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MEASUREMENT DATA

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**AUTOMATED METHODS FOR REAL-TIME ANALYSIS OF
SPENT-FUEL MEASUREMENT DATA***

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ABSTRACT

Software has been developed for "real-time" analysis of neutron and gamma data from GRAND-1/fork measurements on spent-fuel assemblies. Three modules compose the software package. The modules are linked through a database system of files.

The first module is part of a general database processing code. This module prepares input data files with inventory and correction-factor information for the second module.

The second module, called OLAF, operates on a computer attached to the GRAND-1 electronics unit. In this second module, neutron and gamma data from spent-fuel assemblies are analysed to verify consistency in the facility operator declarations for exposure (burnup) and cooling time. From the analysis, potential discrepancies in the measurement data are questioned while equipment is still installed at the facility and is available for additional measurements.

During the measurements, data are written to an output file, called a results file, which can be processed by the third module of the software package. In the third module, printed reports summarising the data and results are prepared, and neutron and gamma data are written to files that are processed by the Deming curve-fitting code.

INTRODUCTION

The GRAND-1/fork detector system, shown in Fig. 1, has been developed for measuring neutron and gamma radiation from spent-fuel assemblies. Such measurements are typically made on fuel assemblies in storage racks at reactor facilities. The data are used to verify consistency in operator-declared information about the spent-fuel assemblies. When measurements are made, the fork detector suspended ~1 m above the storage rack with sections of pipe, as shown in Fig. 2. The assembly to be measured is partially raised

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Fig. 1. GRAND-1 electronics unit and fork detector head. A Toshiba T1100+ computer is sitting on top of the GRAND-1. Both the GRAND-1 and the Toshiba can be operated with ac power or on internal batteries.

from the rack, and the tines of the fork are maneuvered into position surrounding the assembly with the back edge of the fork in contact with the assembly.

There are two fission chambers for neutron measurements and an ion chamber for gross-gamma measurements in each tine. Cables in the pipe sections connect the detector head to the GRAND-1 electronics unit, which is generally located on the storage pond bridge. The neutron and gamma data are collected simultaneously by the GRAND-1. Data collection times are typically 30-60 s per assembly depending on the neutron activity. Total time for each assembly is approximately 5-9 minutes, with bridge and fuel handling operations taking the majority of the time.

The GRAND-1/fork equipment is often used in radiation areas of facilities and therefore radiation protection procedures are required. In most facilities, people working on the bridge wear anticontamination clothing including 1-2 pairs of gloves. Often the GRAND-1 and other electric components are wrapped in plastic for protection. Under these conditions, interaction with equipment that requires extensive button-pushing or

