Presented at the Advances in Nuclear Fuel Management II Conference,
Myrtle Beach, South Carolina, March 23-26, 1997

ROSA, A UTILITY TOOL FOR LOADING PATTERN OPTIMIZATION

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Abstract

The main goal of nuclear fuel management is to reduce fuel cycle costs while complying with a range of safety constraints and operational targets. This goal can be achieved by optimization of assembly composition and/or loading pattern design. At KEMA the ROSA code has been developed for simultaneous fresh fuel assembly composition and core loading pattern optimization. The code combines a high-speed reactor core simulator, a reloading pattern generator, and an optimization algorithm. The optimization is based on simulated annealing, a Monte Carlo algorithm which is fully exploited by the high-speed reactor core simulator. A large number of constraints and objectives can be dealt with in the optimization, while still enabling the benefit of expert hands-on interaction. The flexible fuel management code ROSA has proven to be a very useful tool in improving loading patterns for Pressurized Water Reactors.

Introduction

Designing an optimal or nearly optimal reloading pattern in a light water reactor is very challenging due to the enormous number of possible patterns and the non-linearity of the problem. The complexity asks for an enormous amount of loading patterns to be evaluated. Therefore, an efficient optimization algorithm in combination with an efficient loading pattern evaluation code has to be used.

Simulating annealing[1] is one of the frequently applied optimization algorithms in fuel management codes[e.g. 2,3]. At KEMA simulated annealing is applied in the fuel management code ROSA, an acronym for *Reloading Optimization by Simulated Annealing*. Because of the nature of the optimization algorithm, the optimization result depends on the number of loading patterns that can be evaluated in a reasonable amount of time. Therefore, a high-speed loading pattern evaluation code is important for the optimization. In ROSA an accelerated coarse mesh version of the at KEMA developed reactor simulator code LWRSIM is used.

In view of the practical application of an optimization code, flexibility is an important feature. ROSA has the possibility to optimize a large number of parameters simultaneously, while complying with various constraints. A graphical user interface (GUI) has been developed to interact with the fuel management code. User-friendliness for utility-based users has been a major target with respect to the interface design and the on-line display facilities. Both the momentary progress of the optimization process and the detailed results of a loading pattern evaluation are shown graphically. Moreover, loading patterns can be changed interactively and input parameters can be adjusted in the course of an optimization run.

ROSA has been used for a number of Pressurized Water Reactors. In this paper some results are presented for the Dutch Borssele PWR (Siemens-KWU 480 MWe) and for the US Vogtle-2 PWR (Westinghouse 1160 MWe).

Simulated Annealing

The simulated annealing process is based on the algorithm introduced by Metropolis[4] to simulate a collection of atoms in thermal equilibrium. Given a reloading pattern C_i, a new pattern C_{i+1} is generated by random permutation and/or rotation of some of the assemblies and/or by composition change of some of the fresh assemblies. Suppose one wants to minimize the target function E (in analogy with the energy of the collection of atoms). The probability that the new pattern is accepted is then given by:

$$P_i = \min(1, e^{\frac{E_i - E_{i+1}}{T}}) \qquad (1)$$

in which T is the control parameter (in analogy with k_BT' in which k_B is Boltzmann's constant, T' the temperature), to be called the temperature of the system. Once "equilibrium" at a given temperature is reached, the temperature is reduced. The fraction of accepted reloading patterns is used as a measure for equilibrium. The quality of the solution depends to a large extent on the temperature reduction scheme that is used. A scheme in which the temperature is very slowly reduced is beneficial for the optimization but is a burden for the computational effort to be done. The temperature reduction schemes in ROSA are characterized by the reduction factor by which the previous temperature is multiplied whenever equilibrium is reached. As stated before, the optimization can be done simultaneously for a number of parameters. The loading pattern acceptance probability is then given by the product of the probabilities of acceptance for each of the individual parameters.

