Journal of the Korean Nuclear Society
Volume 36, Number 1, pp.53 ~ 63, February, 2004

Computer Based Core Monitoring System for an Operating CANDU Reactor

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(Received May 29, 2003)

Abstract

The research was performed to develop a CANDU-6 Core Monitoring System(CCMS) that enables operators to have efficient core management by monitoring core power distribution, burnup distribution, and the other important core variables and managing the past core history for Wolsong nuclear power plant unit 1. The CCMS uses Reactor Fueling Simulation Program(RFSP, developed by AECL) for continuous core calculation by integrating the algorithm and assumptions validated and uses the information taken from Digital Control Computer(DCC) for the purpose of producing basic input data. The CCMS has two modules; CCMS server program and CCMS client program. The CCMS server program performs automatic and continuous core calculation and manages overall output controlled by DataBase Management System. The CCMS client program enables users to monitor current and past core status in the predefined GUI(Graphic-User Interface) environment. For the purpose of verifying the effectiveness of CCMS, we compared field-test data with the data used for Wolsong unit 1 operation. In the verification the mean percent differences of both cases were the same(0.008%), which showed that the CCMS could monitor core behaviors well.

Key Words : CANDU, reactor, monitoring, RFSP

1. Introduction

The CCMS is an on-line core surveillance system that is based on the standard in-core instrumentation of the CANDU core(380 fuel channels with 102 vanadium detectors). Accurate and detailed information of core condition is very essential in order to achieve the maximum utilization as well as flexible and efficient operation. From this point of view, "CCMS", an advanced on-line core monitoring system for CANDU 6, has been developed by IAE, and has accumulated data in helping core operation and management at CANDU 6 Reactor at Wolsong unit 1 in Korea. The CCMS is an operation support package which runs on Windows NT systems with a data link to plant computer, DCC, via gateway server. Using standard computer network, the CCMS output and input can be displayed and used at any clients with GUI in the existing network. Together with this system, the CCMS enables flexible and efficient plant operation, early abnormality ahnormality detection, and optimizes core management.

In the preceding study[1], a power calculation algorithm was validated by integrating the algorithm with RFSP code for three cases : power maneuverings in steady state and refueling state, and power derating in setback at Wolsong unit 1[1,2,3]. And then, the algorithm was verified by comparing the mapped values and calculated 2-g fluxes using diffusion equation with detector readings obtained in Wolsong unit 1.

Based on the study mentioned above, the efficiency and accuracy of the CCMS were discussed on this paper. The general descriptions for CCMS architecture were discussed in chapter 2, and the efficiency and accuracy of CCMS were discussed in chapter 3.

2. CANDU Online Core Monitoring System

2.1. CANDU Online Core Monitoring System Architecture

The main functions of CCMS are to monitor maximum channel and bundle powers by calculating power distributions of reactor core and to manage the data using a DBMS(DataBase Management System). Considering these functions, the CCMS has two modules : the CCMS server program and the CCMS client program. The CCMS server program calculates core status automatically and continuously. The CCMS client program provides the users with current and past core status using GUI.

The CCMS server program uses the RFSP(Reactor Fueling Simulation Program) code to calculate reactor core status. The RFSP is a computer code for reactor core analysis developed by AECL, which was used for CANDU core design. In Wolsong unit 1, the RFSP code is used for the in-core management.

The CCMS server program receives RFSP input data from Gateway installed in Wolsong unit 1, which is connected to the DCC(Digital Control Computer). The Gateway provides the CCMS server program with binary data files through FTP(File Transfer Protocol). These Gateway binary files have information such as LZC(Liquid Zone Controller) levels, various detector readings and control rods' positions. They are updated every minute and named as the time at which they are updated. For example, a gateway binary file whose name is 'gw0d14.023' has the data of reactor core at 14:23.

Therefore, the CCMS should be composed of several susbsystems : the Gateway from which the CCMS gets the RFSP input data, the UNIX based workstation for running the RFSP code, a server computer using Windows NT for the CCMS server program and the DBMS, and some client computers using Windows for the CCMS client programs. The CCMS uses TCP/IP, FTP and LAN for the connection of these subsystems. Fig. 1 shows the technical architecture of the CCMS.

