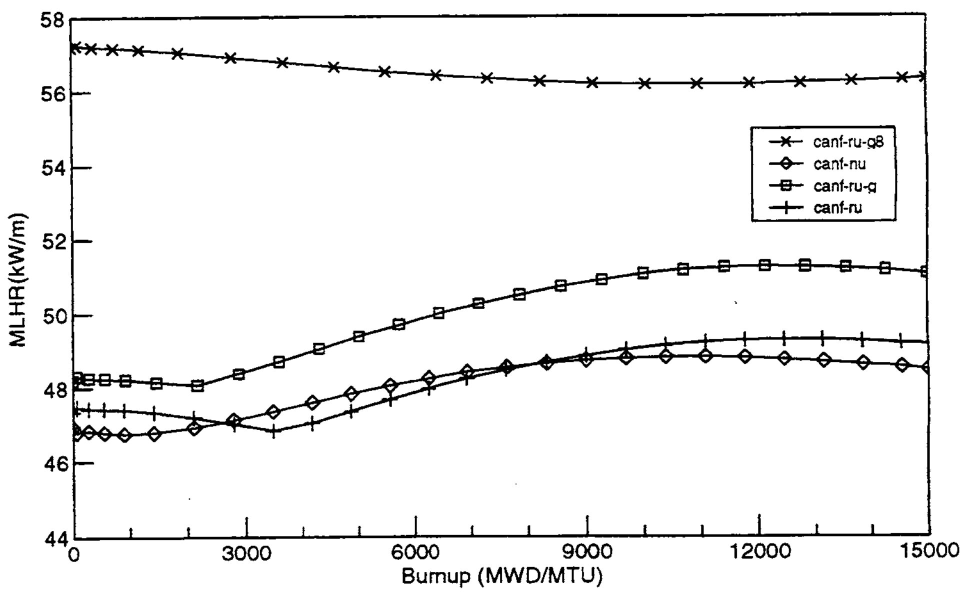

FIGURE 1(b) MLHR FOR 43-ELEMENT BUNDLE

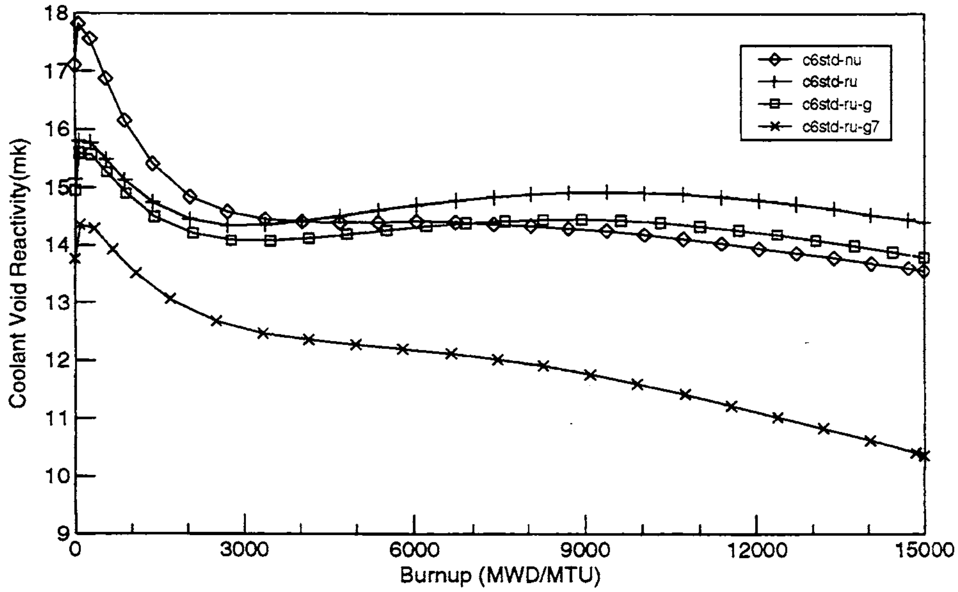

FIGURE 2(a) COOLANT VOID REACTIVITY FOR 37-ELEMENT BUNDLE

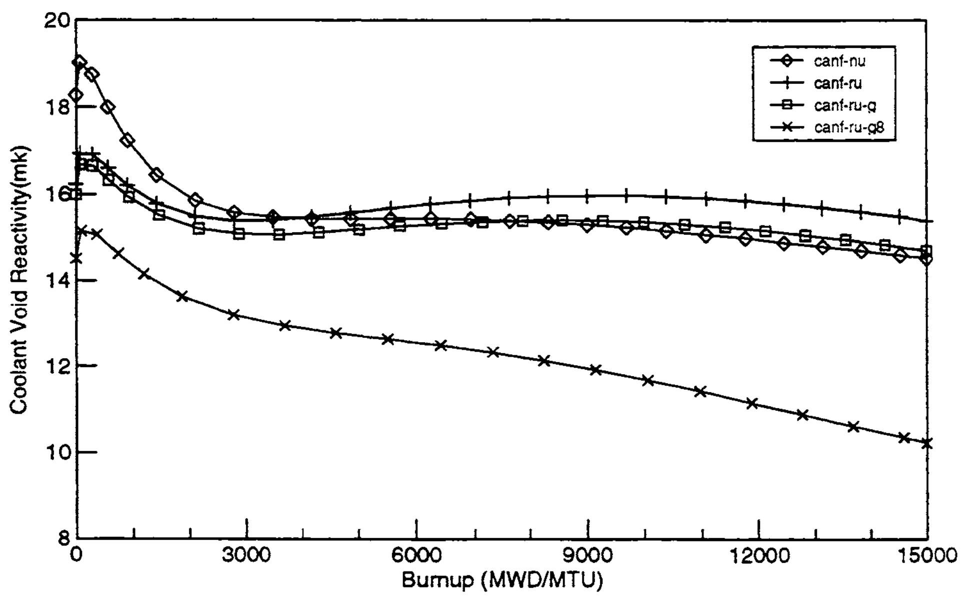