In ROSA constraints are treated in the same way as optimization parameters, except for the placement constraints which are defined in the form of rules. Both for constraints and for optimization parameters target values are defined. Whenever a target value is reached, the optimization with regard to this variable stops. With respect to this variable the acceptance probability is one if the variable has a better value than the target value. By choosing a sound combination of temperature reduction schemes and initial temperatures, the final solution will meet the constraints. This is where engineering judgement and experience play an important role, whereas it used to be important for generating loading patterns in a trial and error approach.

Neutronics

For the optimization to be successful in a reasonable amount of computer time, an efficient reactor simulator model has to be applied. The model in ROSA has been based on LWRSIM. In LWRSIM a one-and-a-half-group neutron diffusion model is applied. The diffusion of neutrons in the fast energy group is calculated using a kernel that gives the probability of absorption for a source neutron as a function of the distance. This kernel has been determined from lattice calculations with LWRWIMS[5]. The actual shape of the kernel depends on the migration length. In case of large spectral effects between two fuel assemblies (e.g. UO_2 and MOX) a spectrum correction method is used.[6]

The neutronics model in ROSA is an accelerated version of LWRSIM. A 3-dimensional coarse mesh (1 radial node and 12 axial nodes per assembly) solution is coupled with a 2-dimensional fine mesh (3x3 radial nodes per assembly) solution to account for radial flux gradients within the fuel assembly.

ROSA uses two-group cross sections as input for the different fuel types. These cross sections are typically generated with a lattice code such as LWRWIMS. Output from a lattice code is simply converted to the required ROSA-format.

For each pattern candidate, a core performance analysis for the cycle is accomplished, considering a user-defined time step resolution.

Implementation

The current ROSA version 2.0 can be used in combination with objectives and constraints given in table 1. In the optimization process objectives and constraints are treated similarly. In practice, only some constraints seriously affect the final solution. By choosing a temperature reduction scheme in which the temperatures for these dominant constraints are frozen more rapidly, or in which the initial temperature is rather low, it is possible to force the final solution to meet such a dominant constraint. As an extreme case, by applying an initial temperature of zero, only improvements with regard to this parameter are accepted.

With regard to the objectives to be used, a combination of objectives is possible, although it is more straightforward to work with one objective such as the total cost. In case of an objective the target value should be out of reach of the optimal loading patterns. Since, the optimization stops with regard to this variable as soon as it has reached the target value.