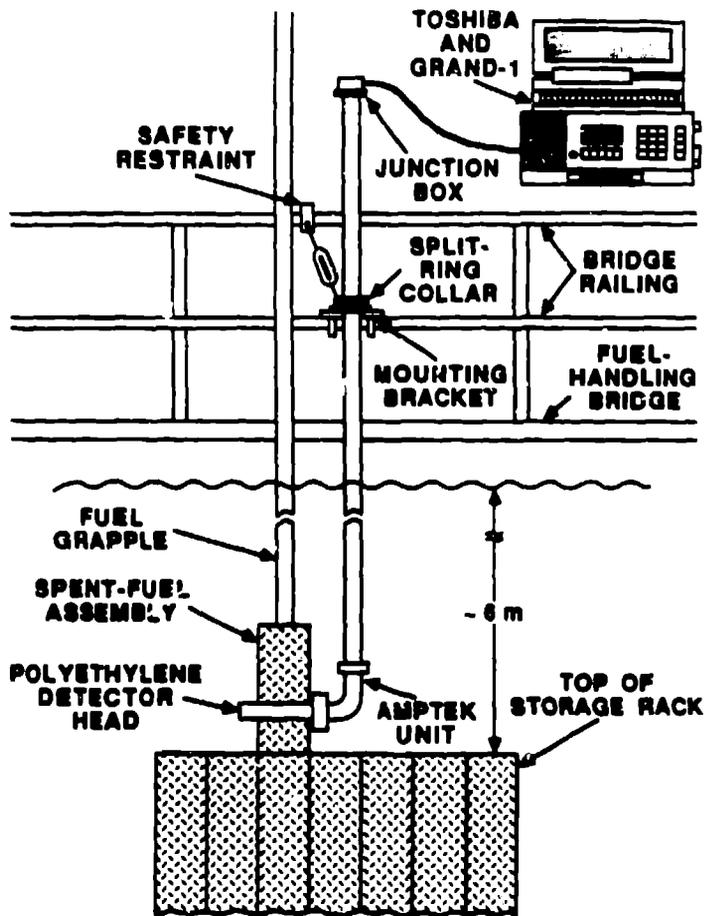


Fig. 2 Schematic diagram showing how the GRAND-1/fork system is used for making neutron and gross-gamma measurements on spent-fuel assemblies. For the measurements, the detector is suspended from the bridge and moved into position around a partially withdrawn assembly. The GRAND-1 and the Toshiba are generally used on the bridge, but could be used in a location off the bridge.

keystrokes would be difficult, because the gloves and plastic would make such interactions cumbersome. As a result, in the past, data collection has been the only activity typically performed on the bridge. As shown in Fig. 3, there have been situations where probable measurement errors occurred. These were not detected until after a full data analysis was done because the data analysis occurred after the equipment was removed from the facility. Remeasurements were not possible and the probable measurement errors could not be confirmed or corrected.

Measurement errors could be minimized if several measurements were routinely made on each assembly instead of just one measurement. However, because of time restraints, multiple measurements on each assembly are not possible and therefore a single measurement is preferred. Additional measurements are appropriate if discrepancies are indicated while data are being collected. In trying to resolve any discrepancies, it is important to

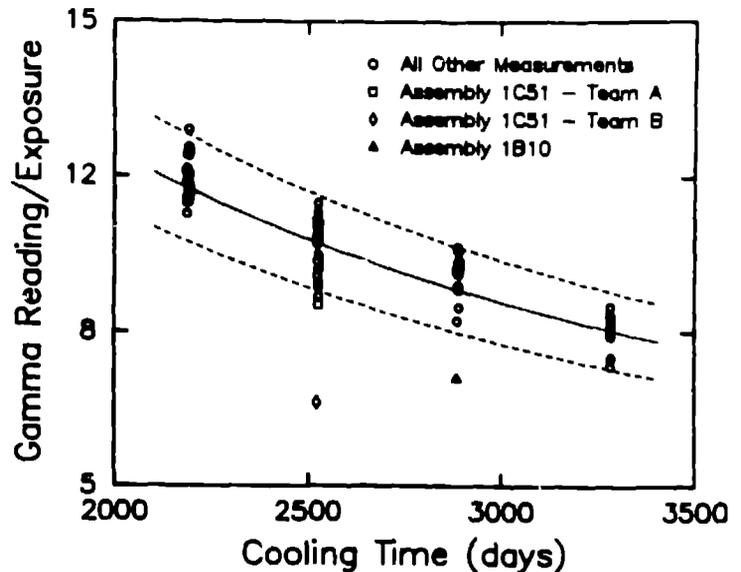


Fig. 3. Gross-gamma measurement data. The solid line through the data is a curve fitted to the function, $GE = a T^b$ (p. 6). The dashed lines are 10% variations from the fitted curve in the y (or in this case GE) variable. The two data points below the lower dashed line (measurement on assembly 1C51 by team B and the measurement on assembly 1B10) represent data with known measurement errors.

obtain more information about the assembly and to eliminate measurement errors as a possible source of the difficulty.

We have now developed techniques for automated data analysis during the measurements. In the new system, measurements with the GRAND-1/fork system are controlled by a computer attached to the GRAND-1. Software called the On-Line Analysis of Spent Fuel (OLAF) controls the measurement procedures and analyzes each set of data as it is collected. OLAF sends commands to the GRAND-1 and receives data through the RS-232 interface. The software has been designed to minimize the number of user interaction keystrokes because of the potential difficulty in operating the equipment through plastic while wearing gloves.

