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The Application of the Goal Programming to CANDU Fuel Management Optimization

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ABSTRACT

A Goal Programming formulation to CANDU fuel management optimization is proposed. Four objectives are considered, respectively : the feed rate, CPPF (Channel Power Peaking Factor), BPPF (Bundle Power Peaking Factor) and CPR (Critical Power Ratio). This problem is investigated using a numerical approach to optimization established on STepMethod and the use of loss matrix. The optimization technique developed is more adequate for fuel management analysis for fissile enriched fuel cycles, in which cases the relative importance of the objectives could be modified. Numerical results are presented for 0.93% SEU fueled CANDU 6Mk1 core and weapons-grade plutonium burning in CANDU 6Mk1 core, using standard 37 rod fuel bundle.

I. INTRODUCTION

The first attempts at CANDU fuel management optimization were made to correct undesirable flux distributions and the methods used were mostly heuristic[1],[2]. More recently, optimization techniques suitable for CANDU reactor fuel management were studied[3],[4]. In the published research studies an economic model, showing a direct dependence of the fuel costs on the feed rate of fresh fuel in the reactor, was used to formulate an optimization problem with one primary objective, minimize the feed rate, while the remaining objectives were expressed as constraints. The characteristics of such a problem and optimization techniques are:

- one primary goal to be minimized;
- targets or constraints are inflexible; no deviations are allowed;
- the equilibrium flux and power distributions are used to evaluate the objective function and to verify the constraints.

The paper proposes a goal programming formulation to CANDU fuel management optimization. Four objectives are considered, respectively: refuel ratio, CPPF (**C**hannel **P**ower **P**eaking **F**actor), BPPF (**B**undle **P**ower **P**eaking **F**actor) and CPR (**C**ritical **P**ower **R**atio). This problem is investigated using a numerical approach to optimization established on STepMethod and the use of loss matrix. The characteristics of this problem and the optimization techniques are:

- all objectives are ranked, each with a target;
- the constraints are flexible, deviations are acceptable. The constraints can be relaxed.
- the objective is to minimize the sum of the undesirable deviations, weighted by their relative importance.
- the equilibrium and instantaneous flux and power distributions and neutronic and thermalhydraulics calculations are called to evaluate the values of objective functions and to verify the constraints.

In Section II we present the mathematical optimization model, the system equation and the constraints and the technique applied to solve the optimization problem. Numerical results are presented in Section III for 0.9% SEU fueled CANDU 6Mk1 core and weapons-grade plutonium burning in CANDU 6Mk1 core, using standard 37 rod fuel bundle. In Section IV the conclusions are provided.

II. OPTIMIZATION TECHNIQUE

The primary purpose of this work was to investigate the feasibility of applying a Goal Programming Optimization Technique to the in-core fuel management of CANDU reactor. Characteristics and requirements of the optimization problem were to be assessed.

The ultimate goal of the optimization is to develop an equilibrium refueling strategy that will keep the reactor operating at critical and maximize the reactor availability by eliminating operations that could induce clad failures or refueling machine outage.

II. 1. The Mathematical Optimization Model

The objectives of fuel management optimization problem are formulated on economic models. Economic models show a direct dependence of the "index of performance", expressed by the actualized cost of generated energy, on the fuel operation conditions, corresponding to fuel management strategy and fuel bundle characteristics, and on the safety requirements.

We quantified these objectives in the following mathematical program:

$$\min_{X\in D} f_1 = \min_{X\in D} \sum_{l=1}^{N} \frac{1}{\theta_l} \sum_{k=1}^{m_l} \overline{F_{lk}\Psi_{lk}}$$

$$\min_{X\in D} f_2 = \min_{X\in D} \sum_{l=1}^{N} \frac{1}{N\,T_l}$$

$$\min_{X\in D} f_3 = \min_{X\in D} \left\{ \max_{l} \left[\frac{P(l)}{P_0(l)} \right] \right\}$$

$$\min_{X\in D} f_4 = \min_{X\in D} \left\{ \max_{i,j,l} \left[\frac{p(i,j,l}{p_0(i,j,l)} \right] \right\}$$

$$\max_{X\subset D} f_5 = \max_{X\subset D} \left\{ \min_{l} \left[\frac{P_{\lim}(l)}{P(l)} \right] \right\}$$

where:

f_1 - feed rate (bundle/day), characterizing the fuel cost

f_2 - feed rate (channels/day), characterizing the refueling machine utilization

f_3 - CPPF (Channel Power Peaking Factor), characterizing the overpower protection

f_4 - BPPF (Bundle Power Peaking Factor), characterizing, by power envelope, the fuel bundle behavior

f_5 - CPR (Critical Power Ratio), characterizing the thermalhydraulic requirements