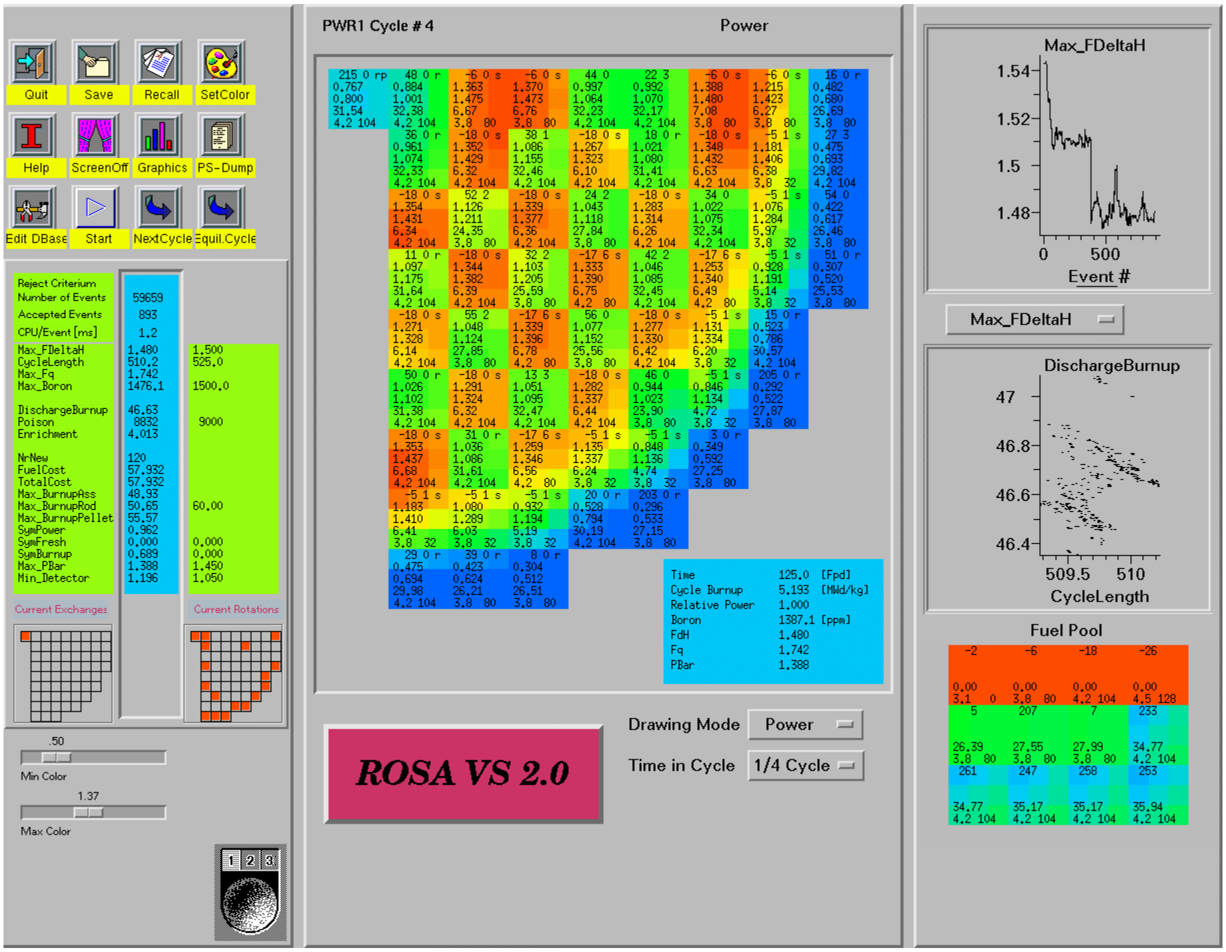
A number of constraints can be given as rules. The reloading patterns have to obey these rules. There are simple rules such as the fixation of a position and/or rotation of a fuel assembly, but also more complicated rules can be used, such as a limitation on the number of fresh fuel assemblies to be placed on the periphery of the reactor core. The rules can be used to implement engineering judgement and to deal with constraints which cannot be treated by the reactor simulator (e.g. shutdown margin).

The graphical user interface of ROSA version 2.0 is shown in figure 1. The central part shows either the power distribution, the burnup distribution, or the distribution of $F_{\Delta H}$ (enthalpy rise hot-channel factor) at specified points in time of the last accepted reloading pattern. Also, the axial distribution of the assembly power or assembly burnup can be shown in the central part of the interface. On the right-hand side of the interface the optimization process itself is shown by plotting an optimization parameter as a function of the number of accepted reloading patterns or as a function of another optimization parameter, showing the solution space. The most reactive assemblies in the fuel pool are also shown on the right-hand side of the interface. On the left-hand side the current values of the optimization parameters is shown as well as the target values. A number of menu buttons is available for influencing either the lay-out, the optimization process (annealing scheme), the neutronics calculations (e.g. number of time steps per cycle), or the next/equilibrium cycle option. Finally, the last-accepted exchanges and rotations are schematically shown in the small core maps on the lower left-hand side. These maps also show the position and rotation locks (rules).

