EXPERT SYSTEM FOR ANALYSIS OF SPECTRA OF NATURAL RADIONUCLIDES

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The phenomenon of radioactivity is tied to the appearance of different types of radiation which are closely connected with radioactive decay of certain elements i.e. their isotopes. These elements by migration arrive in the water, then plants, and so become the part of natural food chain and finally they end in a human body. It is clear that the monitoring of the degree of presence of radioactive elements in all factors of human environment is crucial. In this paper is described the expert system developed to perform analysis of the spectra of natural radionuclides with the aim to determine activities of individual natural radionuclides.

Keywords: expert system, spectra, radiation, natural radionuclides.

1. Introduction

The phenomenon of radioactivity is tied to the appearance of different types of radiation which are closely connected with radioactive decay of certain elements i.e. their isotopes. On Earth exist 330 isotopes that originate from 90 chemical elements. The largest number of isotopes is stable, exactly 270. Elements beginning with bismuth (Bi, Z=83) and ending with uranium (U, Z=92) do not have stable isotopes at all. Out of the total number of unstable isotopes, 45 of them are members of the three known natural radioactive series. The remaining 15 are isotopes of lighter elements, of which the ^{40}K is the one most known.

Beside the fact that the presence of radioactive radionuclides in the ground can be consequence of natural process (as the part of those elements is there since the creation of Earth), one part of them reaches the ground as consequence of numerous human activities.

Independently of the way they reached the ground, these elements by migration arrive in the water, then plants, and so become the part of natural food chain and finally they end in a human body. It is clear that the monitoring of the degree of presence of radioactive elements in all factors of human environment is crucial.

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If we start from the fact that the natural radioactivity and the presence of natural radionuclides is something on which we have no control i.e. their presence is inevitable, there is still a major problem of the existence of radioactivity that occurs as a result of human activities. Consequence of nuclear accidents (on example nuclear accident in Chernobyl, 1986) and nuclear tests leads to emergence of elevated radioactivity in the nature. The radiation area is sometimes in wider, sometimes in narrower environment of the source location, which in principle doesn't depend only from intensity of event, but also from the weather condition (wind), configuration of soil, etc. The consequence of such activities and events can be fatal for the humans as well as for the flora and fauna of the radiation area.

Because of this it is necessary to perform a checking of radioactivity rate in the case when exists the concrete cause but also as the preventive control measure.

The checking of radioactivity means the determination of activity level of biologically important natural radionuclides as well as those that are produced artificially.

In the group of natural radionuclides especially important is ^{40}K, and most important of artificial ones are ^{137}Cs and ^{90}Sr, which are, because of their physical and chemical properties, very toxic..

2. Expert system

In this paper is described the expert system developed to perform analysis of the spectra of natural radionuclides with the aim to determine activities of individual natural radionuclides.

In development and testing of aforementioned expert system was used I2+ **ESBT** (Expert System Building Tools) whose conclusion mechanism uses the backward chaining method which enables that expert system works without a conflict resolution (i.e. situation when more then one rule satisfy an activation condition) which in itself means more stable and faster expert system.

At the Fig. 1 is shown the structure of a knowledge base of aforementioned expert system.

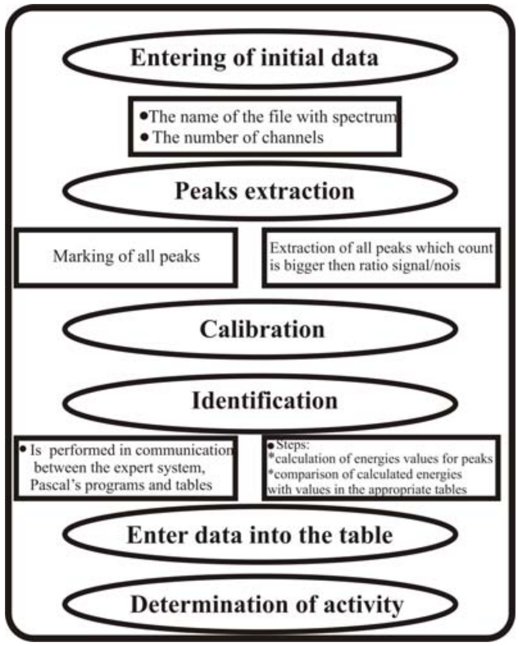


Fig. 1. The structure of a knowledge base

The knowledge base is the part of the expert system structure which contains knowledge which is closely related to the problem that expert system is designed to solve. This knowledge is represented in the form of the production rules, which is the most common way for their representation. The structure of production rules is as following:

RULE The name of rule
IF Condition
THEN Conclusion
ELSE Alternative conclusion

The rules will be chaining only if the condition of first rule is identically equal to conclusion of second rule. One example of chaining rules:

RULE Extraction of Peaks
IF Extracting peaks
THEN **Extracting all peaks**
AND CALL ExtrPeak
SEND NameS
SEND NameP

RULE Decreasing
IF **Extracting all peaks**
THEN Ordering in decreasing array
AND CALL DecrPeak
SEND NameP

From aforementioned rules can be seen that the conclusion of the rule "The extraction of peaks" is identically equal to the condition of rule "Decreasing". In this way is accomplished the condition for rules chaining i.e. coupling.

The knowledge base also contains a user interface and tables. Also, the working memory of computer (RAM) can be treated like its equal component. During the work of the expert system there is permanently in progress a two-direction communication between the knowledge base and each of mentioned components. This communication is initialized by the conclusion mechanism which makes changing of rules and in the lack of necessary informations, it "searches" for the same just on aforementioned places in order for expert system to continue with its work.

The spectra used in development of expert system are obtained on HpGe EG&G ORTEG detector, with resolution of $1{,}7\,\mathrm{KeV}$ and multi-channel analyzer with 8192 channels. The spectra are obtained by measuring of activity which arise from radionuclides in the samples of lend which are taken from ten choosing locations in Kragujevac, the city in the central Serbia. The samples are taken in the shape of rectangular block with dimensions $(10\times10)\,\mathrm{cm}^2$, thickness $2\,\mathrm{cm}$. Stones and plant roots were removed before treatment. Soil samples were dried at $105^0\,\mathrm{C}$ during $24\mathrm{h}$, minced, and then sifted through the sieve [1].

In the Fig. 2 is shown spectrum obtained in this manner.

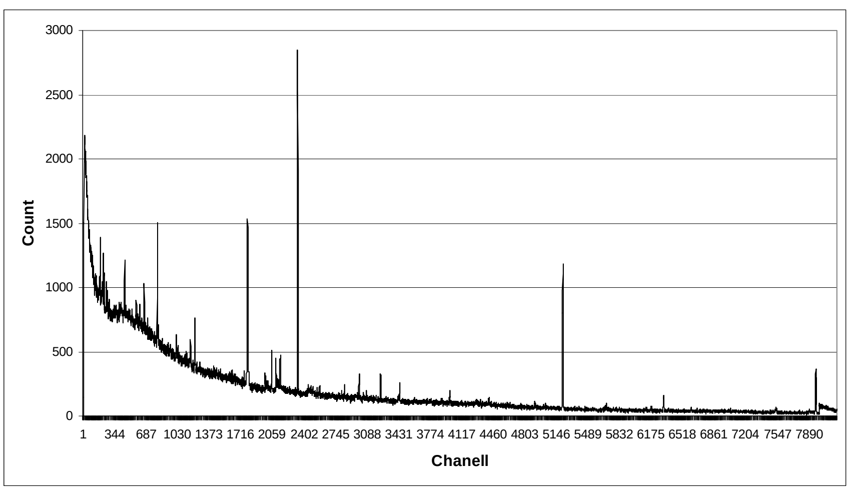


Fig. 2. The spectrum of the sample taken from location "Post Office", at a depth of $2\,\mathrm{cm}$

As can be seen from picture, for aforementioned spectra is characteristic the presence of large number of peaks that arise from different radionuclides.

From the figure can also be seen, regarding the peak intensity, that the spectrum, along with determined number of very well distinctive and defined peaks, contains a large number of smaller ones. The reason for this can be found in the fact that the elements have bigger number of more or less probable decay schemes, which is represented in the spectrum as peaks with corresponding intensity.

Our goal especially was to try to separate from the lot of less distinctive peaks the ones that originate from the particular physical events and not from noise.

The recorded spectra are put in the tables (in DBF III format) which I2+ has implemented within. The structure of aforementioned tables is as follows:

Table 1

The structure of the table with the recorded spectrum

Count	Modified count	Peak	Energy	Origin

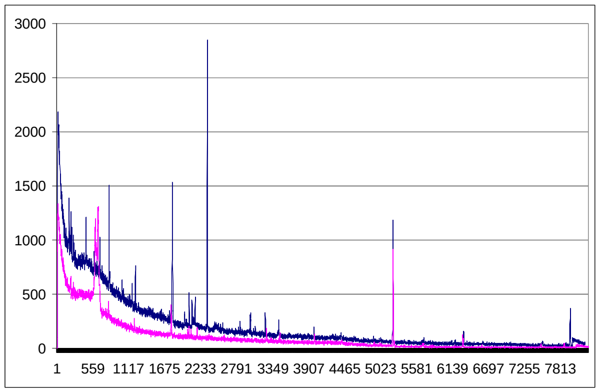
The field "COUNT" contains the values of counts. The values of channel number have not been entered separately but the serial number of record is simultaneously used to also be a appropriate value of the channel.