The complete software system, of which OLAF is one of three modules, includes an input module, which prepares data for OLAF, and an output module for post processing measurement data from OLAF. A code, called CINDER-PC, is called from the input module. CINDER-PC is an IBM-PC version of the CINDER-3 code (one of the CINDER series of codes¹⁻⁴). In the input module, CINDER-PC calculates neutron source rate correction factors for ^{240}Cm and correction factors for differences in the neutron source rate that are due to variations in the initial ^{235}U enrichment in the fuel. The correction factors, when available, are used by OLAF.

CODE STRUCTURE

The structure of the software system is shown in Fig. 4. Code modules are linked through dBASE III Plus™ database files or ASCII format files. The various types of files used in the system and the corresponding DOS extensions are identified in Table I. All modules operate on IBM-PC computers or compatibles using an MS-DOS operating system.

Input Processing Module

The input processing module prepares data for the OLAF module. There are two paths that can be used for preparing OLAF input: with or without correction factors.

Without Correction Factors. In the "without" correction factor mode, the input module processes a database file with spent-fuel inventory data and, from this information, creates an assembly information file (*.ASB) file. Separate inventory database files contain information for each individual storage basin. Once an inventory file has been created, data in the file only change when fuel has been discharged from the core, when fuel is returned to the core, or when

fuel is moved to a different location in the storage basin.

To execute the input module, the user is prompted to identify the facility. (Generally, the name of the reactor facility is used as the name for the inventory file and for the *.ASB file.) A library file containing information about existing data files is checked and if the inventory file exists, it is processed to create the *.ASB file. If an inventory file does not exist for a particular facility, the user is prompted for input to create the inventory file from which the *.ASB file is then created.

Information for each assembly that is written from the inventory file to the *.ASB file includes the operator-declared burnup (exposure), the date the assembly was discharged from the core, the assembly ID or serial number, the location of the assembly in the storage pool, and an identifier indicating during which refueling cycles the assembly was in the core. The *.ASB file is an ASCII file read directly by OLAF. The general *.ASB file structure includes correction factor data, but for this path (without), all correction factor data are set to unity.

With Correction Factors. For the "with" correction factor path, an *.ASB file is created with correction factor data. Data from three different types of database files are required for each facility. Inventory data are taken from the inventory data file, reactor design information is taken from the REACTORS.DBF file, and power history information comes from a power history data file. The structure of the inventory file has been described above for the "without" path.

The REACTORS.DBF is a library-type file containing basic information about all facilities for which data have been entered into the database system. Basic design information for the specific reactors is obtained from the 1987 World Nuclear Industry Handbook.⁵ REACTORS.DBF also contains the names of existing inventory and power history files for the facility.

Power history files contain operating information about reactors. In these files, refueling cycles are divided into constant-power time steps. Each time step is a separate record with the duration entered in days and the power entered as the net electric output.

The same inventory information is written from the inventory file to the *.ASB file as in the "without" path. For the "with" path, the CINDER-PC code is automatically executed to calculate correction factors. The reactor design information and power history information are needed by CINDER-PC (described below). If the data files or the design information do not exist, the user is prompted to enter the appropriate data before an *.ASB file with correction factor information can be created.

