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Application of the Dynamic Control Rod Reactivity Measurement Method to Korea Standard Nuclear Power Plants

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To measure and validate the worth of control bank or shutdown bank, the dynamic control rod reactivity measurement (DCRM) technique has been developed and applied to six cases of Low Power Physics Tests of PWRs including Korea Standard Nuclear Power plant (KSNP) based on the CE System 80 NSSS. Through the DORT results for each two ex-ore detector response and the three dimensional core transient simulations for rod movements, the key parameters of DCRM method are determined to implement into the Direct Digital Reactivity Computer System (DDRCS). A total of 9 bank worths of two KSNP plants were measured to compare with the worths of the conventional rod worth measurement method. The results show that the average error of DCRM method is nearly the same as the conventional Rod Swap and Boron Dilution Method but lower standard deviation. It takes about twenty minutes from the beginning of rod movement to final estimation of the integral static worth of a control bank.

KEYWORDS: Dynamic Reactivity, Low Power Physics Test, Control Bank, DCRM, Rod Swap method, Boron dilution method

1. Introduction

To measure the worth of control banks and shutdown banks during the Low Power Physics Test (LPPT) program of Pressurized water reactors (PWRs), the boron dilution technique and the rod swap method (RSM) are used over 20 years in KOREA. Those methodologies have been well developed and optimized to each nuclear power plants. But the utility has desired to have a fast, simple and reliable technique for rod worth measurement, because the traditional methods have some weak points against the current dynamic methods. The first thing is that it generally takes about twelve hours for measuring the rod worths of five or six banks. The main potion of the measurement time is caused by the boron dilution method for the reference bank having the largest rod worth. In the boron dilution method, the heaviest bank moves just few steps and is held while boron is diluted to compensate for the reactivity loss. And it also should keep the position long enough to avoid the space-time effect for validating the inverse kinetics model in the digital reactivity computer. At the near region of the top or bottom of the core, because of small reactivity changes compared with the large rod movement, one should use different technique to measure a residual rod worth of the reference bank. Therefore, the boron dilution method is a very slow process. But the rod worth of reference bank should be measured as possible as precisely, because it is used as a reference for other bank's worth. RSM is faster than

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the boron dilution method. After the heaviest bank worth is measured, it is partially withdrawn while another test bank is being inserted. The partial worth given by the movement of the reference bank is used to compensate for the worth of the test bank. The accumulated reactivity change of the reference bank is the same as the worth of test bank fully inserted into the bottom of the core. The second is the traditional method produces lots of boron wastes, the third it requires systematic bias like as a shadow effect of the reference bank. Those are why the utility has desired a fast, simple and reliable technique for estimating the bank worths. Actually, to meet their need, Westinghouse and Electric Power Research Center developed the Dynamic Rod Worth Measurement (DRWM) method [1, 2] and the Dynamic Reactivity Measurement of Rod Worth (DRMRW) method [3], respectively. And, they have been successfully applied to WH 2-loop, 3-loop and 4-loop reactor startups in USA, but not for CE-type reactor LPPT. Therefore, Korea Electric Power Research Institute (KEPRI) has developed a similar techniques, the Dynamic Control rod Reactivity Measurement (DCRM) method, to measure the bank worths for PWRs at KOREA including Korea Standard Nuclear Power Plants (KSNP) based on the CE system 80 NSSS. DCRM like as other methods based on the point kinetic model for the test core where the key parameters are obtained by the three-dimensional core transient code, RAST-K (Reactor Analysis code for the Steady and Transient state) [4] and neutron transport code, DORT [5]

2. Method and Measurement Process

Measurement process of the DCRM is nearly the same as those of other dynamic techniques. At the beginning of the DCRM process, the core is critical with a heaviest bank inserted with a reactivity of 50pcm ~ 70pcm which is for recovering the core flux level. Then, the heaviest bank is withdrawn to the top of the core, i.e., the all-rod-out (ARO) position. Once the signal intensities of two ex-core detectors (or core average flux level) increase to 70% ~ 80% of the nuclear heating point, a test bank is fully inserted to the bottom of the core and yanked to the ARO position in a continuous motion at a maximum allowable stepping speed (42steps/min). The signal intensity varies from ~10^2 nA to ~10^0nA and recovers to the initial level after about 15min due to the initial positive reactivity of the heaviest bank. Once ex-core detector signals are collected, one can get the measured integral static worth of the test bank using the inverse kinetic model. Actually, the integral rod worth is shown as a function of axial bank position. The process is repeated for each of the remaining banks, taking about twenty minutes per bank. Because there are no banks but the test bank, one does not need a systematic bias. No change in boron concentration is required during whole process. On the other hand, because the maximum stepping speed is lower than ~70steps/min of WH type plants in USA, the signal-to-noise ratio is relatively high so that KEPRI have to develop a method to remove the background signals from the measured data.