The next column "MODIFIED COUNT" is extremely important because it contains the modified values of count. Recording of any type of spectra is accompanied by noise which is unfortunately inevitable. Influence of the noise on the recorded spectra sometimes can be so large that the entire spectrum becomes useless for analysis. In some spectra there exist the exactly defined criteria (based on working experience) which allow the user a possibility to check, at the beginning, an availability of spectrum for further analysis [2]. If these criteria don't exist (like in the case of spectra that are subject of analysis by this expert system) it is necessary to try, by some actions, to diminish an influence of noise. This procedure has more steps. The first one is a subtraction of recorded noise spectrum from the values of previously recorded spectrum [3,4].

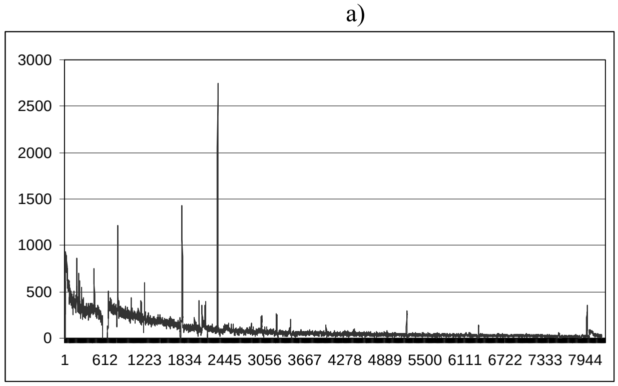
Among the other things, the noise represents a consequence of presence of natural radioactivity which arises from cosmic radiation and environmental radionuclides. As the consequence of that, the detector on certain energies records a cumulative yield that has arisen from radionuclides found in the samples as well as from detector's environment. Because of this it is necessary to separate those two sources of radiation. This separation is performed in the following way: the detector emptied of samples, at previously determined time intervals, keeps recording and in such manner obtains the spectrum which corresponds to the environmental radiation.

The recorded noise is put into the separate table "NOISE.DBF", which contains only the field "COUNT". The expert system then calls a Pascal program that performs a correction of recorded counts and these newly-obtained values writes in aforementioned field "MODIFIED COUNT".

At the figure 3a) are simultaneously shown both the recorded spectrum (spectrum is recorded on location "Post Office" on 2 cm depth) and the noise (colored blue and pink respectively). At the figure 3b) is shown a spectrum with modified values of counts i.e. spectrum after the first correction of noise.



a)



b)

Figure 3. a) Comparative review of recorded spectrum and noise b) Spectrum with modified values of counts

When spectra are compared, there can be seen the lowering of counts at all channels, and especially is visible correction on 5216 channel. This peak corresponds to isotope ^{40}K and in the originally recorded spectrum is very distinguished. This is a consequence of cumulative yield of ^{40}K which originates from sample but also from the table on which detector is situated, more precisely in the wood from which the table was made.

The complete further analysis of spectra is performed with the count values modified in aforementioned manner.

In the next column, named “PEAK”, the expert system writes mark 1 for those counts which satisfied a condition to be proclaimed as peak. The further work of expert system is oriented only on channels with that peaks.

In column named “ENERGY” the expert system writes the calculated energy values of peaks. These values will be used later in the process of identification for determination of the peak origin. In the column named “ORIGIN”, the expert system writes mark which gives to the user an information about the nature of given peak i.e. it points which peaks are consequence of transition and which stem from noise.

The work process of expert system can be divided in several phases.

The first phase of expert system work is preparation for beginning of analysis. Here we are referring to securing all of the necessary informations (or at least one part of them), either in the way that they are implemented in the knowledge base (during the process of building of the expert system) or in a manner in which the expert system get them in the interactive communication with user, again through the mechanisms implemented into the knowledge base.

Beside the tables with recorded spectra and noise, there exist a certain number of other tables which expert system uses in its work. Here we primarily refer to the table with energies of natural radionuclides, but also to the tables which are formed in order for expert system to, in the certain phase of work, put in them different information which enables a better functioning of the expert system. One of these tables is the table with extracted peaks. Using the function INIT, the expert system obtains, at the start of its work, the names of all such tables.

