BUNDLE SPECIFIC DECAY HEAT POWER CALCULATIONS BY CHAOS-W CODE

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Abstract

CHAOS-W version 2.0 is a standard Windows code developed to calculate bundle specific decay heat powers of CANDU reactors by applying the ORIGEN-S code, the ANSI/ANS-5.1-2005 decay heat power standard and other applicable formulas or methods. The code first traces the irradiation history of any fuel bundles in any channels from a series of RFSP-IST input and output data files, and then composes complete operating power history of each individual bundle. CHAOS-W provides users with a powerful and multi-functional platform to perform data management, decay heat power calculations and data processing.

Key Words: CANDU, Bundle Decay Heat Power, CHAOS-W, ORIGEN-S, ANSI/ANS-5.1-2005, RFSP-IST

1. Introduction

An accurate prediction of bundle specific, channel or whole core decay heat powers is essential in the heat sink analysis for outage-related activities. At the end of 1990s, a DOS-based code package named CHAOS (Calculation of Decay Heat Applying ORIGEN-S) was developed by Atlantic Nuclear Services Ltd to satisfy a need for a tool to perform detailed evaluations of bundle decay heat powers at Point Lepreau Generating Station.

This paper reports work done to improve the utility of the code and to make it a multifunctional platform for decay power calculations and data processing. Two conference papers report decay power comparisons [1] between ORIGEN-S [2] with the ANSI/ANS-5.1-2005 standard [3] and a fast computational method [4] relevant to CHAOS-W.

To extend functions of the CHAOS package, CHAOS-W version 2.0, a standard Windows code has been developed to calculate the decay heat powers of the CANDU fuel bundles by applying the ORIGEN-S code, the ANSI/ANS-5.1-2005 decay heat power standard and the other applicable formulas or methods [5, 6].

CHAOS-W first traces the irradiation history of any fuel bundle in any channel from a series of RFSP-IST input and output data files, and then composes complete operating power history of each individual bundle and prepares the input data files for bundle specific decay heat power calculations by applying the following calculation methods or algorithms: (1) the ORIGEN-S code packaged in the SCALE 4.4a system program [2], (2) the ANSI/ANS-5.1-2005 decay heat power standard for light water reactors (LWRs) [3], including its simplified method and the decay heat power formula for pulse operating power histories, (3) the simple decay heat power formulas such as Glasstone formula [5], Todreas-Kazimi formula [6], and (4) a simple decay heat power formula [4] based on ACE algorithm [7].

This paper presents a theoretical overview, features of CHAOS-W version 2.0, and its application to calculating decay heat powers. For the applications described here, the bundle operating power histories are composed from a series of RFST-IST input and output data files.

2. Theoretical Overview

2.1 Bundle Operating Power History

Bundle specific operating power histories used in CHAOS-W are composed from RFSP-IST input/output data files, RFSP history data file, and other data files. These data files contain necessary information associated with operating power history, such as total heat energy, full power days, burnups, date and time at which RFSP-IST was running, shift locations, shift times, shifts, as well as fuel composition parameters, and so on.

Bundle shifts occur between most consecutive RFSP runs. RFSP input files contain a list of the extract times/dates for every bundle shift. However, there is no bundle power information, which is required by a complete bundle power history, at the shift time. In CHAOS-W, the bundle power history is reconstructed.

2.2 Treatment of Fuel Shuffling

CHAOS-W can deal with all fuel shuffling information except for the following limitations:

- When defining which bundles to be calculated, the donor channels should always be tracked before the channels are shuffled, because the history file created for the donor channel is used in composing operating power histories for the bundles in the shuffled channels.
- In any cascade shuffling, the cascade should be open-ended. For example, in the cascade shuffling of type Axx → Byy → Czz, the fuel bundles discharged from the channel Czz cannot be fueled back to channel Axx.
- The fuel bundles that have already undergone one shuffling cannot be used for further shuffling. For example, in the shuffling of type Axx → Byy, the bundles in Byy that have come from Axx will stay in Byy till reaching their target burnups, and will not be unloaded prematurely, and will not be loaded into another channel.