N - total number of channels

n_l - number of fresh bundles loaded in channel l at each visit of the refueling machine

ϑ_l - exit irradiation for channel l

T_l - time interval between two consecutive visits of channel l

$\overline{F_{lk}\Psi_{lk}}$ - normalized fuel flux

P_0 (l) - channel power at equilibrium

P (l) - instantaneous channel power- refueling simulation

P_{lim} (l) - dryout power for channel l

p_0 (i,j,l) - bundle power at equilibrium

p (i,j,l) - instantaneous bundle power- refueling simulation

X - decision variables vector

Regarding the decision variables vector we have considered only the control components characterizing the core configuration and fuel management strategy, respectively:

x_1 - burnup regions configuration

x_2 - axial refueling scheme configuration

x_3 - exit irradiation's distributions

The use of a XYZ geometry representation for the core model leads to a discrete character of the control variables concerning: number of channels in each burnup region, number of channels with different axial refueling schemes, number of fresh bundles loaded in a channel at each visit of the refueling machine. The number of channel positions and the radial symmetry condition for the core configuration were used to evaluate the interval range for these control variables. The exit irradiation distribution was characterized by the value of exit irradiation in central burnup region - θ - and the exit irradiation in burnup region i to exit irradiation in central burnup region ratio- α_i . The exit irradiation in central burnup region is determined by the criticality constraint. In this way only the α_i are control variables and they have a continuos character.

The technique applied to solve the optimization problem is a steepest numerical method, where the decision variables are modified at each iteration. The algorithm steps are:

1. A first guess for the axial refueling scheme is made., which must correspond to a feasible case, and can be obtained from supercell or cell calculations. In the case of cell calculations we use the facilities developed for LATREP-T3S computer program[5].

2. Two burnup regions are considered and a first guess for the number of channels in inner burnup region is made.

3. The optimal discharge burnup (or irradiation) distribution is computed using a numerical alghoritm established on STepMethod and the use of loss matrix.

4. The optimal solution $S^{(i)}$ is stored. A new configuration of burnup regions is defined.

5. The step 3 is repeated and optimal solution $S^{(i+1)}$ is compared to $S^{(i)}$. If $S^{(i+1)}$ is better the step 4 is repeated. If not, the better solution is stored and the axial refueling scheme is changed.

6. The steps 2-5 are repeated until $S^{(n+1)}$ is unacceptable compared to $S^{(n)}$.

The essential step 3 involves the objective functions' evaluations, using the equilibrium and instantaneous flux and power distributions from neutronic and thermalhydraulics calculations, and the optimal discharge burnup distribution evaluations, using a numerical alghoritm developed by R. Benayonu, O. Laritchev, J. de Montgolfier and J. Tergny[6].

The method consists in:

3.1. From numerical tables, for each objective function the optimal values are evaluated.

3.2. The loss matrix $A=\left\|\lambda_{ij} a_{ij}\right\|$ is builded, where:

λ_{ij} - the importance of objective function I

$$a_{ij} = \left|F_i(X_i) - F_i(X_j)\right|$$

X_i, X_j - the optimal solutions for objective function i and j, respectively.

If the functions have equal importance then the loss matrix must be symmetric and then:

$$\lambda_{ij} a_{ij} = \lambda_{ji} a_{ji}$$

and λ_{ij} are computed.