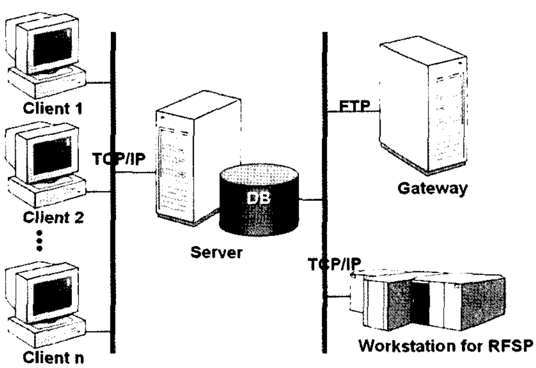

Fig. 1. CANDU Core Monitoring System Architecture

2.2. The CCMS Server Program

The CCMS server program repeats the works listed below in a sequence as shown in Fig. 2.

- To connect to the Gateway FTP server and gets the latest updated gateway binary file,
- to produce the RFSP input data using the information taken from the gateway binary file,
- to manage the RFSP code run,
- to analyze the RFSP output file and store the data into the database.

In Fig. 2., the number in a circle means the order of execution of the CCMS. First, the CCMS server program starts(①). To run the RFSP code, the CCMS server program gets the gateway binary file(②), produces the RFSP input file(③), uploads it to the workstation(④), and commands the workstation to run the RFSP code(⑤). When received the command, the RFSPRun.exe, which is a server program running in the workstation, runs the RFSP code(⑥) using the uploaded RFSP input file and sends a message to the CCMS server program on the end of the RFSP run. The CCMS server program, on receipt the RFSP end message, gets the RFSP output file(⑦) and stores the data into the database(⑧).

A CCMS client program can connect to the CCMS server program at any step of the server program' s processes if the CCMS server program is during execution(①). The number ① means that the connection is independent of the order of the CCMS server program. After the CCMS server program stores the data into the database, it notifies that to the client programs that are on connection(⑨), and the CCMS client programs received the message shows the data to the users(⑩).

Some variables should be converted from the gateway binary file to generate the RFSP input file. The most important input variables among them are channel IDs which labelled channels

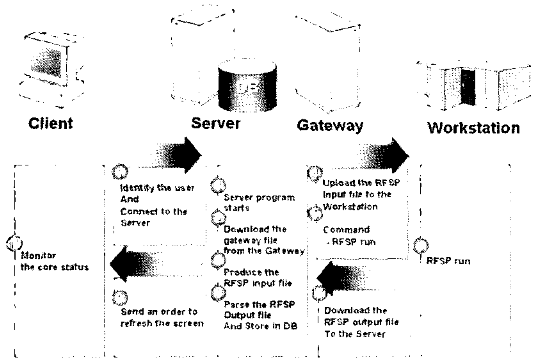

Fig. 2. Operation Sequence of the CCMS

being refueled. As a result of a number of simulations using the data used in the field of Wolsong NPP unit 1, the channel that shows temperature increase by 7% as compared with that of 20 minutes before is regarded as being refueled. Each position of control device is calculated by considering the radius of the sheave. The lattice parameters such as coolant temperature and fuel temperature needed in lattice calculation were calculated using the fitting functions derived from the data in start-up data.

Because the RFSP code runs on the UNIX based workstation, the RFSP input file has to be uploaded to the workstation before the RFSP starts. And the RFSP output file has to be downloaded to the server on which the CCMS server program is being executed to store the data into the database.

In case of RFSP running errors or network errors, the CCMS informs these errors to users by making a log file which describes the symptoms and time of the error. The CCMS backups the database regularly(once per week) and deletes the data that is older than a month so that the database may not be full. Besides, the CCMS stores the RFSP output files and Data Access File(DAF) in a user-defined directory(1 file per day) so that the users may refer to the data that were deleted from the database.