During DCRM process, there are noticeable changes in the flux distribution especially near the control rod position. And the only available information in the process is the time history of the two ex-core detector signals. For the main variable of the inverse kinetic model to estimate the rod worth represented by equation (1) is a core average neutron density, one has to know the relationship between core average density and detector signal as a function of rod insertion.

$$\rho(t_n) = \sum_k \beta_k \left(e^{-(\lambda_k+\omega_n)\Delta t_n} B_{n-1,k} + A_{n,k} \right) + \Lambda\omega_n - \bar{S}_0 \frac{\Lambda}{\bar{n}_n}, \qquad (1)$$

where $n(t_1) = n(t_0)e^{\omega(t_1-t_0)}$, $B_{n,k} = e^{-(\lambda_k+\omega_n)\Delta t_n} B_{n-1,k} + A_{n,k}$, and $A_{n,k} = \frac{\omega_n}{\lambda_k + \omega_n}\left(1 - e^{-(\lambda_k+\omega_n)\Delta t_n}\right)$.

And the relationship should reflect the spatial effect according to the rod motion and the dynamic effect caused by the delayed neutron precursor density variation.

Because it is impossible to get the relationship from the signals itself, KEPRI develop a factor showing the relative detector response of ex-core detectors; DRCF (Density-to-Response Conversion Factor). DRCF is defined as a ratio of relative core average density versus relative detector response for the given rod position, where the core average density and the ex-core detector responses are already normalized as those for the ARO condition. Equation (2) shows the relationship;

$$DRCF^Q(z) \equiv \frac{\sum_{n=1}^{N} \Delta V_n w_n^Q \sum_{g=1}^{2} \kappa\Sigma_{fg}^n(z)\phi_g^n(z)}{\sum_{n=1}^{N} \Delta V_n w_n^Q \sum_{g=1}^{2} \kappa\Sigma_{fg}^n(z_{ARO})\phi_g^n(z_{ARO})}, \qquad (Q = Top\,/\,Bottom) \qquad (2)$$

where w_n means the three-dimensional ex-core detector response factor being obtained by DORT adjoint fluxes for the given reactor model including the core and two ex-core detectors. According to equation (2), DRCFs should be a function of the bank axial position for the given bank and be generated per each cycle because of its dependency on the loading pattern. To determine DRCFs of each control or shutdown bank, KEPRI has used a space-time dependent three-dimensional neutron diffusion code, RAST-K, where the cross sections of each node have been generated by ANC [6] or ROCS [7] for the consistency of nuclear design data.

Another factor to be declared is the relationship between the static reactivity and the dynamic reactivity caused by the variation of six delayed neutron densities. Because it is not possible to get the factor by a mathematical approach, KEPRI defined the Dynamic-to-Static Conversion Factor (DSCF) like as following;

$$DSCF^Q(z) = \frac{\rho_{RAST}^{Static}(z)}{\rho_{INVERSE}^{Dynamic,Simulated,Q}(z)}, \qquad (Q = top\,/\,bottom). \qquad (3)$$

To determine the DSCFs through Eq. (3) per each bank as a function of axial position, one should know the simulated detector responses obtained while the bank moves into the bottom of the core. RAST-K code calculates all information required to generate the DSCFs.

Figure (1) shows how to get final static rod worths from measured signals in DCRM method. Two parameters, DSCFs and DRCFs for each rod bank, are determined in the nuclear design process, tabulated as a function of its axial insertion position, and implemented into the dynamic digital reactivity computer system (DDRCS). The DDRCS consists of 800MHz Pentium-notebook and two electrometers of 16 bit resolutions with which one can measure the detector current signals directly without converting them to voltage signals. At first, the inverse reactivity solver (INVERSE) guesses an initial background current per each ex-core detector respectively and gets the corrected detector signals. They are, then, converted to two core average neutron densities by DRCFs, and the measured dynamic reactivity are calculated by Eq. (1) as a function of axial insertion position. Finally, the integral static rod worth of a given bank is obtained through Eq. (3). Because the guessed constant background current is not correct, the calculated reactivity curve shows unrealistic behaviors. Figure (2) shows an example of the effect of relative background signal strength. The larger the background signal, the larger errors. Although it is very important how to treat and determine the background signal in dynamic method, there is no simple and applicable experimental approach for PWRs. Therefore, KEPRI has developed an iterative technique that determines the optimal background signal based on the characteristics of static reactivity curve. In Figure (2), one can see that the slope of reactivity curve containing no background signal equals to zero at the bottom of the core. INVERSE code iteratively calculates the reactivity curve to meet the zero slope condition while increase the background currents. Figure (3) shows the results of iterative approach to apply the cases in Fig. (2).