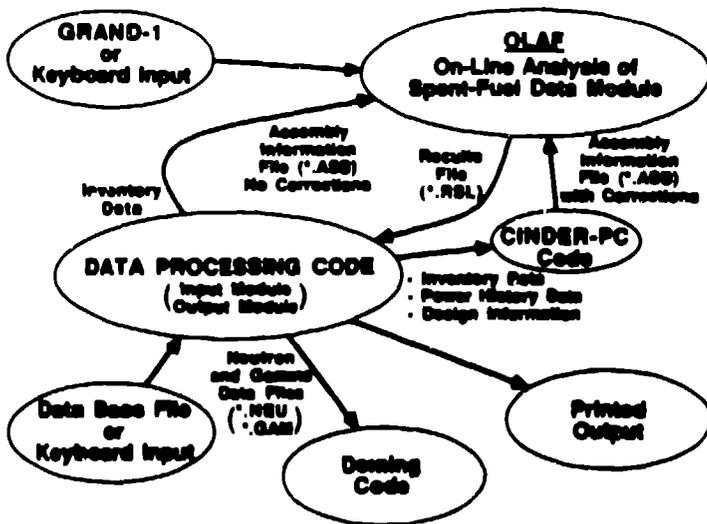


Fig. 4 Code structure diagram. The package includes three basic modules: the input processing module, the OLAF module, and the output processing module. The input and output modules are both part of the data processing module bubble that is shown. The modules are linked by various database and ASCII data files. The CINDER-PC code is used in the input module to calculate correction factors for the fraction of neutrons emitted from ^{244}Cm and for neutron source effects due to variations in initial ^{235}U enrichment. The OLAF module controls measurements made with the GRAND-1 and analyses measurement data as they are collected.

TABLE I

FILES USED BY VARIOUS MODULES IN SPENT-FUEL DATA PROCESSING CODES

Module	File Description	Type ^a of File	Input ^b or Output	DOS Extension
INPUT (including CINDER-PC)	Spent-Fuel Assembly Inventory Data	DB	Both	.DBF
	Reactor Power History Data	DB	Both	.DBF
	REACTORS - Library Information	DB	Both	.DBF
	Assembly Information File	ASC	Output	.ASB
OLAF	Assembly Information File	ASC	Input	.ASB
	Measurement Results File	ASC	Both	.RSL
	GRAND-1 Memory Dump File	ASC	Output	.DMP
	Axial Profile Measurement File	ASC	Output	.SCN
	Setup Parameters File	ASC	Input	.PAR
	Screen Driver File	Bin	Input	.DRV
OUTPUT	Measurement Results File	ASC	Input	.RSL
	Neutron Data for Deming Code	ASC	Output	.NEU
	Gamma Data for Deming Code	ASC	Output	.GAM
	Database Results File	DB	Output	.DBF

^aFile types, DB - Database, ASC - ASCII format, Bin - Binary format

^bFile is used for Input, Output, or Both by the module.

CINDER-PC Code. CINDER-PC calculates actinide isotopic production and depletion for fuel materials from information about initial ^{235}U fuel enrichment, the reactor power history, and reactor design parameters. The calculated isotopic information is combined with neutron yield data for the individual isotopes to determine the fraction of the total neutron source that is emitted from ^{244}Cm . The ^{244}Cm fraction is determined as a function of cooling time for each assembly.

The CINDER-PC code also calculates a correction factor for effects caused by different initial ^{235}U enrichments and writes this factor to the *.ASB file. With the two correction factors, data with different initial enrichments and with different operating histories can be adjusted to fit on the same curve for data analysis.

The ^{244}Cm correction factor data are generated for every assembly in the inventory.DBF file. In CINDER-PC, three exposure (burnup) levels are calculated for each unique set of initial ^{235}U enrichment and irradiation history, as shown in Fig. 5. The first calculation determines the exposure from the average power density information, which was calculated from the power history file. The second and third calculations are made with the power density multiplied by 0.8 and 1.2, respectively. Results of the calculations for each unique set of parameters are written to a temporary disk file. The correction factor curve as a function of cooling time is generated from the temporary file data by using the operator-declared exposure and interpolating between the