3.3. The optimal solution S^* is computed as a solution of the following problem:

$$\min_D\left(\sum_i \sum_j \lambda_{ij}\left(X_j - X_i\right)^2\right)$$

3.4. The deciding user compares and chooses:

- each objective function have an acceptable value for S^*. In this case S^* is the optimal solution and the alghoritm stops.
- none of them have acceptable value for S^*. The problem has not a solution.
- There are a few functions with unacceptable values, but they can accept a penalty of their maximum value by decreasing the maximum value of F_j^*.

3.5. Let be ΔF_j^* the penalty proposed for F_j^*. The alghoritm returns to step 3.2. considering the supplementary constraints:

$$F_j^*(X) \geq F_j^*(S^*) - \Delta F_j^*$$

$$F_j(X) \geq F_j(S^*), j \neq j^*$$

The equilibrium and instantaneous flux and power distributions and neutronic and thermalhydraulics calculations are called to evaluate the values of objective functions and to verify the constraints. For our analysis a key role in objective function's computation is played by fuel management computer program SERA[7],[8], excepting the thermalhydraulic calculations.

For past thermalhydraulic analysis the AECL computer programs HYDNA and NUCCP was used. At the present time, for new analysis, such as weapons-grade plutonium burning in CANDU reactors, we have used, for CRP computation, tabled coefficients as function of axial power shape. That is because, at the present time, we do not have in use a specialized thermalhydraulic code for CANDU reactors.

Equilibrium calculations, using time-average approximation, and refueling simulation, using random-age method, are done in order to compute and to store the objective function values for different values of α_i. The interval range for α_i is chosen from integrated multiplication properties and bundle power to cell flux ratio evolution with burnup.

Apparently, a great number of complex calculations are called to be done. Practically, the number and the computing time are relatively small, due to:

- the flexibility of the alghoritm, which permits the intervention of the deciding user at each step;
- the facilities offered by the fuel management computer code SERA, as there are presented in [5];
- the experience of the deciding user.

Two numerical application are presented in the next Section.

III. NUMERICAL APPLICATIONS

The technique described was used by the authors for advanced fuel cycles analysis for CANDU reactors. Some numerical results are presented in [9], for 1% SEU fueled CANDU 6Mk1 core. In this paper we present two numerical applications for 0.93% SEU fueled CANDU 6Mk1 core and MOX- weapons-grade plutonium- fueled CANDU 6 Mk1 core.

For both applications the same reactor model and assumptions are used These are:

- a detailed XYZ 42x28x22 mesh points core model
- a detailed representation of adjuster rods and ZCU
- 45% water level in ZCU
- the remainder of reactivity devices simulated by 2 mk reactivity excess
- the same thermal absorption cross section increments, for adjuster rods, as for the natural uranium fuel case
- standard 37 rod fuel bundle
- the top to bottom asymmetry, due to ZCU characteristics, was neglected and a radial symmetry for burnup region's configuration was considered.

III.1. Solution of the optimisation problem for 0.93% SEU Fueled CANDU 6Mk1 Core

The choice of a 0.93% enrichment is motivated by the requirement to reach a maximum 18 MWd/kgHE of fuel rod, a constraint for the use of 37 rod fuel bundle. Moreover, this enrichment offers the opportunity to develop a solution independent on uranium source: SEU or RU.

The optimal solution search was initiated with a 4-bundle shift refueling scheme, two burnup regions, with 124 channels in inner burnup region. 3-bundle shift refueling scheme was found as optimal value, for axial refueling decision variable. However, imposing for the number of fresh bundle loaded to be an even number, a 2÷4-bundle shift refueling scheme was searched.

The final optimal solution, concerning refueling scheme and burnup regions' configurations, is illustrated in Figures 1 and 2. The main parameters for core are presented in Table 1. A detailed refueling simulation, for 200 days with a 10 day step, was done in order to verify the solution.

The power envelope and power boost envelope are illustrated in Figures 3 and 4. The solution responds to the use of standard 37 rod fuel bundle constraint.

III.1. Solution of the optimisation problem for MOX-Weapons-grade *Plutonium-Fueled* CANDU 6MK1 Core

High operating neutron flux, high neutron economy and on-power refueling make CANDU particularly suitable for the annihilation of weapons -grade plutonium [10]. The option being considered in this paper for disposing of weapons-grade plutonium is burning the plutonium in the form of a mixed UO_2 - PuO_2 fuel using standard 37 rod fuel bundle.