Analysis begins with noise correction i.e. by subtraction of values of recorded noise from values of recorded spectrum on corresponding channels. In order to perform this, the expert system calls a Pascal program which, after aforementioned subtraction, newly obtained values writes in a column “MODIFIED COUNT” in the tables with spectrum.

In the process of further analysis are interesting only the peaks that the expert system, from all modified values, extracts only those which satisfied condition to be marked as peak. For this purpose, the expert system calls appropriate Pascal program which in corresponding field “PEAK”, for each such count, writes a mark 1. Here it should be noted that it is common to use Pascal programs for all numerical manipulations with data. These programs are called by the expert system in order to perform all necessary calculations, searching tables, and other similar operations, based on the criteria which are given by expert system; the results of their work are returned to the expert system where they become equal factors in conclusion process.

The large number of peaks does not correspond to the concrete physical events i.e. to some transitions, but arise from noise. In order for our future work to limit itself on the smaller number of peaks, the expert system a certain number of these peaks, based on the fact that they arise from noise, eliminates from analysis. The above fact is in practice realized through the ratio signal/noise. This ratio is defined based on certain numbers of count values of the biggest and the smallest peaks. Its concrete value will directly depend on the numbers of peaks that have been used in the process of estimation. It is left to the user to input the value of that number, depending on his working experience with these spectra.

In order for expert system to make aforementioned estimation of ratio signal/noise it is needed for separated peaks to be arranged in decreasing array. To do this, the expert system calls Pascal program which as initial information obtained the name of table with recorded spectrum and the name of table with separated peaks.

In special cases of analysis, in which user want to limited analysis only to peaks of certain level of intensity (on example, only to the biggest) he can, by entering of appropriate number of peaks, to focus the expert system on the target group of peaks.

After entering number of peaks, the expert system calculates value of aforementioned ratio and, in the next step, checks an intensity of all extracted peaks and puts the mark “1” only for counts which are above the calculated limit of ratio. In this way the second correction of noise was made with which the number of peaks which should be analyzed was reduced. Therefore the time required for analysis is reduced i.e. the process of analysis is accelerated.

For concrete case of spectrum which is shown in figure 3b), total number of extracted peaks is 2557. For determination of ratio signal/noise the ten of the biggest and ten of the smallest peaks has been taken. The following value was obtained:

$$S/N = \frac{\sum_{n-9}^{n} O_i}{\sum_{1}^{10} O_j} = \frac{11541}{81} \approx 142 \qquad (1)$$

Only the peaks whose intensity is bigger then calculated ratio will be the object of analysis. In this way the total number of peaks is now 689 which represent approximately 70% reduction in number of originally extracted peaks, and the time needed for analysis is also reduced, while the work of expert system is accelerated.

In the table 2 is given the part of aforementioned spectrum. In the column named “Peak” all peaks have been marked as “1”, thus in the column named “Peak bigger then s/n” only the peaks which have satisfied a calculated value of ratio are included.

Table 2

The part of table with spectrum "Post office 2.dbf"

Channel	Count	Sum	Modified count	Peaks	Peaks bigger then s/n	Energies	Origin
…	…	…	…	…	…		
1791	1455	110	1345				
1792	1531	99	1432	1	1		
1793	1467	101	1366				
1794	1452	118	1334				
.	…	…	…	…	…		
1808	234	112	122				
1809	254	116	138				
1810	257	111	146	1	1		
1811	247	108	139				
1812	238	116	122				
1813	234	133	101				
1814	245	111	134	1			
1815	254	121	133				
…	…	…	…	…	…		
1819	241	112	129	1			
1820	209	128	81				
…	…	…	…	…	…		

Here the first phase of work of the expert system is finished at the end of which are selected only those peaks that will be interesting in the further process of analysis.

In the second phase of work there is a need for translating the spectrum in energy spectrum, i.e. it is needed to join the channels to appropriate values of energy. A necessary precondition for this is to perform calibration of energy scale, i.e. determine energy value per channel.

Determination of the value of the channel is performed based on well-defined and energetically positioned structures i.e. peaks.

Calibration of energy scale in the process of analysis of these spectra is very important for two reasons: because of the large number of channels on which the spectra were recorded and also because the peaks are positioned along the whole range.

The problem which arises as a consequence of large number of channels can be manifested in the situation when the energy value per channel is not an integer, which is usually case in practice, so for that reason the work of the expert system is adapted to the aforementioned situation. Practically, from the perspective of the expert system at work, it means that it is necessary to perform a calibration of energy scale several times during its work, i.e. it is needed, for certain ranges of channels i.e. energies, to set the scale on "zero value" i.e. on certain exactly determined values more than once and from these values, system successively performs a calculation of energy values per channels.

