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Impact of Solid Radial Reflector Water Volume Fraction on Temperature Coefficients in a Soluble Boron Free i-SMR Core

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1. Introduction

The Innovative Small Modular Reactor (i-SMR) currently under development employs coolant temperature variation as a secondary reactivity control system [1]. In this secondary reactivity control system, the temperature coefficient is a critical parameter [2].

In prior studies [2, 3], the i-SMR employed an SS304 radial reflector, however, a SS304 radial reflector may result in unacceptably high temperatures. Therefore, this study examines how the Temperature Coefficients changes when water is introduced into the SS304 radial reflector, and how this affects secondary reactivity control. Specifically, the ITC and MTC responses as a function of the reflector's water volume fraction (0.44, 8, 12, 16 and 20%) were evaluated. All analyses are performed for the core at Cycle 1 and Cycle 8.

In particular, the generation of few group homogenized reflector cross section was performed with the KARMA and ECHO code. For the depletion calculation and temperature coefficients calculation, ASTRA code was used.

Since this paper focuses exclusively in the nuclear impact to the core, mechanical and thermal-hydraulic effects including the secondary system are outside the present scope.

2. Methods and Results

2.1 Computational Method

The two-step procedure is applied to i-SMR core design using the KARMA/ASTRA nuclear design code system. Cross section and form function libraries are obtained from a series of KARMA/ECHO (ECHO: Equivalent Cross Section and Heterogeneous Form Function Organizer for ASTRA) calculations.

Unit fuel assembly depletions for two groups cross section generation were performed with KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly) code which is a two-dimensional multi-group lattice transport code using 47 group cross section library based on ENDF/B-VI.8 [4,5]. ECHO is a post processor of KARMA output specifically HGC file to generate cross section library and form function library suitable to ASTRA [6]. For whole core calculation, ASTRA code was used. ASTRA code is a 3D core depletion code developed by KEPCO NF (KEPCO Nuclear Fuel) as a nuclear design code for the core design of pressurized water reactors (PWRs) based on the reactor physics technologies [7].

The homogenized reflector cross sections are generated to preserve the response matrix of the heterogeneous geometry at the interface of core and reflector.

In the radial reflector region, the water hole is assumed to be homogeneously mixed with stainless steel. The reflector homogenization problem can be simplified to the 1-dimensional spectral geometry. The fine mesh calculations were done by KARMA.

2.2 Core and Radial Reflector Designs

Table I presents the key parameters of the i-SMR core used in this study.

Table I: Core Design Parameters

Parameters	Value
Reactor thermal power [MWt]	520
Number of assemblies	69
Fuel assembly array	17 x 17
Fuel assembly height [cm]	240
Fuel enrichment [wt%]	< 4.95
Burnable absorber material	Enriched Gd_2O_3

Previous work employed a radial reflector with a water hole volume fraction of 0.44%. In this study, four homogenized radial reflector cross section with water hole volume fractions of 8, 12, 16 and 20% were generated, and temperature coefficients (ITC, MTC) were compared.

2.3 Performance Analysis

For SS304 radial reflectors with water hole volume fractions of 0.44, 8, 12, 16 and 20%, the temperature coefficients (ITC, MTC) were evaluated at cycle 1 and cycle 8 over BOC/MOC/EOC and at 100%, 80%, 60%, 40%, and 20% power. This calculation is intended to establish the power dependent temperature coefficient trend and to assess how the reflector water fraction influences temperature based secondary reactivity control.

Fig. 1 shows ITC (Isothermal Temperature Coefficients) versus burnup by power level for the radial reflectors with 0.44% and 20% water fraction at cycle 1. At every power level, the ITC becomes less negative to about 11,000 MWD/MTU, and then slightly becomes more negative. As reactor power decreases, the ITC shifts to more negative values, which strengthens temperature based secondary reactivity control. The curves with 20% water fraction radial reflector are nearly parallel to the curves with 0.44% water fraction radial reflector across burnup, indicating that the power dependent trend is preserved. Across power levels, the largest absolute difference between the 0.44% water fraction radial reflector and 20% water fraction radial reflector cases at cycle 1 is 1.05 pcm/°C.