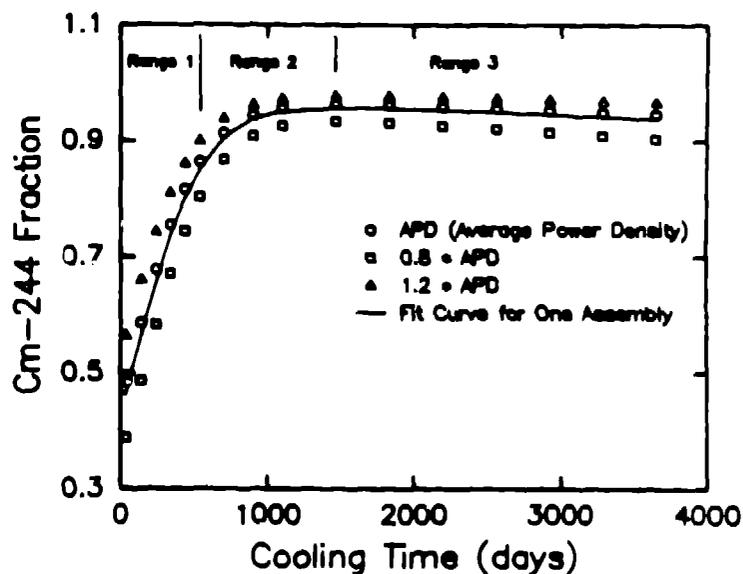


Fig. 5. Curium-244 correction-factor data calculated in the CINDER-PC code. Three separate curves (the three sets of data points in the figure) are calculated by CINDER-PC for unique power histories and initial ^{235}U enrichments. The solid line is the curve for the predicted cooling-time-dependent correction factors for a specific assembly. The curve is determined by using the operator-declared exposure and interpolating between the three sets of calculated data at each cooling-time point. The interpolated data are fit to third-order polynomials for the three ranges shown in the figure, resulting in the solid curve.

data obtained from the three calculations. The interpolated data are divided into three ranges, as shown in Fig. 5, and each data set in each range is fit to a third-order polynomial of the form

$$C_f = a_0 + a_1 (CT) + a_2(CT)^2 + a_3(CT)^3 ,$$

where C_f is the ^{244}Cm correction factor; CT is cooling time; and a_0 , a_1 , a_2 , and a_3 are coefficients. The resulting curve from fitting the interpolated data for one operator-declared burn-up is shown in Fig. 5. The fit coefficients for the three data ranges are given in Table II. The fit coefficients are written along with the inventory data and the enrichment correction factors to the *.ASB file.

The code stores information about the temporary files and processes these files for other assemblies that have the same initial ^{235}U enrichment and irradiation history. New calculations are needed only when the initial enrichment and irradiation history differ from data for previously generated temporary files. This method greatly reduces the computing time by eliminating redundant calculations. Since correction factors are entered as a function of cooling time, data for the individual assemblies in the *.ASB file need to be recalculated only when the irradiation history changes, for example, when the assembly is returned to the core for additional cycles.

OLAF Module

The OLAF module controls the GRAND-1 and analyzes measurement data. In the recommended mode of operation, inventory and correction factor data are read from an *.ASB file that has been prepared through the input processing module. When a measurement is being made, OLAF prompts the user to enter the ID of the assembly being measured. From the data contained in the *.ASB file, OLAF retrieves the inventory information and correction factor coefficients for the specified assembly. The cooling time is determined from the discharge date, which is part of the

information in the *.ASB file, and from the measurement date, which is either the date the measurements are being made or a date entered by the user. A ^{244}Cm correction factor is then calculated from the cooling time and polynomial curves using the appropriate coefficients. The correction factor for initial enrichment is read directly from the *.ASB file. As measurement data are collected, the neutron data are adjusted with the correction factors. The inventory data, correction factor data, corrected data, and original measurement data are written to a measurement results file (*.RSL) in ASCII format.

If an *.ASB file does not exist or if data for an individual assembly do not exist, OLAF will prompt for the necessary information including correction factors. If correction factors are not available, unity is used for both correction factors, and measurement data are not adjusted. This mode of input is not recommended as the normal mode of operation on the storage pond bridge because it requires many keystrokes in a difficult environment. It also requires having such information, which is otherwise stored in the *.ASB file and is transparent to the user, available on the bridge during the measurements.

Corrected neutron data are analyzed in OLAF by fitting the data to a curve of the form