2.3. The CCMS Client Program

The CCMS client program retrieves the data from the database and displays the data in GUI environments. Users' opinions were considered and incorporated during the display framework design process to make the CCMS user-friendly. The CCMS client program was developed in accordance with the requirements of Wolsong plant engineers. The main functions of the CCMS client program are listed in Table 1.

The CCMS client program provides the users with the data and the figures of the reactor core. The data related to each channel are all presented with the CoreMap(a figure of the reactor core in a channelwise x-y plane) and the data related to the bundles are presented below the CoreMap when the user clicks the channel in which the bundles are included(Fig. 3). The data related to the Zone statistics are presented with the ZoneMap(a figure of the reactor core in a zonewise x-y plane)(Fig. 4). The data related to the values of various detectors are displayed with the locations of the VFDs(Vertical Flux Detector) and the HFDs(Horizontal Flux Detector) on which the detectors are attached. The locations of the VFDs and the HFDs are displayed in two views. The VFDs are showed in a x-z plane and a x-y plane, whereas the HFDs in a y-z plane and a x-y plane(Fig. 5). The positions of control rods are the same as those of the VFDs(Fig. 6). These GUI forms are designed to keep the consistency with the documents or programs used in the Wolsong NPP unit 1.

The CCMS client program displays the real-time status of the reactor core through communications with the CCMS server program. As soon as the CCMS server program stores the new data into

Table 1. Main Functions of the CCMS Client Program

Functions	Related Data
Monitoring core power distributions and the status of the reactor core	- Channel & bundle power(2-g and mapped) - Channel & bundle overpower(2-g and mapped) - k increase on refueling - Time of last refueling - Average exit burnup - Burnup over time averaged burnup - Zone statistics
Referring positions of control rods	- Adjustor position - MCA position
Referring the values of various detectors	- Vddet reading value - ZonePt reading value - Sds1det reading value - Sds2det reading value
Referring the past data and trend analyzing	- Channel & bundle power(2-g and mapped) - Channel & bundle overpower(2-g and mapped) - k increase on refueling - Average exit burnup - Burnup over time averaged burnup - Zone statistics
Printing summary papers	- Essential information