Fig. 2. shows ITC versus burnup by power level for the radial reflectors with 0.44% and 20% water fraction at cycle 8. The power dependent trend is the same with the comparison at cycle 8. Across power levels, the largest absolute difference between the 0.44% water fraction radial reflector and 20% water fraction radial reflector cases at cycle 1 is 0.83 pcm/°C.

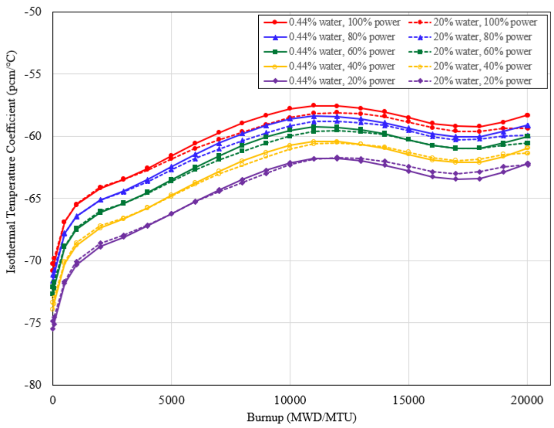

Fig. 1. ITC versus burnup by power level for the radial reflectors with 0.44% and 20% water fraction at cycle 1.

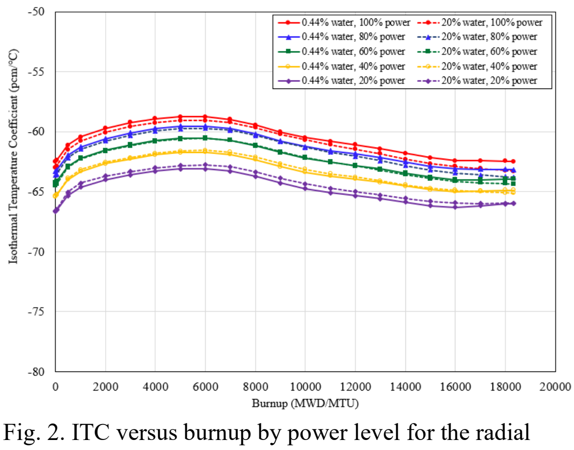

Fig. 2. ITC versus burnup by power level for the radial reflectors with 0.44% and 20% water fraction at cycle 8.

Table II and Table III show the most negative and the least negative temperature coefficients at 100% power by fraction of water hole in the SS radial reflectors. Temperature coefficients are used in temperature based secondary reactivity control. For comparable conditions, a more negative ITC and MTC implies that the same reactivity change can be offset with a smaller coolant temperature change. Therefore, summarizing the most and least negative ITC and MTC at full power offers upper and lower bound indications of the coolant temperature change needed to offset for the reactivity swing of the core in secondary reactivity control. In Table II, the most negative temperature coefficients occur at BOC. At cycle 1, the most negative ITC at a radial reflector with a water fraction of 0.44% is -70.81 pcm/°C, while the corresponding most negative value at a water fraction of 16% is -70.23 pcm/°C. The largest difference among the most negative entries is 0.57 pcm/°C. For the least negative ITC in Table III, the largest difference is 0.56 pcm/°C, occurring between -57.55 pcm/°C at radial reflector with a water fraction of 0.44% and -58.11 pcm/°C with a water fraction of 20%. These gaps are small relative to the overall ITC magnitude, indicating that the coolant temperature swing required for temperature based secondary reactivity control would be only weakly affected by the reflector water fraction.

Fig. 3 and Fig. 4 show ITC and MTC (Moderator Temperature Coefficients) versus burnup by water fraction of radial reflector at cycle 1 each. ITC and MTC tend to become more negative as the radial reflector water fraction increase.