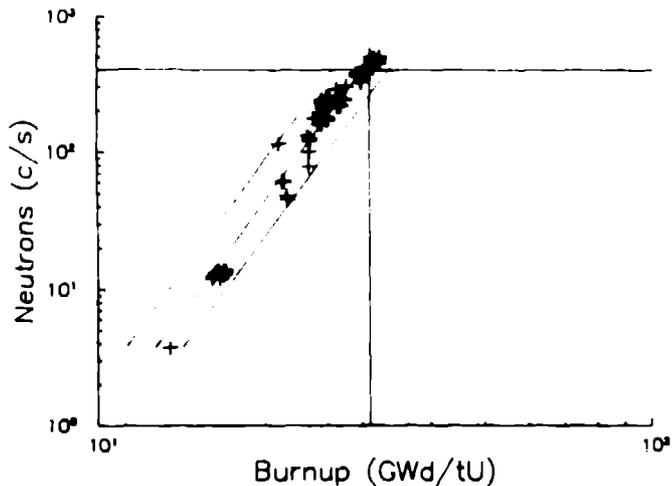
$$CR = \alpha E^\beta ,$$

where CR is the corrected neutron count rate, E is the operator-declared exposure, and α and β are the fit coefficients. Typically, the power of the curve, β , has a value in the range 3-4. Each data point is compared to the fitted curve and an outlier criteria⁶ is applied for determining inconsistent data. A plot of the data and fit curve, as shown in Fig. 6, is displayed on the monitor of the computer. In the display, outliers are conveniently identified to the user so that some action might be taken to resolve the discrepancies.

TABLE II

FIT COEFFICIENTS FOR COOLING TIME vs ^{244}Cm FRACTION CURVE

Cooling-Time Range	Coefficients			
	a_0	a_1	a_2	a_3
0-530 days	0.43030	1.0553×10^{-3}	-2.2627×10^{-7}	-5.0824×10^{-10}
530-1460 days	0.45396	1.1662×10^{-3}	-9.1584×10^{-7}	2.4192×10^{-10}
1460-3650 days	0.94638	2.0264×10^{-5}	-1.0412×10^{-8}	1.1588×10^{-12}



A = 3.94638 * 10⁻⁴ B = 5.420 3 Sigma = 11.8 % PRESS ANY KEY

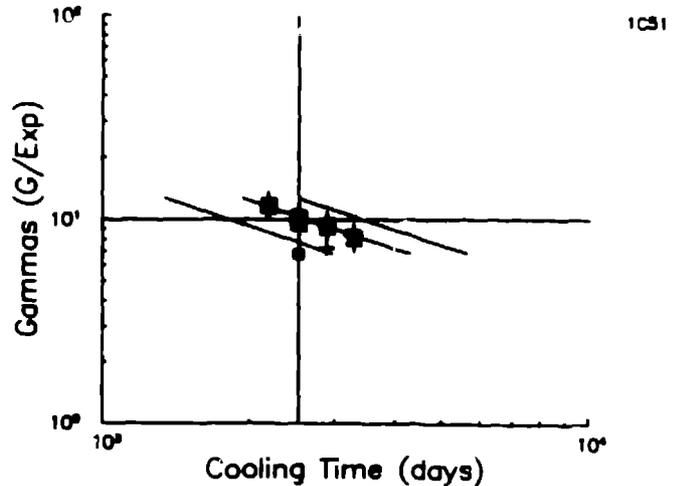
Fig. 6. Typical neutron curve displayed by OLAF. The cross hairs indicate the position of the current measurement. Previous data are also shown as plus symbols. After each measurement, the data are fit to a calibration curve, and an outlier criteria is applied to determine how well the data compare to the calibration curve. Outliers are indicated with a square symbol on the plot. The IDs of any outliers are listed in the upper right corner of the display. The fit coefficients are displayed at the bottom of the screen.

The gross-gamma data are similarly analysed. In this case, a parameter, which is the gamma reading from the GRAND-1 divided by the operator-declared exposure, is fit as a power function of the cooling time, that is,

$$GE = a T^b$$

where GE is the gamma reading/exposure, T is the cooling time, and a and b are fit coefficients. The power of the fit function is typically in the range of -0.8 to -1.0. A plot of these data, as shown in Fig. 7, is also displayed to the user. An outlier criteria is also applied to the gamma data to indicate inconsistencies.

In the event that any outliers (neutron, gamma, or both) are identified, possible immediate actions are suggested to the user. These actions include checking the ID of the assembly and verifying that the operator-declared data have been transcribed correctly, remeasuring the assembly, making a measurement with the fork rotated 90°, or measuring the axial profile of the assembly. Further analysis of the outlier might be needed at a later date if the above actions do not resolve the issue. However, at least the correctness of the measurement data would be confirmed.