Table 1

Optimization Objectives and Constraints Options Available in ROSA Version 2.0

Variable	Comment
$F_{\Delta H}$	Enthalpy rise hot-channel factor
Cycle length	Natural cycle length in full power days
F_q	Heat-flux peaking factor
Boron	Maximum boron concentration in cycle
Discharge Burnup	Average burnup of the discharged fuel
Poison	Total number of poison rods in the fresh fuel assemblies
Enrichment	Average fuel enrichment in the fresh fuel assemblies
Fuel Cost	Fuel cost according to the economy model used
Total Cost	Fuel cost taking production loss during coast-down into account
Maximum Burnup Assembly	Maximum EOC assembly burnup
Maximum Burnup Rod	Maximum EOC rod burnup (corrosion)
Maximum Burnup Pellet	Maximum EOC pellet burnup
Symmetry Power	Proportional to the octant symmetry in the power distribution
Symmetry Fresh	Proportional to the octant symmetry in the positioning of the fresh assemblies with respect to both enrichment and number of poison rods
Symmetry Burnup	Proportional to the octant symmetry in the positioning of the assemblies with respect to the Begin-Of-Cycle (BOC) burnup
P-bar	Maximum relative assembly power minus limit (limit may depend on boron concentration)
Detector	Minimum relative power in assemblies in neighbourhood of detector



Reject Criterium		
Number of Events	59659	
Accepted Events	893	
CPU/Event [ms]	1.2	
Max_FDeltaH	1.480	1.500
CycleLength	510.2	525.0
Max_Fq	1.742	
Max_Boron	1476.1	1500.0
DischargeBurnup	46.63	
Poison	8832	9000
Enrichment	4.013	
NrNew	120	
FuelCost	57.932	
TotalCost	57.932	
Max_BurnupAss	48.93	
Max_BurnupRod	50.65	60.00
Max_BurnupPellet	55.57	
SymPower	0.962	
SymFresh	0.000	0.000
SymBurnup	0.689	0.000
Max_PBar	1.388	1.450
Min_Detector	1.196	1.050

215 0 rp 0.767 0.800 31.54 4.2 104	48 0 r 0.884 1.001 32.38 4.2 104	-6 0 s 1.363 1.475 6.67 3.8 80	-6 0 s 1.370 1.473 6.76 3.8 80	44 0 0.997 1.064 32.23 4.2 104	22 3 0.992 1.070 32.17 4.2 104	-6 0 s 1.388 1.480 7.08 3.8 80	-6 0 s 1.215 1.423 6.27 3.8 80	16 0 r 0.482 0.680 26.69 3.8 80
	36 0 r 0.961 1.074 32.33 4.2 104	-18 0 s 1.352 1.429 6.32 4.2 104	38 1 1.086 1.155 32.46 4.2 104	-18 0 s 1.267 1.323 6.10 4.2 104	18 0 r 1.021 1.080 31.41 4.2 104	-18 0 s 1.348 1.432 6.63 4.2 104	-5 1 s 1.181 1.406 6.38 3.8 32	27 3 0.475 0.693 29.82 4.2 104
	-18 0 s 1.354 1.431 6.34 4.2 104	52 2 1.126 1.211 24.35 3.8 80	-18 0 s 1.339 1.377 6.36 4.2 104	24 2 1.043 1.118 27.84 3.8 80	-18 0 s 1.283 1.314 6.26 4.2 104	34 0 1.022 1.075 32.34 4.2 104	-5 1 s 1.076 1.284 5.97 3.8 32	54 0 0.422 0.617 26.46 3.8 80
	11 0 r 1.097 1.175 31.64 4.2 104	-18 0 s 1.344 1.382 6.39 4.2 104	32 2 1.103 1.205 25.59 3.8 80	-17 6 s 1.333 1.390 6.75 4.2 80	42 2 1.046 1.085 32.45 4.2 104	-17 6 s 1.253 1.340 6.49 4.2 80	-5 1 s 0.928 1.191 5.14 3.8 32	51 0 r 0.307 0.520 25.53 3.8 80
	-18 0 s 1.271 1.328 6.14 4.2 104	55 2 1.048 1.124 27.85 3.8 80	-17 6 s 1.339 1.396 6.78 4.2 80	56 0 1.077 1.152 25.56 3.8 80	-18 0 s 1.277 1.330 6.42 4.2 104	-5 1 s 1.131 1.334 6.20 3.8 32	15 0 r 0.523 0.786 30.57 4.2 104	
	50 0 r 1.026 1.102 31.38 4.2 104	-18 0 s 1.291 1.324 6.32 4.2 104	13 3 1.051 1.095 32.47 4.2 104	-18 0 s 1.282 1.337 6.44 4.2 104	46 0 0.944 1.023 23.90 3.8 80	-5 1 s 0.846 1.134 4.72 3.8 32	205 0 r 0.292 0.522 27.87 3.8 80	
	-18 0 s 1.353 1.437 6.68 4.2 104	31 0 r 1.036 1.086 31.61 4.2 104	-17 6 s 1.259 1.346 6.56 4.2 80	-5 1 s 1.135 1.337 6.24 3.8 32	-5 1 s 0.848 1.136 4.74 3.8 32	3 0 r 0.349 0.592 27.25 3.8 80		
	-5 1 s 1.183 1.410 6.41 3.8 32	-5 1 s 1.080 1.289 6.03 3.8 32	-5 1 s 0.932 1.194 5.19 3.8 32	20 0 r 0.528 0.794 30.19 4.2 104	203 0 r 0.296 0.533 27.15 3.8 80			
	29 0 r 0.475 0.694 29.98 4.2 104	39 0 r 0.423 0.624 26.21 3.8 80	8 0 r 0.304 0.512 26.51 3.8 80					