2.3 Decay Heat Power Calculation Methods

In CHAOS-W, bundle specific decay heat powers can be calculated through:

(1) The ORIGEN-S Code -- The ORIGEN-S code packaged in SCALE4.4a [2] program is considered to be one of the applications with most accurate decay heat power results, and has been verified and validated in Canadian nuclear industry. The ORIGEN-S input data files are generated automatically in CHAOS-W according to the bundle fuel composition and operating power histories including shuffling information.
(2) The ANSI/ANS-5.1-2005 Standard -- So far, the most accurate experimental formula is considered to be the algorithms of the ANSI/ANS-5.1-2005 standard [3], which is used widely and internationally as decay heat power standards for light water reactors, and incorporated into CHAOS-W. The reactor operating history with refuelling is represented by a histogram of a series of time intervals with constant power, which is created automatically in CHAOS-W. For each time interval of the histogram, fission fractions of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu via burnups for different fuel types can be entered manually or obtained by running the WIMS-IST code through an interface provided in CHAOS-W, if WIMS-IST is installed. Coding of the ANS standard has been validated through the examples described in its appendixes [3].
(3) Simple Formulas Based on ACE Algorithm -- This formula [4] is derived based on data mapping through the Alternating Conditional Expectation (ACE) algorithm [7]. Such a formula is simple but the decay heat results are close to those of the ORIGEN-S. It could be useful for accurate and fast calculations of decay heat powers.
(4) Other Approximate Formulas -- Other applicable formulas like Glasstone formula [5] and Todreas formula [6] are also incorporated into CHAOS-W. These simple formulas are available in some nuclear engineering books and articles, are much simpler but not so accurate, and sometimes used in reactor decay heat power calculations. The Glasstone formula is said to be an approximation to the early ANSI/ANS-5.1 standard.

2.4 Decay Heat Powers and Its Uncertainties

For decay heat calculations using the ORIGEN-S code, CHAOS-W searches decay heat powers for each of three components after all ORIGEN-S runs are finished. That is, it groups the components, light elements, actinides and fission products using context recognition techniques.

Values of the decay heat powers for specific bundles depend on the cooling time after shutdown. Accordingly, decay heat powers for specific channels and the entire core can be calculated by adding up those of the bundles. Bundle, channel or core decay heat powers at any cooling time are calculated by using a linear interpolation algorithm. The fraction of decay heat powers deposited into the coolant can be specified.

A 2-sigma decay heat power uncertainty (e.g. 9.5%) arising from an ORIGEN-S calculation consists of 1-sigma RFSP history data uncertainty (e.g. 2.5%) and 1-sigma ORIGEN-S based error uncertainty (e.g. 4%). This uncertainty can be added to the final decay powers or not according to the users' request.

Decay heat power uncertainties for the ANSI/ANS-5.1-2005 standard are systematically assigned as per the detailed calculation conditions in CHAOS-W.

3. Features of CHAOS-W

Development of the CHAOS-W version 2.0 code followed the software quality assurance (SQA) plan developed by Atlantic Nuclear Services Ltd. This SQA plan is in full compliance with the guidelines stated in the N286.7 standard [8]. Although CHAOS-W has been developed, validated and verified based on a CANDU6 reactor core, it can be applied to other CANDU reactors' bundle specific decay heat assessments, with little or no modifications. The current CHAOS-W code has the following main features:

- Calculate and compare decay heat powers of specific bundles, channels or core by applying various methods or algorithms presented in section 2.3, not only for bundle operating power histories derived from RFSP-IST data files, but also for arbitrary irradiation histories entered by users.
- Manage and control executing the external applications such as the ORIGEN-S code and the WIMS-IST code, and automatically process its outputs as per the decay power calculation requirements.
- Output calculation results in both text and graphic formats. These results include decay power and its uncertainty time curves for specific bundles, channels and core, operating power histories for specific bundles, core face map indicated by channel powers, maximum bundle powers and its positions at any cooling time, etc.
- Compose bundle specific operating power histories based on RFSP-IST input/output data files that may be in any directories (folders) on a PC or the local area network (LAN) and adopt general file name convention.
- Prepare input data and calculation conditions through multi-functional graphic user interfaces (GUIs). For examples, all data necessary to create ORIGEN-S input data files, all data that must be justified by users according to the ANS standard, all data relevant to the bundle, channel and core parameters.
- Cross-check all calculation conditions and data files and automatically create some of them if required by the users. Provide users with online help on data errors, calculation problems and result explanations.
- Run on Windows 98, NT, 2000, XP or 2003 Operating Systems. Perform data file, calculations task and result file managements in standard Windows mode.

4. Application of CHAOS-W

Figure 1 shows the main interface of CHAOS-W version 2.0, in which the decay heat powers will be calculated for specific bundles in channels A09, D19, M20 and N18 in the CANDU6 reactor at PLGS. The bundles to be calculated can be re-defined by users

through a data edit dialog box in Figure 2 where file explanation and function buttons are provided.
For example, channel M20 underwent fuel shuffling on 18 April 2002, the donor bundles were bundle 1 to 12 in channel N18. Bundles in channel M20 were shuffled to channel D19 on the same date. The core bundle shift requirements can be defined through dialog box in Figure 3.