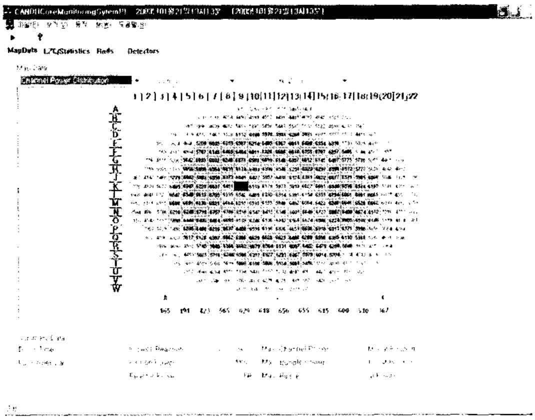

Fig. 3. CCMS Client Program GUI - CoreMap

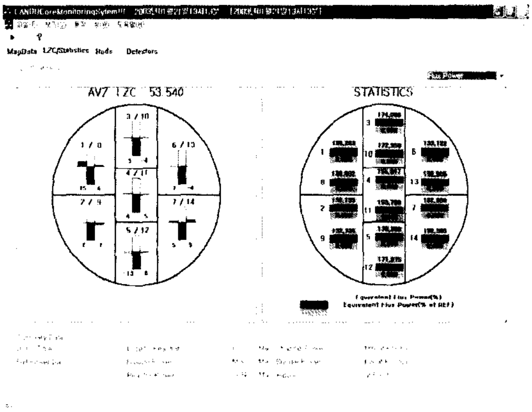

Fig. 4 CCMS Client Program GUI - ZoneMap

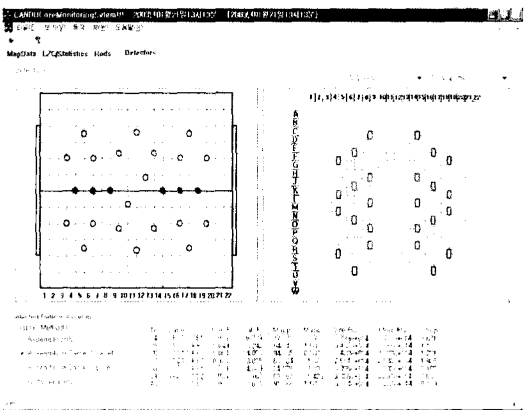

Fig. 5 CCMS Client Program GUI - Detectors

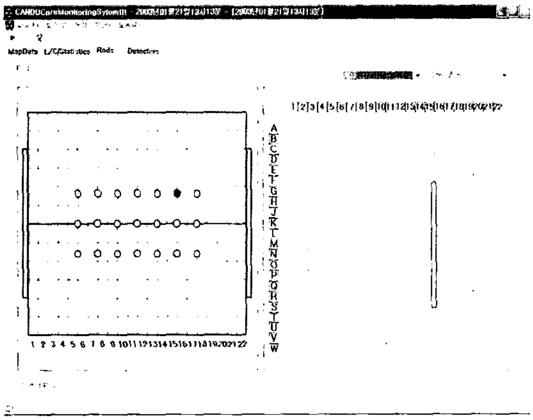

Fig. 6 CCMS Client Program GUI - Control Rods

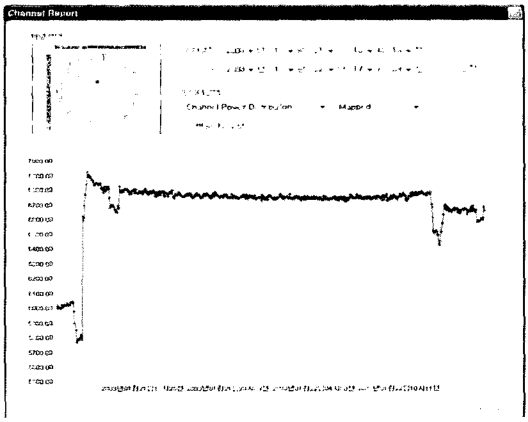

Fig. 7 CCMS Client Program GUI - Time Series

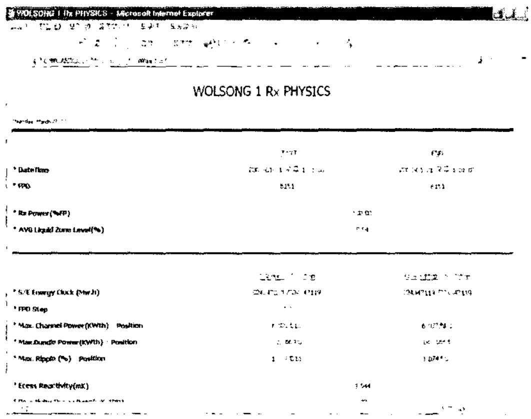

Fig. 8 CCMS Client Program GUI - Report

the database, it notifies that event to the CCMS client program and the CCMS client program refreshes the screen with the new data. In addition, the users can refer the past data by clicking the time-string that they want to refer in a tree view. The users are also able to make time series analysis of a specific variable(Fig. 7), make out and print a summary report to support the reactor core management(Fig. 8).

2.4. Data Modeling

A database is a collection of integrated, organized and computerized data that is indispensable for a system. The process that analyze and organize the data is called 'Data Modeling' [4]. The main output of data modeling is Entity Relationship Diagram(ERD) that is presented by P. Chen in 1976[5]. In the Entity Relation(ER) modeling, entities are the objects to be structured, attributes are the properties of the entities, and the relationships are the relations of entities. An ERD is a figure which present the relations of entities, attributes, and relationships.