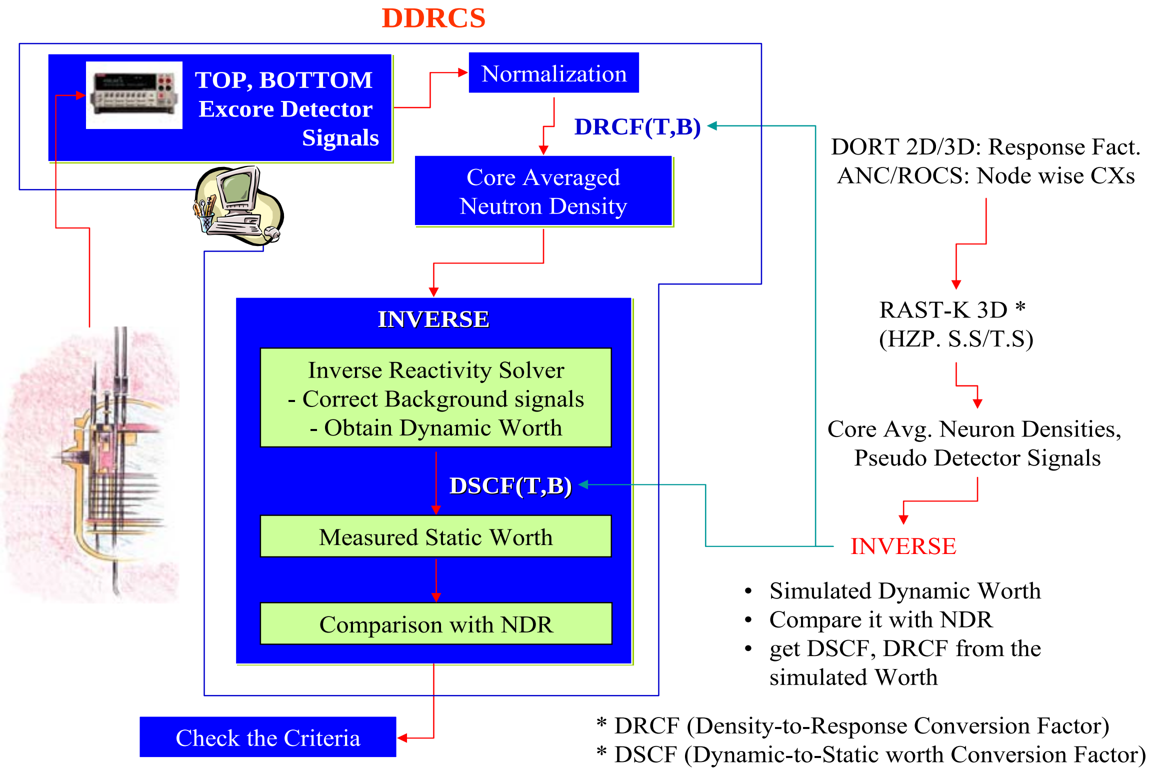

Fig. 1 Overall Data Flows in the DCRM method

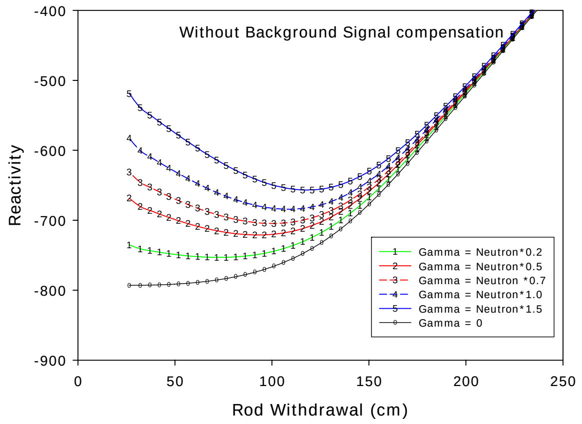

Fig. 2 The Effect of background signals to the reactivity curve

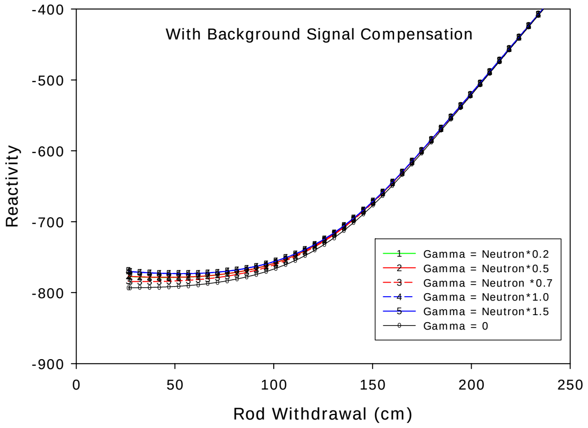

Fig. 3 The reactivity curve after the background signal compensation

3. Results and Conclusion

For the first time in the world, KEPRI applied the DCRM method to two reload cores (case I, II) of KSNPs. A total of nine bank worths were estimated and compared with the results of conventional method. All required parameters were obtained from the RAST-K results for the simulation of bank movements. ROCS code had generated the node-wise cross sections and incremental cross sections of control rods for the LPPT condition. Two reactors are the same in the reactor type but the loading pattern. Figure 4 shows the time history of rod movement and measured detector signals. In the case I the initial positive reactivity was ~30pcm so that it took more time to get back to its initial flux level, while it was ~70pcm in the case II. That is why we have spent 2.2hrs to measure four bank worths in the case I while 1.75hrs for five banks in the case II. As an example, Figure 5 presents the DSCFs and DRCFs of regulating bank 3 and 4 per each reactor. Although the radial bank position was the same in two reactors, DSCF values of bank 3(or bank 4) are not similar near the bottom of the core. KEPRI has already observed that DRCF and DSCF depend on the loading patterns in several applications including WH type reactors. That's why they should be recalculated for every cycle. Fig 6 also is an example of solution of regulating bank 4 per each reactor.

Table 1 summarizes the measured nine static bank worths. One can see the average error of estimated rod worths by the DCRM method is decreased ~ 2% compared with that of the conventional rod swap method and the boron dilution method. As for standard deviation, the DCRM method shows 1.5% while the traditional method 4.4%. Similar results were obtained when the DCRM method was applied to the four LPPTs of WH 2-loop, and 3-loop PWRs in KOREA. The test results also shows that the DCRM method can save 8 ~ 10 hrs in the LPPT process. All the test results point out that the DCRM method is a simple and fast technique with reasonable accuracy and can be used to measure the rod worths in the LPPT of KSNPs (i.e., CE type reactors) as well as of WH type reactors.

