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Automatic Analysis of Gamma Ray Spectra for Surveillance of the Nuclear Fuel Integrity

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핵연료 건전성 점검을 위한 감마선 스펙트럼의 자동 분석

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Abstract

The program of performing a fast and automatic analysis of gamma ray spectra obtained by a Multi-Channel Analyzer (MCA) is developed for the surveillance of the nuclear fuel integrity. The integrity of the nuclear fuel is confirmed by the measurement of the radiation level of the reactor coolant through the real time monitoring and the periodic sampling analysis. In Yonggwang nuclear power plants 3 and 4, the Process Radiation Monitoring System (PRMS), which is a real time monitoring system, provides a measure of the fuel integrity. Currently, its spectrometer channel can identify only one radionuclide at a time since the signal processing unit of the spectrometer channel is a Single Channel Analyzer (SCA). To improve the PRMS, it is necessary to substitute the MCA for the SCA. The program is operated in a real time mode and an on-demand mode, and automatically performed for all procedures. The test results by using the National Bureau of Standards (NBS) mixed standard source are in good agreement with those from Canberra System 100 which is a commercial MCA. Consequently, the developed program seems to be employed for automatic monitoring of gamma rays in nuclear power plants.

요 약

핵연료 건전성 점검을 위하여 다중채널분석기로 얻은 감마선 스펙트럼을 자동으로 빨리 분석하는 프로그램을 개발하였다. 핵연료의 건전성은 실시간 감시와 주기적인 시료 분석을 통한 원자로냉각재내의 방사선준위로 확인된다. 영광 3 · 4 호기의 경우, 실시간 감시 계통인 프로세스 방사선 감시 계통(PRMS)이 핵연료의 건전성을 확인한다. 현재, PRMS의 스펙트로미터 채널의 신호처리기는 단일채널분석기이어서 오직 하나의 방사성핵종만을 파악할 수 있다. 따라서 PRMS를 개선하기 위해서는 단일채널분석기를 다중채널분석기로 대치하여야 한다. 이 프로그램은 실시간 모드와 수동모드로 실행되며, 모든 과정을 자동으로 수행한다. 미 국가표준국의 혼합 표준 선원에 대한 시험 결과는 상용 다중채널분석기인 Canberra System 100의 결과와 잘 일치하였다. 결론적으로 개발된 프로그램은 원자력발전소의 감마선 감시에 사용할 수 있을 것으로 보인다.

1. Introduction

In nuclear power plants, the integrity of the nuclear fuel is confirmed by the measurement of the radiation level of the reactor coolant, typically gamma rays, through the real time monitoring and the periodic sampling analysis. In Yonggwang nuclear power plants 3 and 4, the real time monitoring is accomplished by the Process Radiation Monitoring System (PRMS).

The PRMS is installed at letdown line and is composed of NaI(Tl) detector, photomultiplier tube, and signal processing unit, etc. It provides a continuous recording in the control room of the reactor coolant gross gamma radiation and the specific fission product gamma activity, thus indicating a measure of the nuclear fuel integrity. Gross channel and spectrometer channel signals are sent to Plant Monitoring System (PMS), Plant Annunciator System (PAS), recorder and area radiation monitoring system computer (IBM PC) for indication, annunciation, recording and to keep and analyze the data, respectively. Spectrometer channel utilizes the gamma ray spectrometry principle which allows isolated measurement of a selected radionuclide, Rb-88, which is high on the fission yield curve and whose presence in the reactor coolant is a sign of possible fuel clad leakage. Since the signal processing unit of spectrometer channel is a Single Channel Analyzer (SCA), the spectrometer channel can identify only one radionuclide at a time. Accordingly, Multi-Channel Analyzer (MCA) is required to obtain the adequate information of radionuclides in reactor coolant.