Table II: Most Negative Temperature Coefficients at Full Power by water fraction of radial reflector

Temperature Coefficients		**0.44%**	**8%**	**12%**	**16%**	**20%**
ITC [pcm/°C]	Cy 1	-70.81	-70.38	-70.28	-70.23	-70.28
	Cy 8	-62.49	-62.94	-63.11	-63.26	-63.29
MTC [pcm/°C]	Cy 1	-67.65	-67.23	-67.12	-67.08	-67.13
	Cy 8	-59.12	-59.29	-59.47	-59.59	-59.62

Table III : Least Negative Temperature Coefficients at Full Power by water fraction of radial reflector

Temperature Coefficients		**0.44%**	**8%**	**12%**	**16%**	**20%**
ITC [pcm/°C]	Cy 1	-57.55	-57.89	-58.01	-58.08	-58.11
	Cy 8	-58.74	-58.85	-58.96	-59.02	-59.05
MTC [pcm/°C]	Cy 1	-53.96	-54.29	-54.41	-54.48	-54.52
	Cy 8	-55.17	-55.30	-55.42	-55.48	-55.51

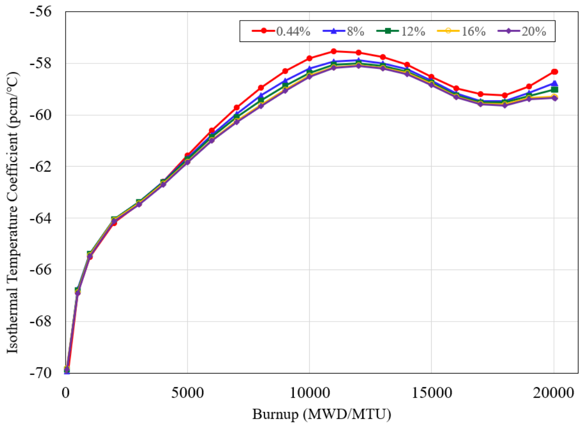

Fig. 3. ITC versus burnup by water fraction of radial reflector at cycle 1.

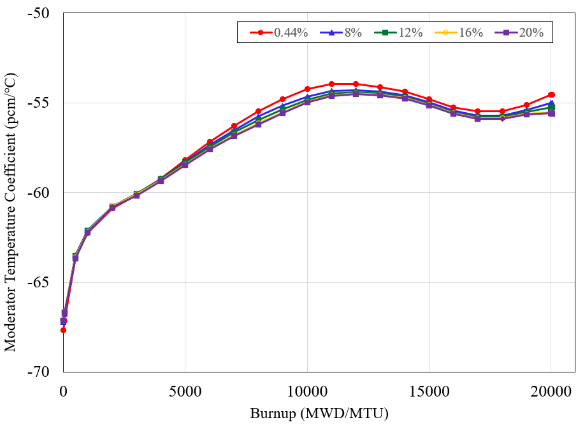

Fig. 4. MTC versus burnup by water fraction of radial reflector at cycle 1.

3. Conclusions

This study extended a prior i-SMR baseline with a 0.44% water hole SS radial reflector by generating four additional reflector cross-section sets with water hole volume fractions of 8, 12, 16, and 20%, and by evaluating ITC and MTC at five power levels (100 to 20%) for Cycle 1 and Cycle 8.

As the reflector water fraction increases, ITC and MTC tend to become more negative. The most negative values frequently appeared at BOC, however case to case differences were small, and minor deviations did not change the overall trend. Accordingly, the radial reflector configuration introduced only a modest bias, and the strongly negative MTC characteristic of the soluble boron free core was preserved. The proposed reflectors are not expected to alter the overall temperature based secondary reactivity control strategy and remain compatible with daily load follow operation.

In future work, changes in cycle length and core excess reactivity induced by variations in the radial reflector water hole volume fraction will be quantified and integrated with the present ITC set to refine estimates of the coolant temperature swing and to further evaluate temperature based secondary reactivity control for the soluble boron free i-SMR core with modified reflector.

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