FIGURE 2(b) COOLANT VOID REACTIVITY FOR 43-ELEMENT BUNDLE

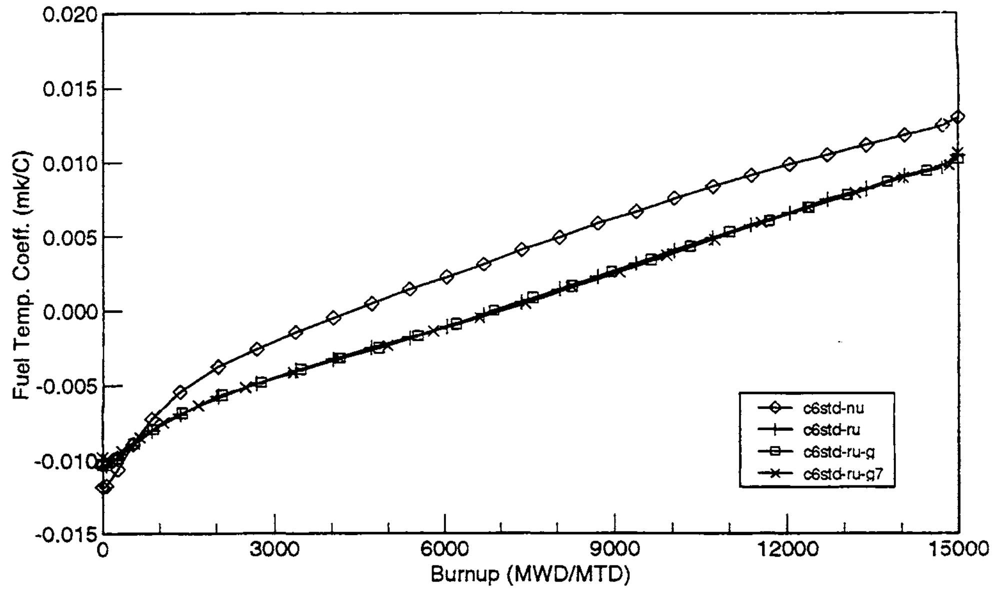

FIGURE 3(a) FUEL TEMPERATURE COEFFICIENTS FOR 37-ELEMENT BUNDLE

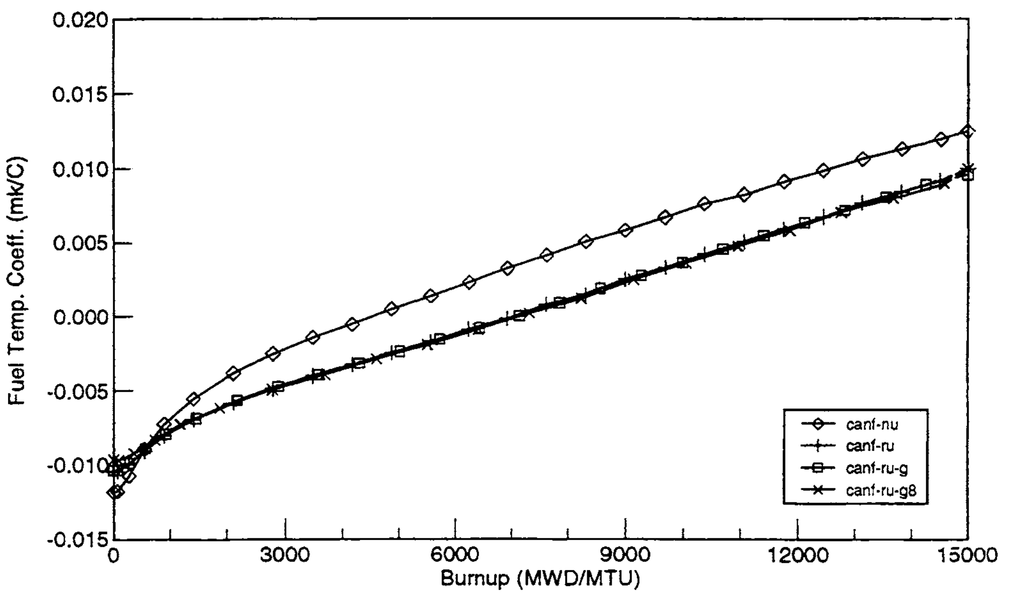

FIGURE 3(b) FUEL TEMPERATURE COEFFICIENTS FOR 43-ELEMENT BUNDLE