Time	125.0	[Fpd]
Cycle Burnup	5.193	[MWd/kg]
Relative Power	1.000	
Boron	1387.1	[ppm]
FdH	1.480	
Fq	1.742	
PBar	1.388	

Drawing Mode: Power

Time in Cycle: 1/4 Cycle

Fuel Pool

-2 0.00 3.1 0	-6 0.00 3.8 80	-18 0.00 4.2 104	-26 0.00 4.5 128
5 26.39 3.8 80	207 27.55 3.8 80	7 27.99 3.8 80	233 34.77 4.2 104
261 34.77 4.2 104	247 35.17 4.2 104	258 35.17 4.2 104	253 35.94 4.2 104

Figure 1
Graphical User Interface for ROSA Version 2.0

Results

ROSA has been used for the optimization of reloading patterns for several PWR's. The determination of the loading pattern to be used in a new cycle starts with a ROSA optimization calculation. Then, the resulting loading pattern proposal is checked by the licensing code of the reactor operator. Because of the necessary assumptions in the neutronics model used for optimization studies, the candidate loading pattern may not meet the constraints according to the licensing code. Experience shows that in such a case one additional ROSA-calculation renders a new loading pattern that does meet all constraints. The average speed of loading pattern evaluation mainly depends on the size of the reactor core, the number of time steps that has to be evaluated, and the annealing scheme. Typical CPU-time on a HP9000/735 for a cycle evaluation with 5-10 time steps is 50 ms. Because in practice a lot of patterns are rejected early in the cycle, especially when the temperature in the annealing process is low, the average CPU-time per pattern for a typical optimization run is about 10 ms. About 10 million patterns can then be evaluated per day.

To validate the neutronics code numerous comparisons have been made against licensing code results. As an example figure 2 shows the power distribution at the beginning of a cycle 24 reload proposal in a quarter core of the Dutch Borssele PWR (KCB) as calculated with ROSA and as calculated with the Siemens-KWU licensing codes[7]. The differences in the results are very small; only the relative power in the central fuel assembly shows a somewhat higher deviation. This particular assembly has been stored for a long time (13 years) in the fuel pool, and has therefore lost a considerable part of its Pu-241 content by decay. This effect is not yet taken into account in ROSA.