The source for uranium can be: recycled uranium from LWR, low enriched uranium from enriching plant or CANDU spent fuel. For this analysis the fuel consists in a mixed CANDU spent fuel (0.23% U^{235}, 0.25% Pu^{239}) and Pu^{239}.

The objectives of the study were as follows:

- to preserve the power envelope of the standard 37 rod fuel bundle;
- to reduce to zero the void reactivity effect for equilibrium fuel.

Details regarding fuel bundle composition configuration are presented in [11]. We present in this paper only the results of the fuel management optimization procedure applied for the average 1.5% Pu^{239} enriched fuel bundle. The fuel bundle composition is illustrated in Table 2. The optimisation procedure was completed with an external search for optimal fuel bundle configuration.

The optimal solution search was initiated with a 1-bundle shift refueling scheme, two burnup regions, with 124 channels in inner burnup region. The alghoritm was stopped when acceptable values for BPPF and CPPF were obtained. The main reason is the high priority level accorded to the objective regarding the preservation of power envelope of standard 37 rod fuel bundle.

The increase of the importance of feed rate (channels/day), describing the cost component corresponding to refueling machine utilization, leads to a change in fuel bundle configuration, concerning fissile distribution, and a 2-bundle shift refueling scheme can be achieved.

A similar situation was repeated for an average 1.2% Pu^{239} enriched fuel bundle, for which a 2 or 4-bundle shift refueling scheme as optimal solution is dependent on radial distribution of fissile in fuel bundle rings.

The main results are presented in Table 3 and the power envelopes are illustrated in Figures 6 and 7.

To illustrate the importance of a detailed physics model an intermediate solution is also presented. By the point of view of equilibrium model this solution appears to be acceptable. In fact it is not, as is illustrated by the power envelope.

IV. CONCLUSIONS

The paper presents a Goal Programming formulation of in-core fuel management optimization for CANDU 6Mk1 core. The main characteristics of the mathematical model and of the technique developed for solving the optimisation problem are:

- three main components of economic "index of performance" are involved, respectively: fuel cost, refueling machine utilization and reactor availability. Five objective functions are used to describe the cost components.
- a numerical approach to optimization established on STepMethod and the use of loss matrix is used. A detailed physical description of the core is preferred to a sophisticated analytical mathematical method.
- the constraints are flexible, deviations are acceptable. The constraints can be relaxed.
- the objective is to minimise the sum of the undesirable deviations, weighted by their relative importance.
- apparently, a great number of complex calculations are called to be done. Practically, the number and the computing time are relatively small, due to the flexibility of the alghoritm, which permits the intervention of the deciding user at each step, and to the performances offered by the new PC generation and the facilities than can be developed for fuel management computer programs.

Two numerical applications, for 0.93% SEU and MOX- weapons-grade plutonium-fueled CANDU 6Mk1 core, are presented. The results do not exhaust the physical aspects implied by the use of these fuels. Nevertheless, the optimal fuel management solutions demonstrate the feasibility of using these fuel cycles in the CANDU 6Mk1 reactor, without constructive and operational alterations.

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Table 1. The main parameters for 0.93% SEU fueled CANDU 6Mk1 Core

Equilibrium maximum channel power (kW)	6375 (M-17)
Equilibrium maximum bundle power (kW)	762 (M-14, 3)
Equilibrium CPR	1.42
Maximum power envelope (kW)	839
Maximum overpower envelope (kW)	943
Discharge burnup (MWd/kgHE): region 1	13.53
region 2	15.41
region 3	16.05
average	15.05
Equilibrium feed rate: channels/day	2.36
bundle/day	7.62
Instantaneous maximum average channel power (kW) (random-age method)	7084
Instantaneous maximum average bundle power (kW) (random-age method)	872
Average CPPF (random-age method)	1.216
Average BPPF (random-age method)	1.237
Average CPR (random-age method)	1.312
Maximum channel power (kW) (detailed refueling simulation)	7197
Maximum bundle power (kW) (detailed refueling simulation)	892

Table 2. Standard 37 rod fuel bundle configuration
MOX-Weapons-grade Plutonium- Fuel