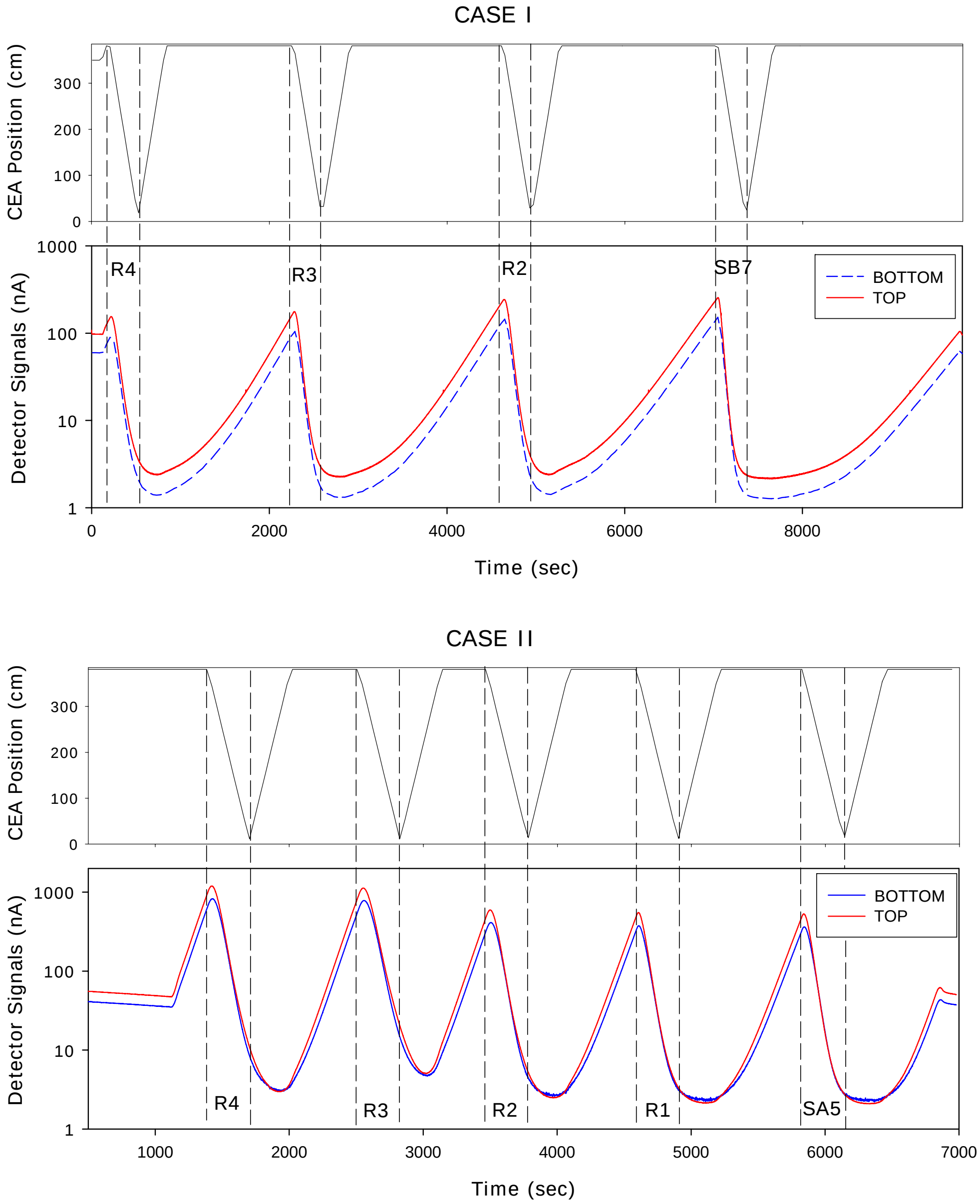

Fig. 4 The time history of bank position and detector signals for case I & II

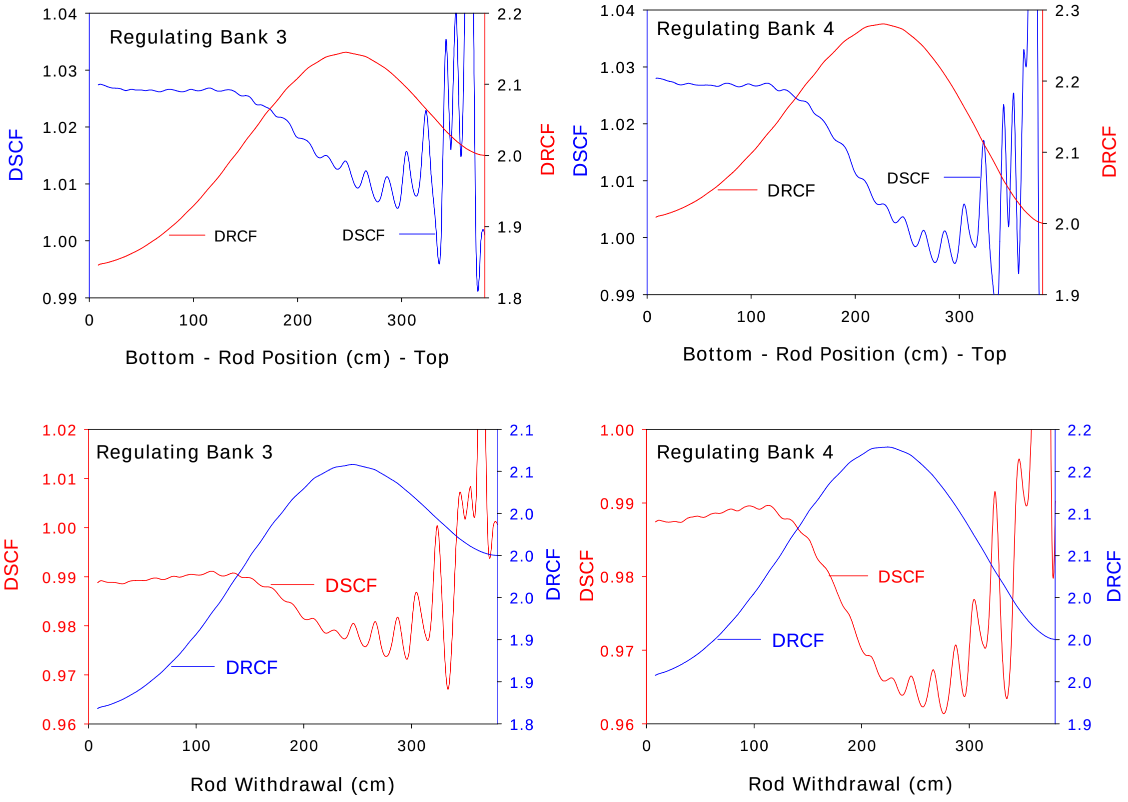

Fig. 5 Examples of DRCFs and DSCFs (two tops for Case I, two bottoms for Case II)

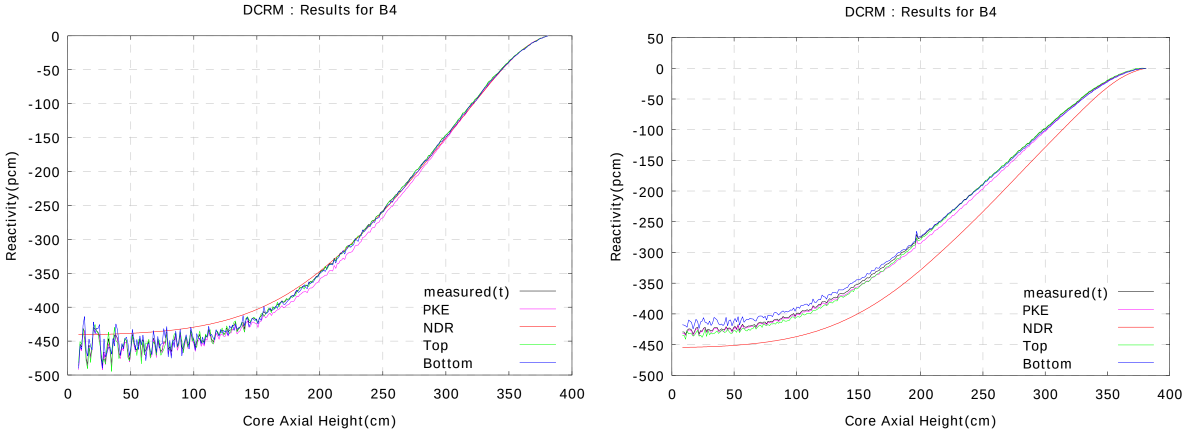

Fig. 6 Final reactivity curve of Regulating Bank 4 (the left: Case I, the right: Case II)

Table 1. The summary of measured static bank worths for two KSNP cores

CASE	CEA TYPE	RSM	RSM	Error	Acceptance	DCRM	DCRM	Error
		(Design, ppm)	(Measured, pcm)	(%, x)	Criteria	(Design, ppm)	(Measured , pcm)	(%)
CASE I	R5	807.8	829.3	2.6	|x|<15%	308.8	325.3	5.4
	R4					440.5	451.4	2.5
	R3	283.2	305.2	7.2	|x|<15%	341.5	354.3	3.8
	SB7	840.	840.0	0.0	|x|<10%	837.3	879.0	5.0
	Σ	1931.0	1974.5	2.2	|x|<10%	1928.1	2010.0	4.2
CASE II	R1	600.1	632.2	5.4	|x|<15%	604.1	627.9	3.9
	R2	528.1	462.9	-12.3	|x|<15%	485.5	477.4	-1.7
	R3	382.7	333.8	-12.8	|x|<15%	340.5	321.1	-5.7
	R4	426.3	389.6	-8.6	|x|<15%	454.4	425.4	-6.4
	SA5	840	788.3	-4.7	|x|<10%	819.9	788.6	-3.8
	Σ	2777.2	2606.8	-6.1	|x|<10%	2704.4	2640.4	-3.1
Avg. Error(%)				6.7				4.2
Standard Dev.				4.4				1.5
Max.Error(%)				-12.8				-6.4

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