0.876 0.911	1.061 1.057	1.515 1.517	1.000 1.016	1.283 1.283	1.238 1.245	0.343 0.358
	1.484 1.486	1.272 1.260	1.201 1.202	1.507 1.502	1.099 1.097	0.253 0.263
	1.271 1.258	1.191 1.191	1.247 1.250	1.319 1.328	0.508 0.515	
	1.198 1.198	1.238 1.235	1.540 1.528	0.844 0.839	0.241 0.245	
	1.523 1.507	1.333 1.331	0.861 0.844	0.345 0.342		
	1.107 1.101	0.500 0.505	0.244 0.245			
	0.270 0.276					

Figure 2
KCB Power Distribution for a Proposed Loading Pattern at BOC 24 (6 fpd) as Calculated by Siemens-KWU Licensing Code (Upper) and as Calculated by ROSA (Lower)

Table 2

Comparison Between Calculated and Measured Natural Cycle Length for Borssele PWR

Cycle Number	Cycle Length (fpd) Measured	Cycle Length (fpd) LWRSIM	Cycle Length (fpd) ROSA
19	273.9	271.9	271.9
20	253.3	253.4	253.6
21	273.9	274.8	274.6
22	278.3	280.1	280.0
23	-	281.4	281.5
24	-	304.1	304.1

Table 2 shows the measured natural cycle lengths (5 ppm point) for the Borssele PWR over recent fuel cycles. These cycle lengths are compared with the cycle lengths as calculated with ROSA and LWRSIM. The differences in results are very small (within 2 days).

ROSA has also been applied in a benchmark study for the optimization of three cycles of the US PWR Vogtle-2. As a reference case reloading patterns are used which have been generated by the reactor operator with the available optimization tools. In figure 3 the comparison between the reference power distribution derived from flux-map data and the power distribution calculated by ROSA is shown at the beginning of cycle 5. Figure 4 shows the same comparison for the $F_{\Delta H}$ distribution. ROSA shows to be able to calculate both distributions accurately.

1.107	1.171	1.345	1.165	1.189	1.076	1.092	0.447
1.105	1.170	1.338	1.161	1.196	1.066	1.085	0.442
	1.347	1.242	1.308	1.112	1.173	1.089	0.389
	1.342	1.235	1.308	1.114	1.179	1.084	0.388
	1.242	1.248	1.170	1.274	1.106	1.079	0.422
	1.234	1.245	1.170	1.284	1.101	1.077	0.422
	1.308	1.171	1.299	1.171	1.239	1.014	0.260
	1.308	1.171	1.314	1.175	1.234	1.018	0.275
	1.113	1.277	1.176	1.161	1.249	0.587	
	1.115	1.287	1.180	1.164	1.253	0.584	
	1.176	1.112	1.248	1.258	0.973	0.298	
	1.183	1.106	1.242	1.259	0.972	0.296	
	1.095	1.089	1.023	0.593	0.307		
	1.091	1.087	1.026	0.586	0.297		
	0.393	0.443	0.262				
	0.392	0.442	0.276				

1.155	1.237	1.394	1.277	1.251	1.126	1.246	0.706
1.146	1.227	1.390	1.268	1.252	1.111	1.253	0.639
	1.415	1.373	1.381	1.216	1.221	1.255	0.652
	1.408	1.377	1.372	1.219	1.240	1.261	0.565
	1.374	1.391	1.238	1.325	1.181	1.250	0.688
	1.377	1.406	1.220	1.341	1.173	1.261	0.629
	1.381	1.239	1.337	1.260	1.317	1.271	0.511
	1.371	1.220	1.365	1.270	1.315	1.296	0.485
	1.218	1.327	1.265	1.246	1.401	0.925	
	1.220	1.343	1.273	1.257	1.406	0.882	
	1.224	1.186	1.328	1.411	1.304	0.645	
	1.243	1.179	1.323	1.416	1.321	0.542	
	1.261	1.259	1.281	0.932	0.701		
	1.268	1.269	1.305	0.887	0.544		
	0.657	0.718	0.511				
	0.569	0.659	0.488				