The data related to the CCMS are classified into three groups. The data in the first group are independent of time. They are the information about the reactor components such as channels, bundles, zones, detectors, and control rods. They are modeled as 'entity', and the entities in the first group are CHANNEL, BUNDLE, ZONE, VDDET, SDS1DET, SDS2DET, ZONEPT, ADJ, MCA, VFD, HFD. The data in the second group is for the execution of the RFSP code. This entity is not a real thing but the embodiment of the code execution. The entity in the second group is one and the name is RFSPRUN. The data in the third group are modeled as relationships between the entities in first the group and the entity in the second group(RFSPRUN). They are what are related with the entities in the first group among

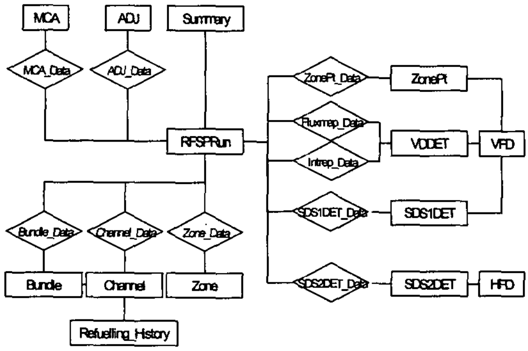

Fig. 9 ERD of the CCMS

the results of the RFSP code execution(RFSPRUN). For example, the CHANNEL entity represents the essential information about the channels such as id., name, the position in the reactor core, refuel scheme and so on. The information about the channels (such as channel power, channel burnup, etc.) among the results of the RFSP code execution are modeled as relationship between CHANNEL entity and RFSPRUN entity. The name of the relationship relationship is CHANNEL_DATA. Fig. 9 shows the ERD of the CCMS. In the figure, entities are shaped as rectangles and relationships as diamonds.

3. Results and Discussions

3.1. Test Results and Discussions

The CCMS was tested to verify its effectiveness. During the test, the CCMS was continuously executed every one minute for about 43 hours from 1/21/2003 13:00 to 1/23/2003 08:00. The CCMS used the data from the Wolsong unit 1 during the test. A virtual gateway server was installed for the test. And the gateway binary files which were created during the test period were uploaded to the virtual gateway server every one minute in a sequence. The CCMS connected to the virtual gateway server to get the gateway

Table 2. Conditions of the Test

Start point of the test	End point of the test
1/21/2003 13:12	1/23/2003 08:00
6151 FPD	6153 FPD
Energy clock : 304347085	Energy clock : 304435207

Table 3. List of the Refueled Channels During the Test Period

Channel ID refueled	Time refueled
J11	1/21/2003 13:52-15:19
R13	1/21/2003 16:05-17:15
Q04	1/22/2003 10:00-11:09
P11	1/22/2003 11:52-13:12
F17	1/22/2003 14:30-15:42
C08	1/22/2003 16:34-18:02

binary files.

Table 2. represents the period of the test. The refueled channels during the test period are listed in Table 3.

Fig. 10 shows the % Full Power(%FP) during the test. The FP values ranged from 0.997 to 1.004. In the %FP case, the values during the refueling were significant. They went up and down steeply.

Fig. 11, Fig. 12 and Fig. 13 contain the data resulted from both 2-g diffusion analysis and flux mapping. The latter was evaluated as more reliable than the former in the previous research[2]. Fig. 11 and Fig. 12 present the maximum channel powers and the maximum bundle powers respectively. The maximum channel and bundle powers resulted from 2-g analysis continue a 8-hour curve. The results show that neutron poison (Xe^{135} and Sm^{149}) concentrations varies by power oscillations during refueling. The maximum channel and bundle powers resulted from flux mapping are stable ranging from 6,800kW to 6,900kW and from 820kW to 840kW respectively. Fig. 13 shows the average differences between the site fluxes and the interpolated fluxes('2g' suffixed) and between the mapped fluxes and the measured fluxes('mapped' suffixed). The average difference named as 'mean_diff_2g' in the figure ranged from -0.333% to 0.048% and were mostly in the range of -0.2% ~ -0.1%. The average differences between the mapped fluxes and the measured fluxes named as 'mean_diff_mapped' in the figure