Generally, gamma ray spectra obtained by the MCA are complex and difficult to be analyzed by the analytical methods[1]. Various methods[2−4, 8−10] have been suggested to analyze the gamma ray spectra numerically. But most of the methods are inappropriate to apply to nuclear power plants where speed and automation of the gamma ray monitoring system are required. In that respect, the purpose of this work is to develop the program that meets the above requirements.

2. Algorithm Description

The algorithm used in the developed program is described in the following sections. The peak finding algorithm is described first, and then the Compton background is estimated. The method of determining peak positions, Full Width at Half Maximums (FWHMs) and areas of the gamma ray spectrum in the real time mode operation is described in section 2.3. Finally, the least squares fitting algorithm is described. The flow diagram of the program is shown in Figure 1. The program is automatically performed for all procedures for each mode of operation after the determination of the appropriate threshold value. The program was written in the C-language and compiled to run on the IBM compatible PC using TURBO C 2.0 of Borland Inc.

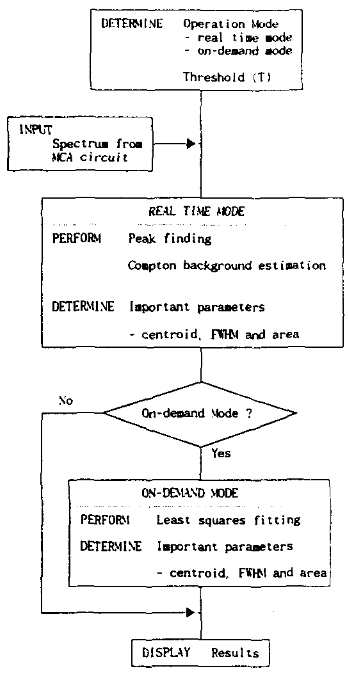

Fig. 1. Flow Diagram of the Program

2.1. Peak Finding

The most straight-forward and computationally simplest way for a peak finding is to examine the variation of the second derivative throughout the spectrum. With a Gaussian line-shape, the central part of a peak should be characterized by a region of negative second derivatives with a minimum value in the vicinity of the peak position. For each region where a negative second derivative is found, the scan is performed until the point Y_i with the maximum negative value Y_i'' is encountered.

To remove the strongly fluctuating background, a smoothing procedure is appropriate. For this purpose, the convolution method of Savitzky and Golay [5] has been employed.

Consider a number of $2k+1$ consecutive data points; y_{i-k}, $y_{i-(k-1)}$, ⋯, y_i, ⋯, y_{i+k}. In this case, these are simply a subset of the recorded spectrum. To these points, one can define a set of convoluting integers $C_{-k,2k+1}$, $C_{-k+1,2k+1}$, ⋯, $C_{0,2k+1}$, ⋯, $C_{k,2k+1}$ and a normalizing constant N_{2k+1}. The new and smoothened value, Y_i, is then obtained by forming the sum:

$$Y_i = \frac{1}{N_{2k+1}} \sum_{j=-k}^{k} C_{j,2k+1} \cdot y_{i+j} \tag{1}$$

By a suitable choice of the convoluting integers, the value of Y_i will be exactly equal to that obtained by a least squares fit of an nth degree polynomial to the $2k+1$ original data points and substituting it into the abscissa of y_i. The first and higher order derivatives are computed using the following:

$$Y_{n,i} = \frac{1}{N_{n,2k+1}} \sum_{j=-k}^{k} C_{n,2k+1} \cdot y_{i+j} \tag{2}$$

where, n is the order of derivative.

A complete set of tables of convoluting integers for obtaining ordinary smoothing and smoothened derivatives has been given by Savitzky and Golay.

The counting rate numbers, Y_i, become smaller for increasing channel number i due to the smaller detection efficiency of the counter for higher gamma-energies. To get a nearly energy independent quantity, we define a filter function F(i) as follows:

$$F(i) = Y_i'' / \Delta Y_i'' \tag{3}$$

$$\Delta Y_i'' = \frac{1}{N_{n,2k+1}} \left(\sum_{j=-k}^{k} C_{n,2k+1}^{2} \cdot y_{i+j} \right)^{1/2} \tag{4}$$

where, $\Delta Y_i''$ is the standard deviation of Y_i''.