Bundle Type	***O15***	***D15***	***CF15***	***B12***	***CF12***
Central Rod	1.5% Pu-239 2.0% B-10	1.9% Pu-239 2.0% B-10	0.25% Pu-239 2.0% B-10	1.75% Pu-239 1.23% B-10	0.25% Pu-239 1.35% B-10
1-st Inner Ring	1.5% Pu-239 2.0% B-10	1.9% Pu-239 2.0% B-10	0.25% Pu-239 2.0% B-10	1.75% Pu-239 1.23% B-10	0.25% Pu-239 1.35% B-10
2-nd Inner Ring	1.5% Pu-239	2.01% Pu-239	2.56% Pu-239	1.48% Pu-239	2.03% Pu-239
External Ring	1.5% Pu-239	1.00% Pu-239	1.28% Pu-239	0.80% Pu-239	1.01% Pu-239

Table 3. The main parameters for MOX- weapons-grade plutonium-fueled CANDU 6MK1 core

Parameter	**Bundle O15** *1-bundle shift*	**Bundle O15** *2-bundle shift*	**Bundle D15** *2-bundle shift*	**Bundle B12** *4-bundle shift*	**Bundle CF12** *2-bundle shift*
Equilibrium Maximum Channel Power (kW)	6402	6398	6406	6471	6404
Equilibrium Maximum Bundle Power (kW)	749	757	725	745	731
Maximum Average Channel Power (kW)	6688	6976	6817	7035	6840
Maximum Average Bundle Power (kW)	782	857	793	871	803
Average CPPF	1.07	1.12	1.09	1.18	1.11
Average BPPF	1.07	1.16	1.11	1.27	1.12

Figure 1. Burnup Regions' Configuration: 0.93% SEU Fueled CANDU 6Mk1 Core

Exit Irradiations (n/kb):

region 1=2.9432113; region 2=3.344558; region 3=3.511786

☐	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	☐
A									1	1	1	1	1	1									A
B						1	1	1	1	1	1	1	1	1	1	1	1						B
C					1	1	1	1	1	3	3	3	3	1	1	1	1	1					C
D				1	1	1	3	3	3	3	3	3	3	3	3	3	1	1	1				D
E			1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1			E
F			1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1			F
G		1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1		G
H		1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1		H
J	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	J
K	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	K
L	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	L
M	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	M
N	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	N
O	1	1	1	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	1	1	1	O
P		1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1		P
Q		1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1		Q
R			1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1			R
S			1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1			S
T				1	1	1	3	3	3	3	3	3	3	3	3	3	1	1	1				T
U					1	1	1	1	1	3	3	3	3	1	1	1	1	1					U
V						1	1	1	1	1	1	1	1	1	1	1	1						V
W									1	1	1	1	1	1									W
☐	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	☐

Figure 2. Axial Refueling Scheme Configuration: 0.93% SEU Fueled CANDU 6Mk1 Core

☐	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	22	☐
A									4	-4	4	-4	4	-4									A
B						4	-4	4	-4	4	-4	4	-4	4	-4	4	-4						B
C					4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4					C
D				4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4				D
E			4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4			E
F			-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4			F
G		-4	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4	4		G
H		4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4		H
J	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4	J
K	-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4	K
L	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4	L
M	-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4	M
N	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4	N
O	-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4	O
P		-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4		P
Q		4	-4	4	-4	2	-2	2	-2	2	-2	2	-2	2	-2	2	-2	4	-4	4	-4		Q
R			4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	-4	4	-4			R
S		-	4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4			S
T				-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4				T
U					-4	4	-4	4	-4	4	-4	4	-4	4	-4	4	-4	4					U
V						-4	4	-4	4	-4	4	-4	4	-4	4	-4	4						V
W									-4	4	-4	4	-4	4									W
☐	1	2	3	4	5	6	7	8	9	1	11	12	13	14	15	16	17	18	19	2	21	22	☐