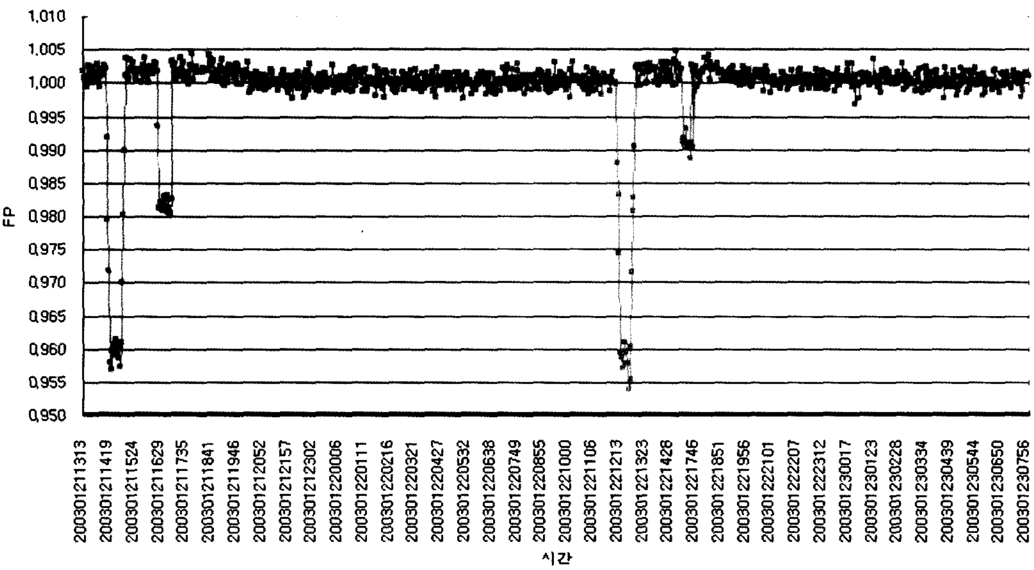

Fig.10. FP Behaviors During the Test

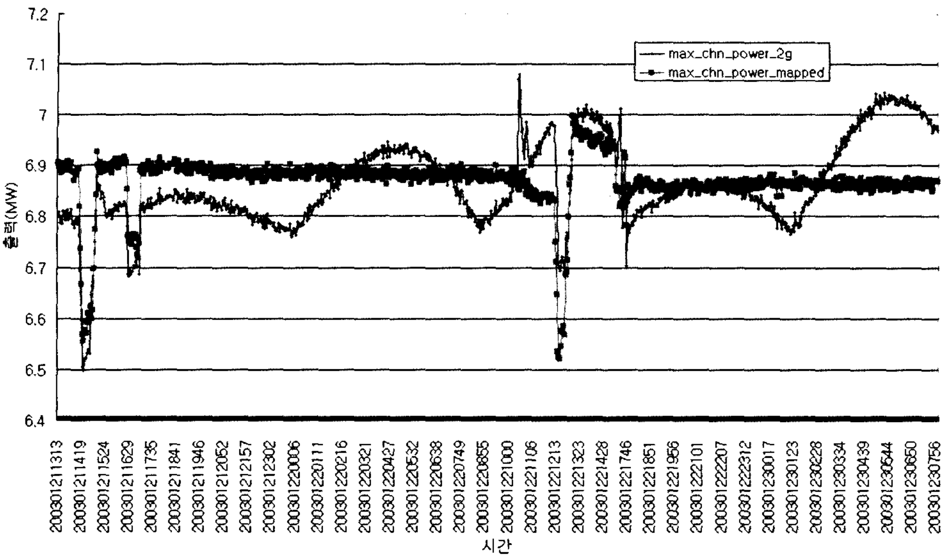

Fig. 11. Maximum Channel Powers During the Test

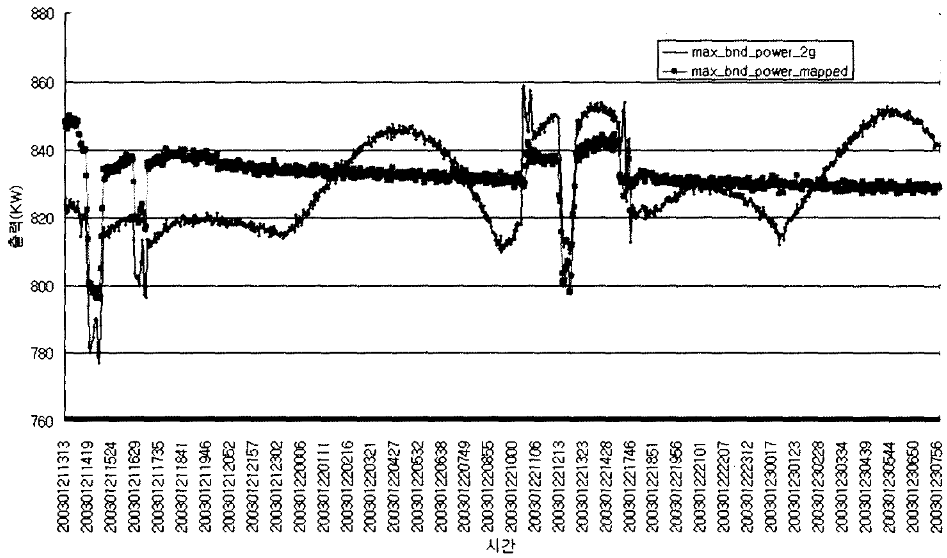

Fig. 12 Maximum Bundle Powers During the Test

ranged from -0.033% to 0.028%. These near zero differences (especially in case of 'mean_diff_mapped') prove the validity of the CCMS. The standard deviations between the site fluxes and the interpolated fluxes(which were named as 'stdv_2g' in the figure) ranged from 1.8 to 5. On the other hand, the standard deviations between the mapped