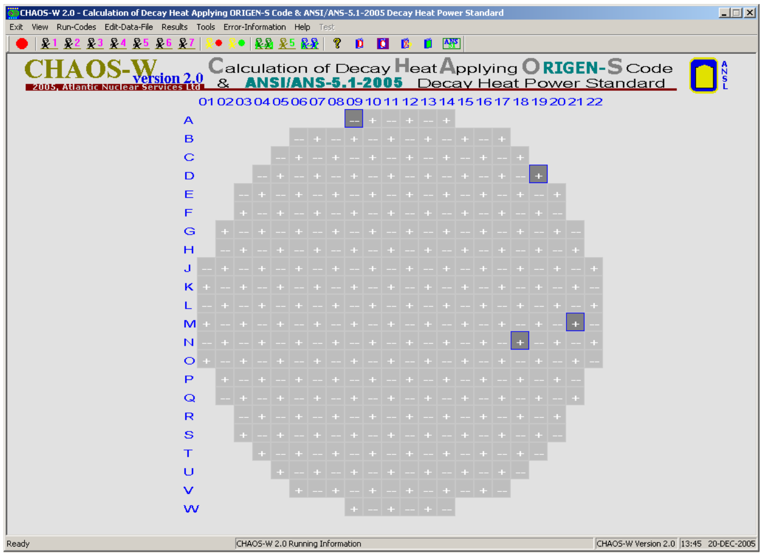

Figure 1 Main Interface of CHAOS-W Version 2.0

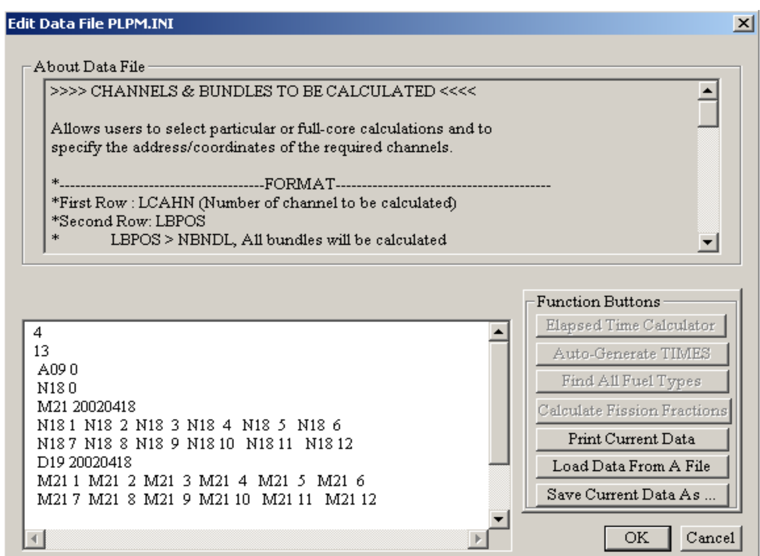

Figure 2 Data File Edit Dialog Box

Fuel data such as type and mass can be input through the dialog box in Figure 4. For the present decay heat power calculation, the reactor operating power history started at 10:00, 30 July 1999, with total heat energy 253776 GWh (5129.53 FPD), and ended at 22:27, 19 April 19, 2002, with total heat energy 293413 GWh (5930.71 FPD). The last shutdown time is 22:27, 19 April 2002. The maximum cooling time to be used for calculation is 720 days. All the data is displayed in Figure 5 after CHAOS-W cross-checks all essential data files that can be modified through the dialog box in Figure 2 or menus in CHAOS-W. When all data files are consistent with the calculation requirements, the user executes one of the CHAOS-W commands to compose bundle specific operating power history data files. Then they select one of the methods or algorithms described in Section 2.3 through the dialog box in Figure 6 to calculate bundle specific decay heat powers. If the selected decay heat power calculation method is the ANSI/ANS-5.1-2005 standard, some parameters will be justified by the user through the dialog box in Figure 7.