A peak is detected at position i if the F(i) fulfils the following three conditions:

i) $F(i) \leq -T$, (5a)

ii) $F(i+1) \geq F(i)$ AND $F(i-1) \geq F(i)$, (5b)

iii) $F(i-1) + F(i+1) \leq -1.4 \cdot T$. (5c)

T is a threshold which is a positive number chosen to discriminate between photopeaks and the fluctuating background. Typical values employed are between 2 and 5. The second criterion is due to an assumed maximum in channel i of the line while the third criterion was empirically found by Nyman [6].

Suppose a peak was found at channel number i. Now, the interval has to be fixed to which model function should be fitted. Therefore, we look for the 2nd channel il fulfilling: $F(il) \leq 0$ and $F(il+1) \geq 0$. We assume il to be the left boundary. Now a similar procedure is applied to find the right fitting interval boundary at ir: $F(ir-1) \geq 0$ and $F(ir) \leq 0$.

2.2. Compton Background Estimation

For the calculation of the Compton background distribution under peaks in a gamma ray spectrum, one has to define the interval start and end channels, to get the linearly approximated Compton distributions, and to calculate the individual integral functions. Instead of searching for peaks in the spectrum to define the intervals, we use a fast method which is based on the fact that the properly normalized integral function of small intervals without peaks is an approximation equivalent to the smooth Compton background in the interval.

A 3-point smoothing procedure described in previous section is applied to remove large statistical fluctuations in the measured spectrum. The smoothed number of counts in each channel i is calculated as follows:

$$Y_i = [Y_{i-1} + 2 \cdot Y_i + Y_{i+1}] / 4 \tag{6}$$

Minima, which may be taken as interval start and end channels, are then searched in a double pass procedure. Starting from the first channel number where a non-zero number of counts is encountered, which takes account of the possibility of a lower-level discriminator, we search for the minimum number of counts per channel within successive small intervals. The channel numbers detected by this method are tagged as provisional minima. For the first-pass minimum search, the interval length is set to be three times the average FWHM of the peaks in the spectrum, whereas the second pass takes an interval length of 5 FWHM. Channel numbers which are tagged as provisional minima in both passes are now accepted as minima.

In order to reject minima which are one channel drop-outs or which lie within very broad complex peak multiplets, a minimum discard operation is applied. In this pass, a comparison of the number of counts in the channels which are accepted minima with the content of neighboring channels is made. For minima which lie closer together than 2 FWHM channels, only the one with lower content is kept.

The minima, which have been found in the smoothed spectrum by the above procedures, are then connected by straight lines which are the first approximation to the Compton background distribution. In a last pass, the calculated background distribution is smoothed once with a 5-point smoothing function:

$$Y_i = [17 \cdot Y_i + 12 \cdot (Y_{i-1} + Y_{i+1}) - 3 \cdot (Y_{i-2} + Y_{i+2})] / 35 \tag{7}$$

As an example of background functions calculated according to this formalism, Figure 2 shows a measured spectrum, together with the calculated background function. After obtaining the background function, the background corrected spectrum is determined by subtracting the background function from the original spectrum.

2.3. Determination of Peak Position, FWHM and Area

Once the existence of a peak has been established, an approximate value for the peak position (centroid) is calculated. The centroid (C) is calculated using the concept of "Geometric Center of Gravity" as follows:

$$C = \frac{\sum_{i=lh}^{rh} i \cdot Y_i}{\sum_{i=lh}^{rh} Y_i} \tag{8}$$

where, lh and rh are left and right boundaries corresponding to the half maximum value of the peak and Y_i is the background corrected count rate determined in section 2.2. The FWHM is determined by the difference between the left boundary (lh) and the right boundary (rh) corresponding to the half maximum value of the peak.