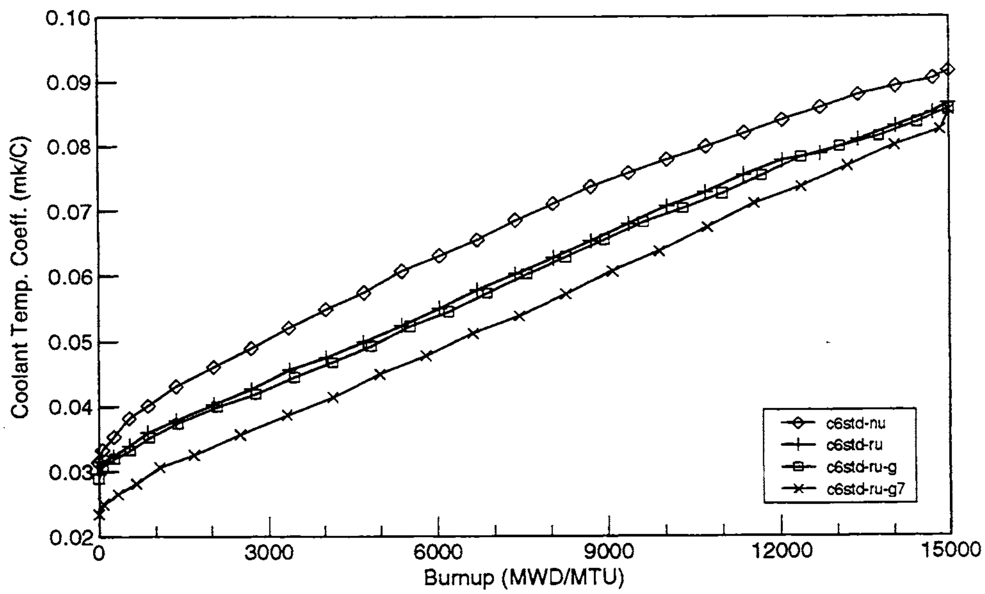

FIGURE 4(a) COOLANT TEMPERATURE COEFFICIENTS FOR 37-ELEMENT BUNDLE

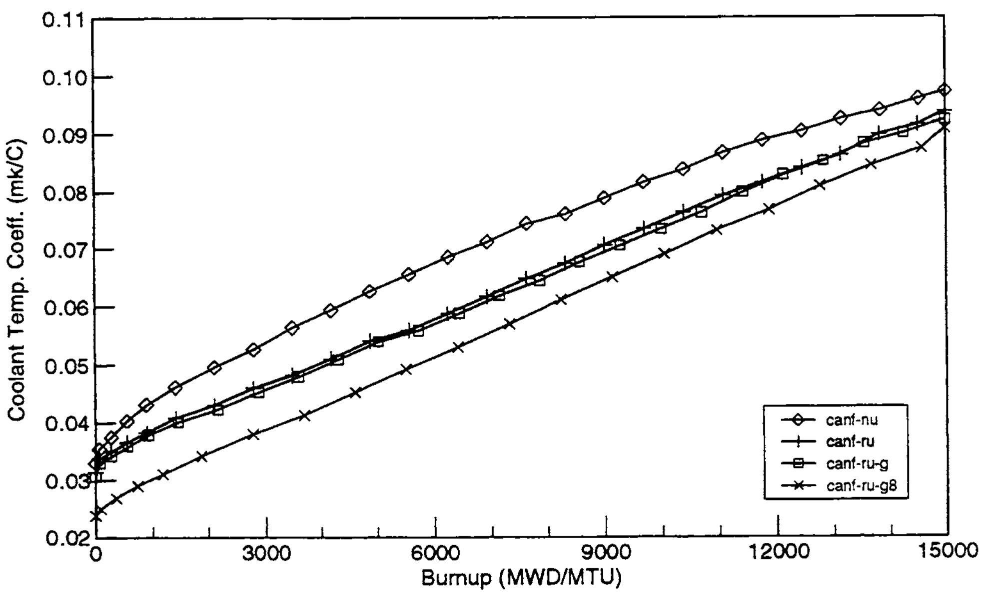

FIGURE 4(b) COOLANT TEMPERATURE COEFFICIENTS FOR 43-ELEMENT BUNDLE