Figure 3. Equilibrium Channels Power Map

□	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	□
A									3407	3494	3568	3568	3494	3408									A
B						3137	3719	4211	4475	4626	4669	4669	4626	4475	4212	3720	3138						B
C					3453	4125	4718	5131	5362	5274	5248	5249	5275	5363	5132	4719	4127	3454					C
D				3602	4357	4996	5299	5585	5734	5751	5647	5647	5751	5735	5586	5300	4998	4359	3603				D
E			3529	4453	5140	5455	5772	5959	6025	6001	5877	5878	6002	6026	5960	5774	5457	5142	4454	3531			E
F			4356	5193	5698	5836	6009	6099	6050	6009	5948	5948	6010	6051	6101	6011	5838	5700	5195	4358			F
G		3971	4959	5711	5977	5988	6132	6186	6119	6098	6117	6117	6099	6120	6188	6133	5990	5980	5713	4961	3973		G
H		4501	5455	6043	5961	6066	6157	6203	6179	6182	6220	6221	6183	6180	6204	6159	6068	5963	6046	5457	4503		H
J	3651	4855	5794	6053	6065	6124	6179	6224	6288	6295	6311	6312	6296	6290	6225	6181	6127	6067	6055	5796	4857	3652	J
K	3859	5130	6029	6204	6137	6163	6224	6257	6316	6291	6217	6218	6291	6317	6259	6226	6165	6140	6207	6032	5132	3861	K
L	3991	5273	6164	6328	6306	6310	6293	6291	6330	6282	6176	6177	6283	6332	6293	6296	6313	6308	6331	6167	5276	3993	L
M	3993	5279	6181	6364	6369	6373	6329	6307	6336	6283	6176	6176	6284	6337	6308	6331	6375	6371	6367	6183	5282	3994	M
N	3861	5141	6067	6296	6342	6364	6317	6292	6326	6291	6216	6216	6292	6327	6294	6319	6367	6345	6299	6069	5143	3862	N
O	3644	4854	5815	6127	6254	6310	6254	6243	6286	6289	6306	6306	6290	6288	6245	6256	6312	6257	6129	5817	4856	3645	O
P		4470	5422	6024	5971	6076	6139	6169	6147	6162	6212	6212	6162	6149	6171	6140	6078	5973	6026	5424	4472		P
Q		3904	4862	5577	5812	5829	6000	6083	6045	6061	6114	6114	6061	6046	6084	6002	5831	5814	5579	4864	3905		Q
R			4205	4960	5347	5502	5772	5927	5928	5945	5974	5974	5946	5929	5928	5774	5503	5349	4962	4207			R
S			3365	4193	4752	5081	5489	5737	5847	5863	5777	5777	5863	5848	5738	5490	5082	4753	4195	3366			S
T				3385	4083	4708	5032	5346	5516	5542	5437	5437	5543	5517	5347	5033	4709	4084	3386				T
U					3256	3909	4481	4894	5122	5023	4944	4944	5024	5123	4895	4482	3910	3256					U
V						2974	3532	4008	4260	4393	4426	4426	4393	4260	4009	3533	2975						V
W									3239	3316	3389	3389	3316	3239									W
□	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	□

Figure 4. CPR Values Map

	1	2	3	4	5	6	7	8	9	10	11
A									1.72	1.69	1.65
B						1.80	1.58	1.69	1.60	1.60	1.62
C					1.73	1.62	1.59	1.49	1.51	1.57	1.62
D				1.69	1.57	1.55	1.53	1.42	1.51	1.56	1.58
E			1.78	1.51	1.54	1.52	1.51	1.52	1.50	1.53	1.51
F			1.57	1.52	1.50	1.53	1.56	1.51	1.50	1.52	1.54
G		1.62	1.57	1.58	1.55	1.51	1.50	1.53	1.51	1.50	1.51
H		1.65	1.51	1.53	1.54	1.51	1.50	1.49	1.48	1.49	1.48
J	1.67	1.58	1.56	1.53	1.57	1.51	1.50	1.49	1.52	1.50	1.52
K	1.62	1.55	1.50	1.53	1.52	1.55	1.50	1.51	1.53	1.50	1.49
L	1.67	1.52	1.49	1.51	1.53.	1.54	1.50	1.49	1.48	1.52	1.49
M	1.67	1.52	1.49	1.51	1.53.	1.54	1.50	1.49	1.48	1.52	1.49
N	1.62	1.55	1.50	1.53	1.52	1.55	1.50	1.51	1.53	1.50	1.49
O	1.67	1.58	1.56	1.53	1.57	1.51	1.50	1.49	1.52	1.50	1.52
P		1.65	1.51	1.53	1.54	1.51	1.50	1.49	1.48	1.49	1.48
Q		1.62	1.57	1.58	1.55	1.51	1.50	1.53	1.51	1.50	1.51
R			1.57	1.52	1.50	1.53	1.56	1.51	1.50	1.52	1.54
S			1.78	1.51	1.54	1.52	1.51	1.52	1.50	1.53	1.51
T				1.69	1.57	1.55	1.53	1.42	1.51	1.56	1.58
U					1.73	1.62	1.59	1.49	1.51	1.57	1.62
V						1.80	1.58	1.69	1.60	1.60	1.62
W									1.72	1.69	1.65