Figures 3,4

Vogtle-2 Power Distribution (Left) and $F_{\Delta H}$ Distribution (Right) at BOC 5 (11 fpd) as Calculated by the Licensing Code (Upper) and as Calculated by ROSA (Lower)

By applying ROSA for a one-cycle (cycle 6) evaluation in which the average enrichment of the fresh fuel assemblies was to be reduced, it was possible to reduce the average fresh fuel enrichment by 0.057 w/o, while gaining 1 day in natural cycle length. The savings in one cycle may have negative effects on future fuel cycles. Therefore also a multi-cycle study has been done for the Vogtle-2 PWR, involving cycles 6, 7, and 8. Because a different number of fresh fuel assemblies and a different target cycle length had to be used for each cycle, the ROSA automatic equilibrium cycle methodology could not be used. Instead, an interactive approach involving 3 consecutive optimization studies has been used. In this three-cycle optimization, a scenario has been found in which about the same cycle length for each cycle has been established as for the reference case, yielding an average fresh fuel enrichment reduction of about 0.015 w/o.

The reference cases for the fuel management studies for Vogtle-2 are optimized full low-leakage patterns. The application of ROSA has demonstrated the ability to improve these patterns even further.

Outlook

So far the development of ROSA has been concentrated on obtaining a flexible, user-friendly, reloading pattern optimization code, which improves the loading patterns of PWR's. Experiences with several reactor operators are very positive.

A lot of effort has been put in obtaining an accurate high-speed reactor simulator, which we feel is necessary for the simulated annealing algorithm to be exploited to the fullest. The neutronics model in ROSA is able to predict the optimization objectives and constraints quite well. The question is how the simplifications in the model influence the optimization itself. On the other hand, a more extensive neutronics model would require a much faster freezing in the simulated annealing process. This has a negative impact on the optimization. The challenge is to find the optimum trade-off between speed and accuracy.

Moreover, a better understanding of the multi-parameter optimization is important in view of choosing optimal temperature reduction schemes. Also multi-cycle optimization deserves further attendance. With respect to the neutronics an improved pin-power reconstruction model is to be implemented.

Apart from the development of ROSA for PWR's, a separate development is on its way for BWR's. A test version for the Dutch natural circulation BWR Dodewaard has been developed. Development of a generalized BWR-version is envisaged.

Acknowledgements

This study was partially undertaken by order of the Dutch Electricity Production Companies; in addition the authors thank KCB and Siemens-KWU for permission to use their data in this paper.

References

1. S. Kirkpatrick, C.D. Gelatt Jr., and M.P. Vecchi, "Optimization by Simulated Annealing," *Science.* Vol. 220, No. 4598, p. 671 (1983).
2. D.J. Kropaczek and P.J. Turinsky, "In-Core Nuclear Fuel Management for Pressurized Water Reactors Utilizing Simulated Annealing," *Nucl. Technol.,* Vol. 95, No. 1, p. 9 (1991).
3. J.G. Stevens, K.S. Smith, K.R. Rempe, and T.J. Downar, "Optimization of Pressurized Water Reactor Shuffling by Simulated Annealing with Heuristics," *Nucl. Sci. Eng.,* Vol. 121, No. 1, p. 67 (1995).
4. N. Metropolis, A. Rosenbluth, M. Rosenbluth, A. Teller, E. Teller, "Equation of State Calculations by Fast Computing Machines," *J. Chem. Phys.,* Vol. 21, p. 1087 (1953).
5. *LWR-WIMS, a Computer Code for Light Water Reactor Calculations*. Winfrith, UK: AEE, June1982, AEEW-R 1498.
6. M. Becker, "Incorporation of Spectral Effects into One-Group Nodal Simulators," *Nucl. Sci. Eng.,* Vol. 59, No. 3, p. 276 (1976).
7. K. Koebke, G. Ambrosius, L. Hetzelt, S. Merk, and H.-J. Winter, "The Core Design Procedure SAV90 for Pressurized Water Reactors," *Kerntechnik*, Vol. 57, No. 1, p. 37 (1992).