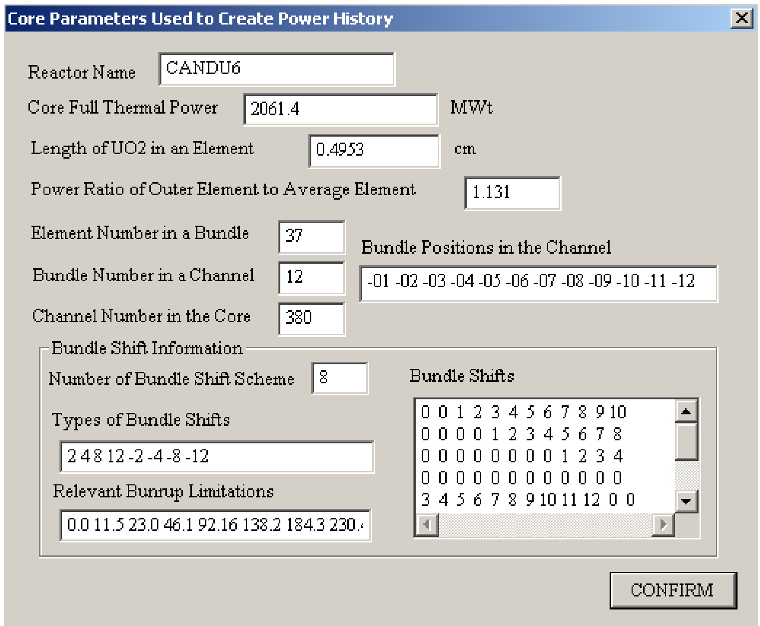

Figure 3 Bundle, Channel and Core Parameters

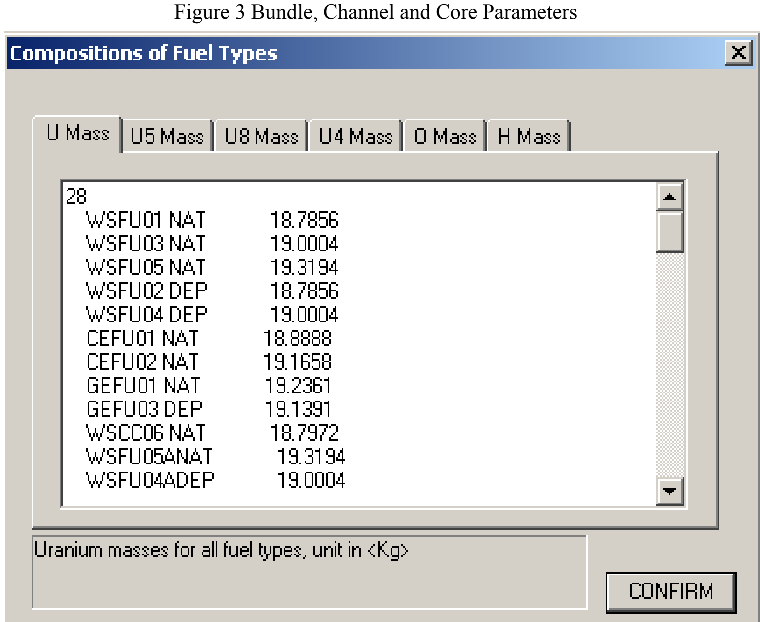

Figure 4 Fuel Data Dialog Box

The calculation results related to decay heat powers are summarized in Table 1, and can be output in both graphic and text formats by using the dialog boxes in Figures 8 and 9 and command menus of CHAOS-W.

Figure 10 shows the total decay heat power curve vs. cooling time for channel D19. It can be seen that the decay heat powers between the ORIGEN-S code and the ANS-5.1-2005 standard agree well. Figure 11 presents the ANS-5.1-2005 results of all bundle specific decay heat powers in channel M21. More results for V&V of CHAOS-W and comparisons between the ORIGEN-S code and the ANSI/ANS-5.1-2005 standard are described in Reference [1].