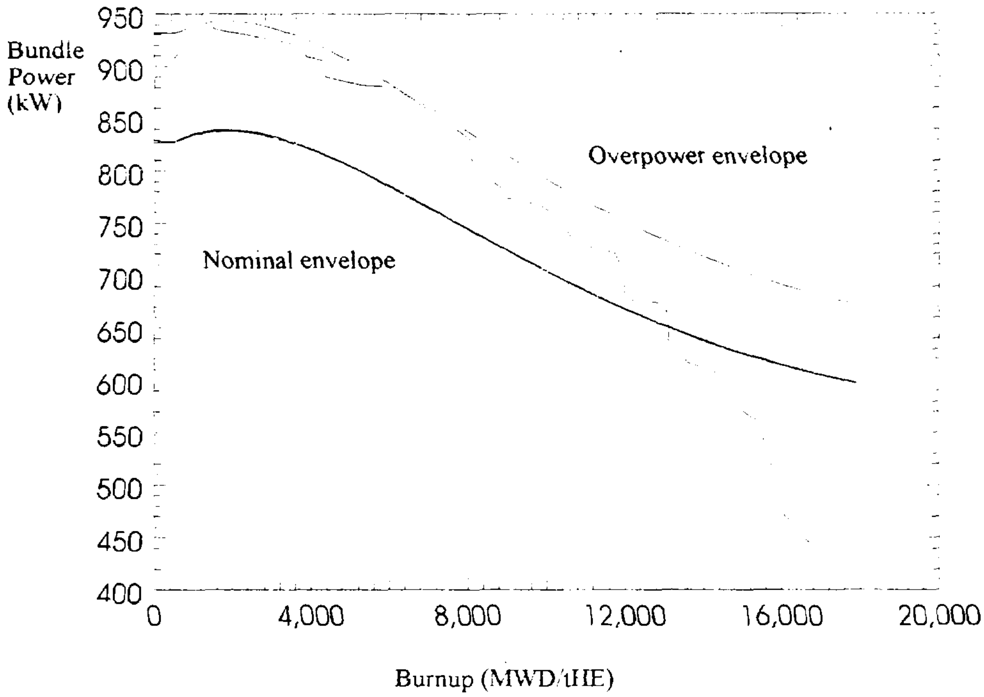

Figure 5. Power Envelope: 0.93% SEU Fuel Bundle

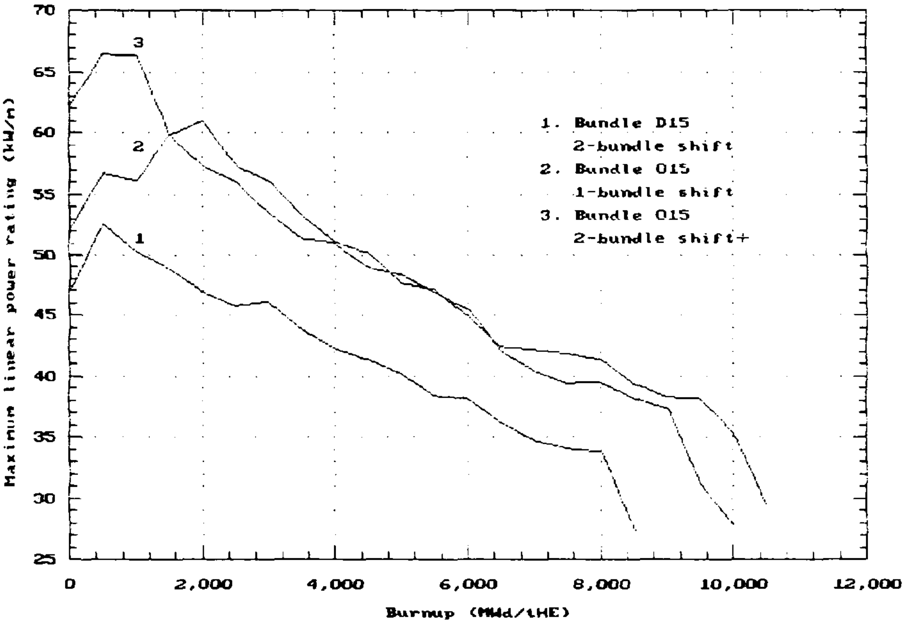