fluxed and the measured fluxes were less than 1.5. These differences between the standard deviations in the two cases verify that the data resulted from flux mapping are more reliable than the data resulted from 2-g diffusion analysis.

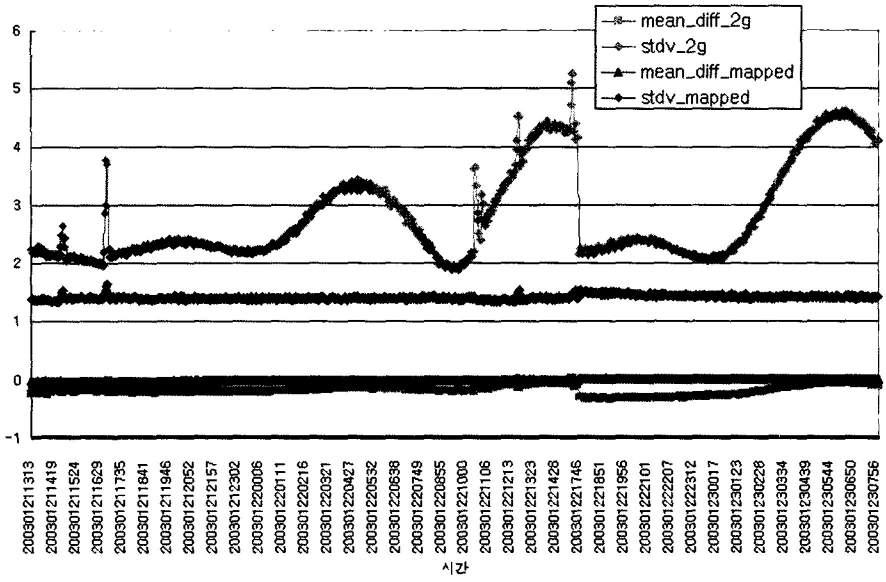

Fig. 13. Error Analysis Between 2-g/Mapped Fluxes and Detector Readings

3.2. Comparison with the Field Data

To verify the effectiveness of the CCMS, the data at the end of the test or at 1/23/2003 08:00 were compared with the data calculated at the same time in the Wolsong NPP unit 1. The results are listed in Table 4.