The area is calculated by summing the background corrected count rate through the peak interval as follows:

$$Area = \sum_{i=il}^{ir} Y_i \tag{9}$$

where, il and ir are boundaries of peak determined in section 2.1. Centroid, FWHM and area obtained in this section will be used as the initial parameters of least squares fitting.

2.4. Fit to Photopeaks

Two additional methods identifying peaks can be employed only after fitting a model function Y to the data. For simplicity, only a pure Gaussian function is considered here:

$$Y = A_0 \cdot \exp\{-0.5 \cdot [(x-A_1) / A_2]^2\} \quad (10)$$

with parameters A_0, A_1 and A_2 which are varied so as to minimize the following quantity:

$$Q = \sum_{i=l}^{r} Gi\,[\,Y_i - Y\,]^2 \quad (11)$$

where, G_i denotes the statistical weight of the channel content Y_i and Y_i is the background corrected spectrum.

The least squares fitting is performed using Grid Search Algorithm[7] and the initial value of A_0 is the maximum count rate in peak interval. The initial value of A_1 is the centroid determined in the previous section and the initial value of A_2 is determined as follows:

$$A_2 = FWHM/[\,2 \cdot (2 \cdot Ln2)^{1/2}\,]$$
$$= FWHM/2.35482 \quad (12)$$

where, FWHM was determined in the previous section.

3. Results and Discussion

The data supplied with Canberra System 100[8], which is a commercial MCA, were analyzed to illustrate the performance of the program. These data were obtained by detecting the National Bureau of Standards (NBS) mixed standard source for 4,000 seconds using a Ge(Li) detector. The natural background channel of the data is 4 and the spectrum of the data is illustrated at Figure 2.

The results of the peak search are shown in both Figure 2 and Table 1. When the threshold T was 1, 2 and 3, we found 31, 18 and 15 peaks, respectively. T1, T2 and T3 of Figure 2 indicate the peaks found when T is 1, 2 and 3. The Compton background function is shown below the spectrum in Figure 2. The peaks were found with the adequate sensitivity when T was between 2 and 3. Peak intervals