Figure 6. Power Envelopes: Equivalent 1.5% Pu-239 Fuel Bundle

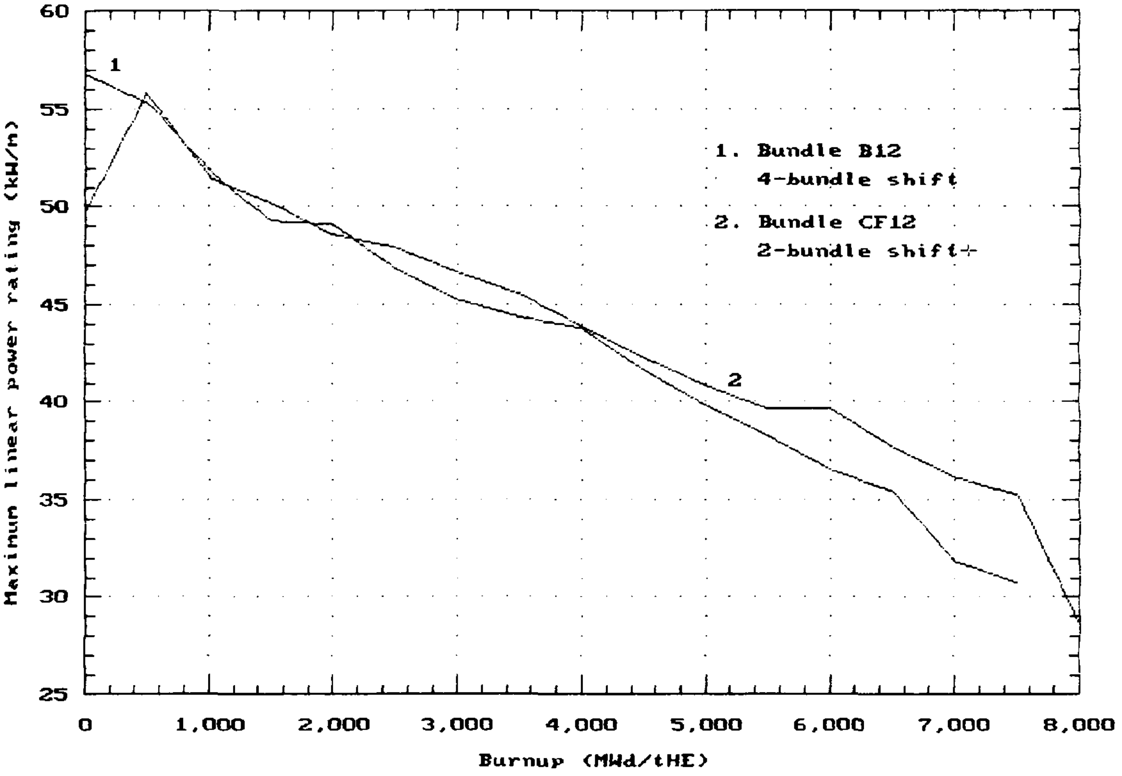

Figure 7. Power Envelopes: Equivalent 1.2% Pu-239 Fuel Bundle