In these results, the difference between the energy clocks in the two cases is due to the variation of %FP during the test period. This difference is because %FP in the CCMS are considered as actual values while that in the plant operation are supposed to be 100%.

There are great differences in case of the maximum channel and bundle powers in 2-g diffusion analysis. The channel ID and the bundle ID that have the maximum value are different, and the maximum values are also different by more than 200kWh and 25kWh respectively. It is due to the neutron poison dynamics as mentioned above.

On the other hand, in case of channel and bundle powers resulted from flux mapping, we can say that the differences could be ignorant. The channel ID and bundle ID that have the maximum value are same and each maximum value is similar, too.

The *COMPARE module in the RFSP compares the site fluxes with the interpolated fluxes at the 102 positions of vanadium flux detectors. The mean percent difference of the test(-0.089%) is less than that of the field(-0.204%) in absolute value. Hence the CCMS presents the core status better than actual plant. But the standard deviation of the test(4.101) is greater than that of the plant(2.132). That is because the test in the CCMS was performed with fine time interval(1min) while field data in the plant operation was extracted twice per week. That means continuous run of RFSP, which includes static diffusion algorithm, could heighten the local deviations by poison accumulation. Thus it was needed to test CCMS by using *FLUXMAP for the purpose of more accurate results and difference compensation.

The *FLUXMAP module in the RFSP compares the mapped fluxes with the measured fluxes at the

Table 4. Data Comparison

Variables		Field Data	Test Data
SDATE(Start Date)		2003-01-20 08:00	2003-01-23 07:58
EDATE(End Date)		2003-01-23 08:00	2003-01-23 08:00
Energy Clock		304434973	304435207
Excess Reactivity(mk)		4.114	4.207
Max Chanel Power(2-g, kW, Channel ID)		6757.3 at N08	6970.3 at G15
Max Bundle Power(2-g, kW, Channel ID, Bundle ID)		815.0 at O18, #6	841.4 at F15, #7
Max Chanel Power(mapped, kW, Channel ID, Bundle ID)		6857.6 at N08	6868.8 at N08
Max Bundle Power(mapped, kW, Channel ID, Bundle ID)		827.4 at O18, #6	829.2 at O18, #6
Site Fluxes vs INTREP Fluxes (*COMPARE)	Mean of Detector Flux from INTREP	0.26767E+15	0.26759E+15
	Mean of Detector Flux from Site	0.26735E+15	0.26726E+15
	Mean Percent Difference(%)	-0.204	-0.089
	Largest Positive Percent Difference(%)	5.598(#51)	8.821(#51)
	Largest Negative Percent Difference(%)	-5.046(#96)	-8.951(#99)
	Standard Deviation of Percent Difference	2.132	4.101
Reading Fluxes vs Mapped Fluxes (*FLUXMAP)	Mean of Readings	78.018	73.202
	Mean of Mapped values	78.018	73.201
	Mean Percent Difference(%)	0.008	0.008
	Largest Positive Difference(%)	6.521(#65)	6.434(#65)
	Largest Negative Difference(%)	-3.324(#92)	-3.190(#92)
	Standard Deviation of Percent Difference	1.429	1.426

positions of the vanadium flux detectors. The mean percent differences in the two cases are the same(0.008%), which shows that both the CCMS and the actual plant operation data can monitor core well. The standard deviations are also similar.

4. Conclusions

Accurate and detailed information of core condition by CCMS is indispensible in order to make the best use of core and fuel capability and to achieve flexible and efficient operation. The CCMS presents current reactor core status continuously using the RFSP code and the data taken from the DCC, shows the real-time data with GUI environments, and stores the data in the database so that the users may refer to the past data.

In case of channel and bundle powers resulted from flux mapping in the CCMS, we can say that the differences between the CCMS and the actual plant could be ignorant. The channel ID and bundle ID that have the maximum value are same and each maximum value is similar, too.

A test was conducted for about 43 hours to verify the effectiveness of the CCMS. As a result of a comparison the test data with the field data, the CCMS turned out to be valid.

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