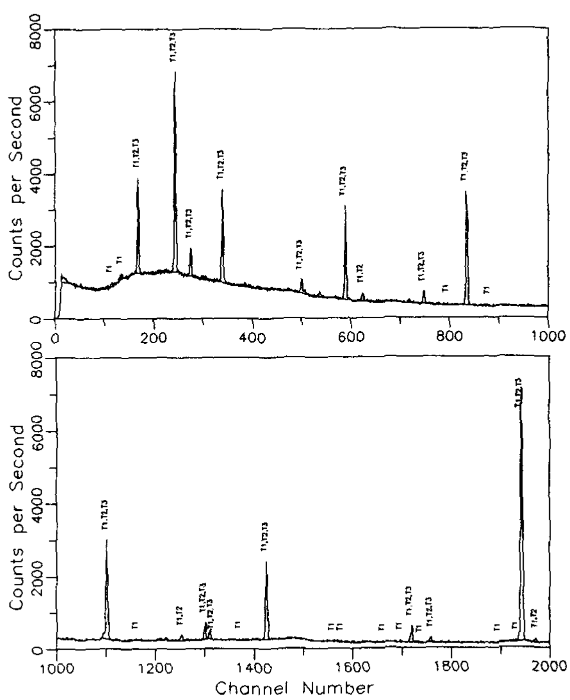

Fig. 2. Results of Peak Search and Background Estimation

Table 1. Results of Peak Search

T = 2	T = 3	Canberra System 100
162 - 177	162 - 177	156 - 180
237 - 250	237 - 250	236 - 252
271 - 281	271 - 281	269 - 282
333 - 347	333 - 347	332 - 348
490 - 505	490 - 505	494 - 503
578 - 595	578 - 595	581 - 595
615 - 629	Not found	Not Found
742 - 753	742 - 753	743 - 752
827 - 845	827 - 845	825 - 843
1095 - 1109	1095 - 1109	1094 - 1110
1251 - 1261	Not found	1246 - 1261
1294 - 1310	1294 - 1310	1297 - 1305
1302 - 1319	1302 - 1319	1307 - 1315
1414 - 1434	1414 - 1434	1418 - 1433
1713 - 1725	1713 - 1725	1714 - 1724
1752 - 1764	1752 - 1764	1753 - 1765
1932 - 1953	1932 - 1953	1932 - 1954
1967 - 1977	Not found	1965 - 1981

obtained when the T was 2 and 3 are compared with Region of Interest (ROI) obtained from Canberra System 100 at Table 1. The Canberra System 100 performs the peak finding using the second difference method [8] and the ROI is determined by the SAMPO method [9]. The peaks were found with the same sensitivity of Canberra System 100 when T was 2.7.

Centroids, FWHMs and areas of the peaks corresponding to the value of 3 for T are given in Table 2. Most of the results obtained by this program were approximately consistent with the results of Canberra System 100, and calculated areas were slightly larger than those of Canberra System 100. The area of peak #11 in Canberra System 100 was smaller than the real value because peaks #10 and #11 were slightly overlapped and Canberra System 100 calculates the peak area using the Total Peak Area method [10] which considers the background to be a linear function. Also, Table 2 shows that the parameters determined in the real time mode are accurate enough to be used for the real time gamma ray spectrum analysis.

4. Conclusions

The program has been developed using a personal computer which fast and automatically analyzes gamma ray spectra for the surveillance of the nuclear fuel integrity. Through test for NBS mixed standard source, the program was compared with the Canberra System 100. Most of the results obtained by this program were consistent with the results of Canberra System 100. It is consequently considered that the developed program can be employed to monitor gamma rays automatically in nuclear power plants. The program is developed using an IBM compatible PC to enhance the compatibility and utilization. For Yonggwang nuclear power plants 3 and 4, this program is considered to be used without further modifications if the signal processing unit is replaced to the MCA.

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Table 2. Results of Real Time Mode, On-Demand Mode and Canberra System 100

Peak	Present Study						Canberra System 100		
	real time mode			on-demand mode					
No.	centroid	FWHM	area	centroid	FWHM	area	centroid	FWHM	area
# 1	169.05	3.10	8732.12	169.10	3.10	8642.93	169.05	3.11	8497
# 2	243.88	3.12	18313.42	243.87	3.09	18528.60	243.88	3.07	17369
# 3	275.08	3.19	2735.54	275.47	3.27	2750.22	275.08	2.94	1556
# 4	339.92	3.30	9221.00	339.84	3.33	9075.71	339.92	3.28	8670
# 5	499.04	3.29	1768.75	499.14	3.99	1507.08	499.04	2.95	1087
# 6	588.06	3.31	9446.33	588.10	3.39	9196.15	588.06	3.27	8914
# 7	747.48	3.81	1381.00	747.63	2.83	1176.69	747.48	3.61	979
# 8	834.46	3.60	12049.04	834.41	3.56	12004.99	834.46	3.59	11837
# 9	1102.31	3.85	11544.78	1102.12	3.58	10943.57	1102.31	3.74	10125
#10	1300.98	3.46	2145.38	1300.95	3.68	1774.60	1300.98	3.08	1286
#11	1311.01	3.47	1731.57	1311.21	3.17	1036.12	1311.01	3.10	260
#12	1425.48	4.16	9551.69	1425.46	4.19	9467.23	1425.48	4.05	9375
#13	1719.47	3.99	2049.48	1719.36	4.31	1978.38	1719.47	3.41	1372
#14	1758.97	4.55	713.40	1758.79	4.44	694.46	1759.02	3.67	417
#15	1942.95	4.41	33053.13	1942.89	4.50	32771.97	1942.95	4.51	32775

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