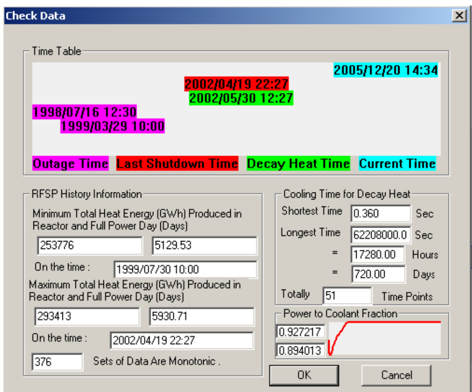

Figure 5 Summary of Calculation Conditions

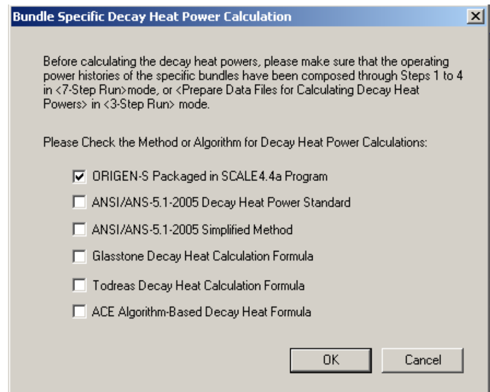

Figure 6 Selection of Decay Heat Power Methods

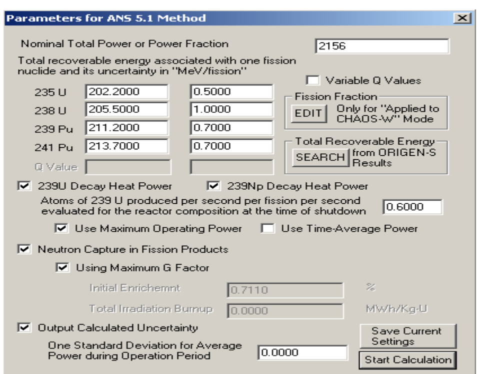

Figure 7 Settings of ANS-5.1 Method

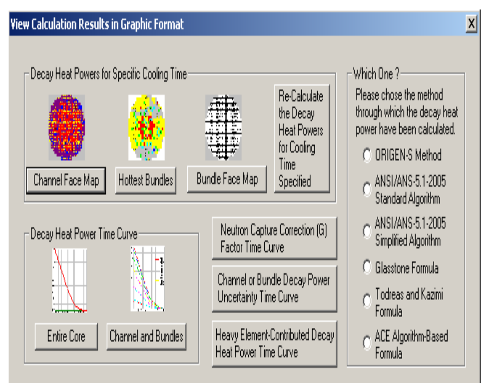

Figure 8 Output Results in Graphic Format

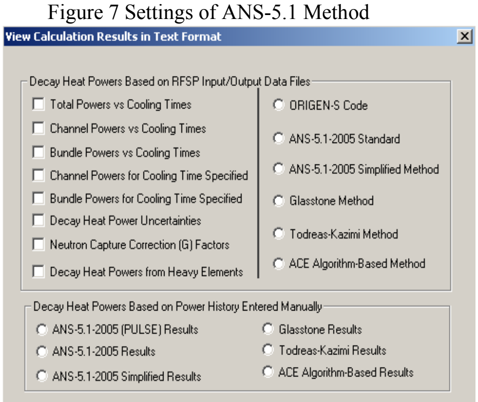

Figure 9 Output Results in Text Format

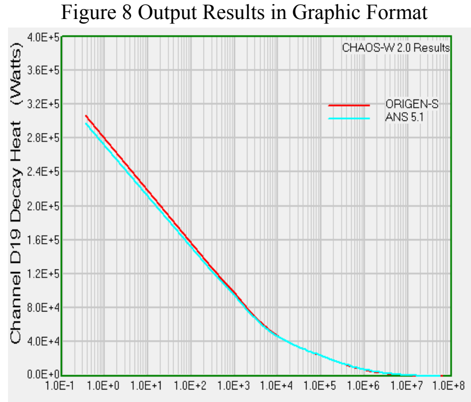

Figure 10 Channel D19 Decay Heat Power Comparison between ORIGEN-S Code and ANS-5.1 standard

Table 1 Available Results in CHAOS-W Version 2.0 (Symbol * means available)

RESULTS	Decay Heat Power Calculation Methods						History Data		Format	
	ORIGEN	ANS51	ANS SM	Glasstone	Todreas	ACE	RFSP	Entered	G	T
Core Total DHP Time Curve	*	*	*	*	*	*	*	*	*	*
Channel DHP Time Curve	*	*	*	*	*	*	*	*	*	*
Bundle DHP Time Curve	*	*	*	*	*	*	*	*	*	*
Total DHP at Specified Cooling Time	*	*	*	*	*	*	*	*		*
Channel DHP at Specific Cooling Time	*	*	*	*	*	*	*	*		*
Bundle DHP at Specified Cooling Time	*	*	*	*	*	*	*	*		*
Bundle DHP Uncertainty Time Curve		*	*				*	*	*	*
Neutron Capture Correction (G) Factor Time Curve		*	*				*	*	*	*
DHP Contributed by Heavy Elements		*	*				*	*	*	*
Face Map with Channel DHP	*	*	*	*	*	*	*		*	*
Face Map with Max Bundle DHP	*	*	*	*	*	*	*		*	*
Face Map with Bundle Positions Having Max. DHP	*	*	*	*	*	*	*		*	*
Max. Bundle DHP Time Curve	*	*	*	*	*	*	*		*	*
Max. Channel DHP Time Curve	*	*	*	*	*	*	*		*	*
Bundle Operating Power History Curve							*		*	*

Note: Format G means graphic, T text; ANS SM means ANSI/ANS-5.1-2005 Simplified Method; DHP means Decay Heat Power

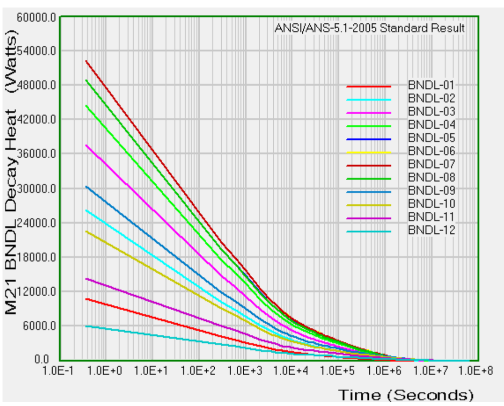

Figure 11 Bundle Decay Heat Powers in Channel M21 (ANS-5.1-2005 Results)