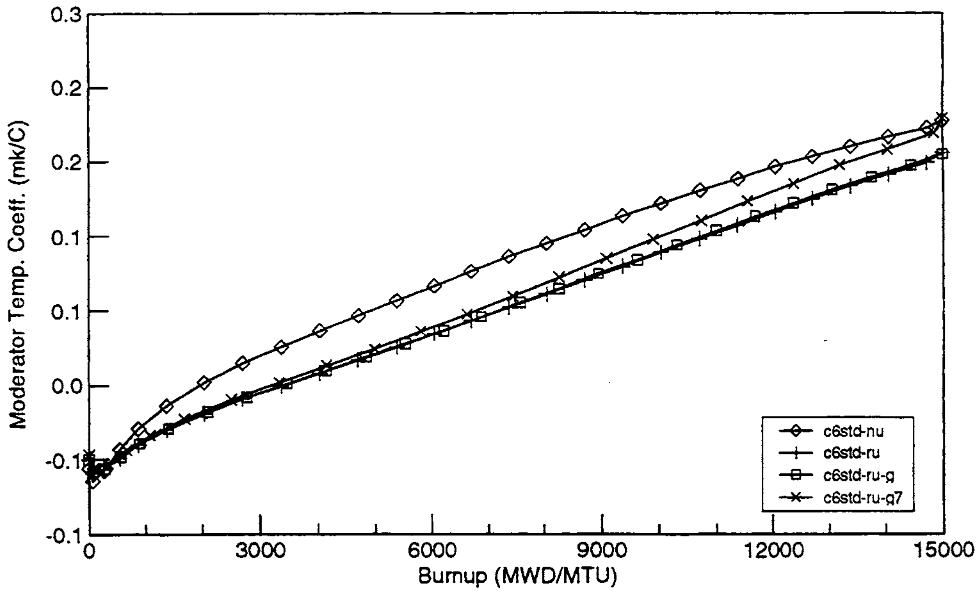

FIGURE 5(a) MODERATOR TEMPERATURE COEFFICIENTS FOR 37-ELEMENT BUNDLE

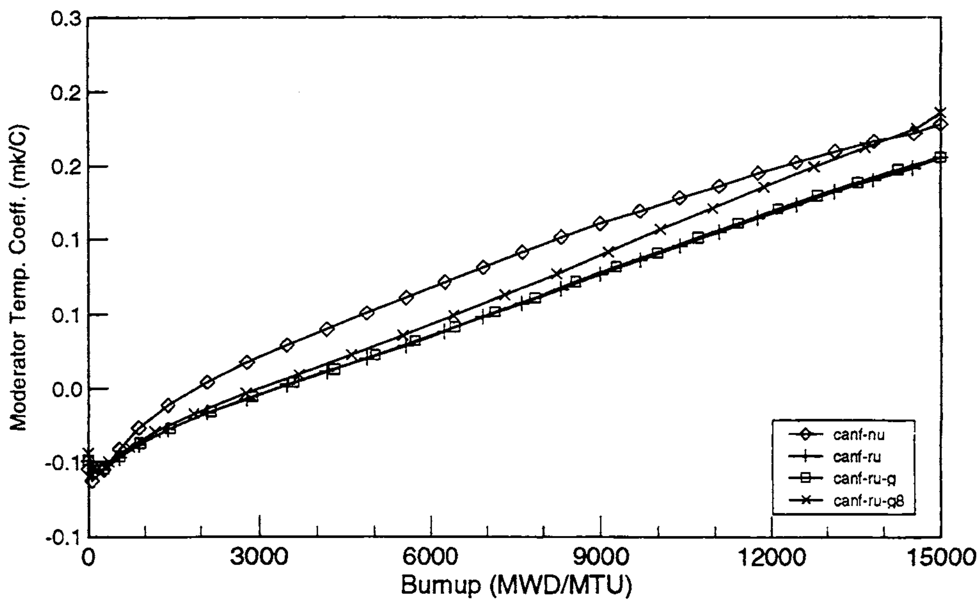

FIGURE 5(b) MODERATOR TEMPERATURE COEFFICIENTS FOR 43-ELEMTNE BUNDLE