A = 4.48574 * 10⁰ B = -0.776 3 Sigma = 30.9 % PRESS ANY KEY

Fig. 7. Typical gross-gamma curve displayed by OLAF. The cross hairs indicate the position of the current measurement. Previous data are also shown as plus symbols. After each measurement, the data are fit to a calibration curve, and an outlier criteria is applied to determine how well the data compare to the calibration curve. Outliers are indicated with a square symbol on the plot. The IDs of any outliers are listed in the upper right corner of the display. The fit coefficients are displayed at the bottom of the screen.

The OLAF module creates three types of ASCII data files:

*.RSL	measurement results file,
*.DMP	GRAND-1 memory dump file, and
*.SCN	axial profile measurement file.

After each measurement, the measurement data and inventory data are written to an *.RSL file as previously described. This file can be processed by the output module or it can be read back into OLAF for further data analysis.

During a measurement campaign, data for each measurement are stored internally in the nonvolatile memory of the GRAND-1 unit. An option is available in OLAF for transferring the GRAND-1 memory data to a disk file (*.DMP). Another option available in OLAF allows for making a series of measurements at different axial positions on an assembly. Data from these axial profile measurements are written to an *.SCN file.

Output Module

The output module is an option available through the general dBASE III data processing package. The module reads measurement results files (*.RSL) from OLAF and writes corresponding database files. From the database files, options can be selected for printing summarized results and for writing ASCII data files with appropriate neutron and gamma data, *.NEU and *.GAM. The

*.NEU and *.GAM files can be processed directly by the Deming curve-fitting code.⁷

Computer Requirements

The input and output modules are written and compiled in CLIPPER™ language, which is an independent application of the dBASE III programming language. The input and output modules are part of a single executable code that can be run on any IBM-PC or compatible computer. The computer should have at least two separate disk drives—either two floppy drives or one hard disk and one floppy disk. The processor code requires approximately 210 kbytes of memory for execution. If CINDER-PC is executed, then 640 kbytes of memory is required. Usually, the input and output modules would be executed in a nonradiation area of the facility or outside the facility entirely. A printer would be used in this application to obtain a summary of the data and results.

CINDER-PC is written in FORTRAN-77 and executes on any IBM-PC or compatible computer. For best results, the computer should have a math coprocessor chip (8087, 80287, etc.) installed, or execution times will be inordinately long. On a computer with a coprocessor, each time-step iteration takes 5-7 s. Without the coprocessor, an iteration might take 2 minutes or more. The code is loaded and executed automatically from the input processor module.

OLAF is written and compiled in Microsoft Quick Basic. The code is designed to operate on a battery-powered computer such as the Toshiba 1100+ or T1200 without a printer. The computer and GRAND-1 communicate through a standard RS-232 interface. A printer is not used for two reasons. First, a printer on the bridge would mean one more piece of equipment requiring protection. Second, there is a printer on the GRAND-1 that can be used to record the actual measurement data. In the unlikely event that both the *.RSL and *.DMP data are lost, the printed record could be used or manually transcribing the data.

CONCLUSION

A computer database package has been developed to automate data collection and data analysis of spent-fuel measurement data. The package includes a module (OLAF) that is used with the GRAND-1/fork measurement system on the bridge over a storage pool. OLAF collects and archives data and performs real-time data analysis. There are two advantages to the package. First, with the communications link between a computer and the GRAND-1 electronics unit, data are processed automatically and are conveniently written to database files. This eliminates the need for hand recording the data, greatly reduces transcription errors, and enhances data analysis. By using established database files, the data can also be processed by commercially available software.

The second advantage is the ability to analyze data as it is being collected in the difficult environment of a spent-fuel storage basin. The impact of such measurements on a facility is great, and there is significant pressure by the operator to make the measurements as quickly as possible. Equipment is generally removed from the pool at the conclusion of the measurements. Under these conditions, measurement errors are distinctly possible. Such errors are either suspected during detailed data analysis that would be done after the user leaves the facility or, potentially, the errors are not discovered at all. In either case, there would be unanswerable questions about outliers. It is difficult to return to the facility for additional measurements once the equipment has been removed. With the on-line data analysis, outliers are immediately identified so that additional measurements can be made while the equipment is installed at the facility.

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