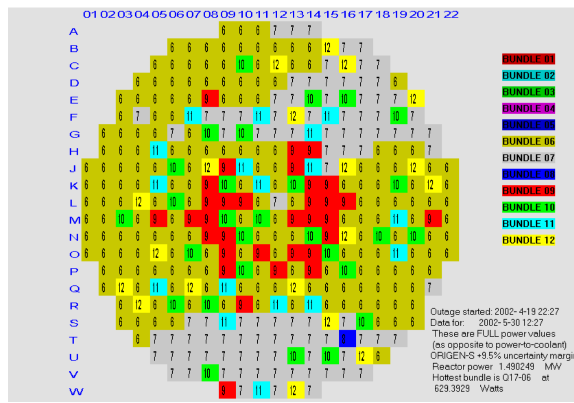

Figure 12 Core Face Map with Bundle Positions Having Max. Decay Heat Powers at Specified Cooling Time

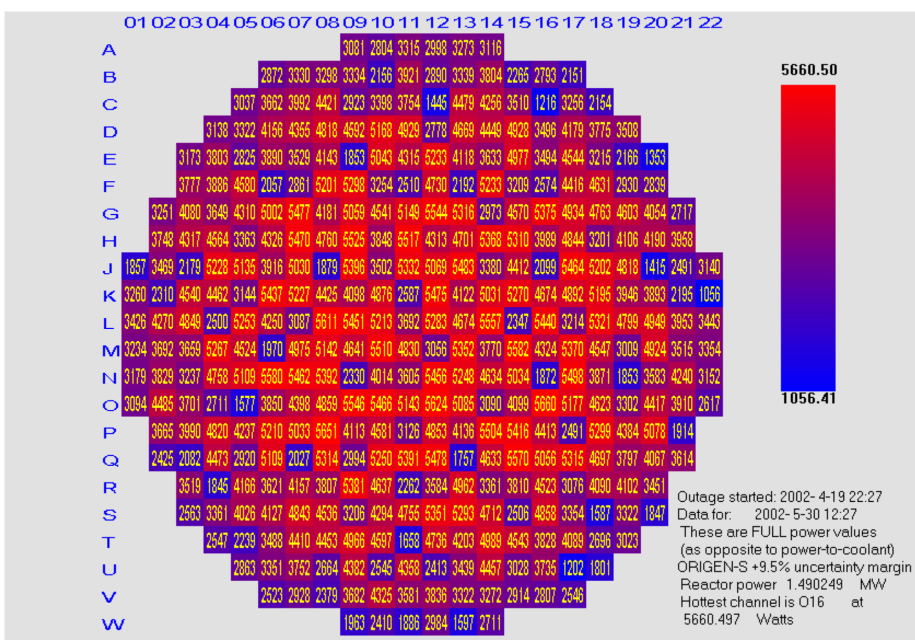

Figure 13 Core Face Map with Channel Decay Heat Powers at Specified Cooling Time

CHAOS-W provides users with a colorful core face map showing maximum bundle decay heat powers at any specified cooling times or by the bundles' positions. Figure 12 is the core face map (for entire core calculation) with bundle specific positions that have the maximum decay heat powers at cooling time 12:27, 30 May, 2002 (i.e. 970 hours after shutdown). The corresponding core face map with channel decay heat powers at the same cooling time are shown in Figure 13. At this time, the total reactor decay heat power was 1.47 MW, the hottest channel was O16 with power 5654.92 Watts, and the maximum bundle power was 629.38 Watts at position 06 of channel Q17. The results have been demonstrated to be correct and reasonable.

5. Conclusions

In summary, CHAOS-W version 2.0 can be used for heat sink analysis and planning of outage/maintenance activities related to post-shutdown heat generation due to radioactive decay. It is capable of modelling all CANDU6 fuel bundles (extended to other CANDU bundles with little changes) to which ORIGEN-S can be applied. The calculations relevant to decay heat powers at any given cooling time for any bundles, channels or whole core can be performed easily because CHAOS-W automatically composes bundle specific operating power histories based on RFSP-IST data files, effectively manages the applications of the ORIGEN-S code, the WIMS-IST code, the ANSI/ANS-5.1-2005 standard and other applicable decay heat power algorithms, as well as conveniently outputs the results.

6. References

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