In order for this to be possible, it is necessary that a calibration spectrum in the wider range has well-defined and energy exactly positioned structures.

With this in mind, the idea to use for this purpose the Cs spectrum and its referents points was not completely optimal and applicable without additional steps because the discrete structures in this spectrum are ended with photopeak on 662 KeV. This is the reason for possible manifestation of a problem during the identification of the peaks in spectra of natural radionuclides. In order to circumvent this, it is necessary to perform the corrections of calculated values of peak energies at channels that have been selected as referential ones. In practice this will represent the correction of calculated energy value at the given, selected channel, based on initial calibration for energy value that has been calculated as multiple of number of channels and energy value lost during the process of rounding. The expert system rounds the calculated value of energy by channel at given number of decimals, maximally three, most often two, so that there emerges a difference between real value and the one used later by the expert system itself. When a system deals with spectra recorded at smaller number of channels, aforementioned difference is small and can be neglected. However, at number of channels at which the spectra were recorded, that are subject of analysis by this expert system, these approximations are not acceptable.

In order to circumvent this, the more complex solution was chosen, the one that for calibration uses the spectrum of europium[6], ^{152}Eu .

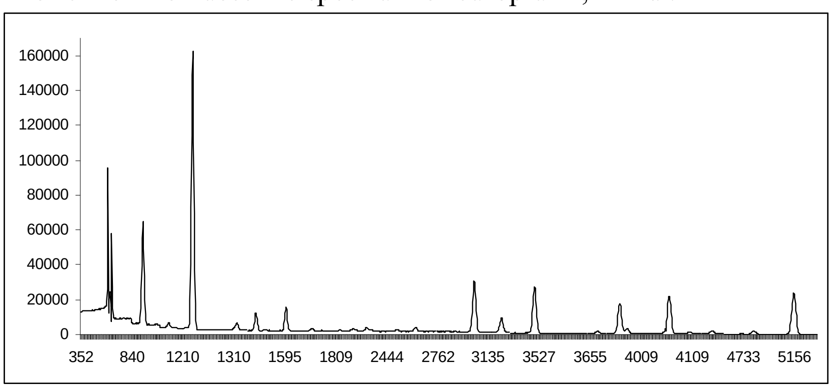


Fig. 4. Spectrum of europium

[6] Calibration source ^{152}Eu was sent from Laboratoire de Metrologie des Rayonnements Ionisants, Bureau Netional de Metrologie, in France.

As can be seen in the figure 4, this spectrum has more separated and defined structures which are suitable for using as the calibration referent points. Especially important thing is the fact that those structures are distributed along the whole spectrum. The table "Kalib.dbf" was formed, which contains data about characteristic peaks, their energies and channels on which they were located.

Calibration by using characteristic peaks from europium's spectrum is performed in such way that the expert system successively loads the referent calibration peaks and then positions itself on their corresponding channels, and so joins their values to variables k_1 and k_2. Also, the expert system loads energy values from these peaks and joins them to variables E_1 and E_2. Using these variables the expert system calculates energy value per channel:

$$\Delta E = \frac{E_2 - E_1}{k_2 - k_1} \tag{2}$$

When energy value per channel is calculated, the expert system joins those energies to channels that lie in the range between referential channels k_1 and k_2:

$$E_n = E_{rf1} + k_n \Delta E \tag{3}$$

where E_n, k_n are energy and value of n^{th} channel, and E_{rf1} is energy of lower positioned referent peak.

This procedure is repeated and when the whole energy scale is calibrated, the expert system will begin with an identification of extracted peaks.

Identification of peaks is performed in communication between *the expert system, Pascal's programs* and *Tables.*

As was already mentioned, the radioactive elements have several schemes of decay with different probabilities that can have values from several percents to 100% that corresponds to situation when only one decay scheme exists. For nuclear physicists of interest are only the peaks which correspond to decays whose probability is greater than ten percent. From this reason the expert system first identifies these peaks. The identification is performed in such a way that the expert system calls Pascal's program which calculates an energy value from a given peak, then compares it with energy values of natural radionuclides. In the case when there exists a match of these energies, the peak will be classified as a peak which arises from transition and in the field "ORIGIN" in the table with spectrum the expert system writes mark 1. All other peaks in this phase obtain mark 2. For user this means that peaks arise from noise or that they simply are not interesting for further calculations. For visibility, all data which are related to transition's peaks are putted into separate table "RESULT.DBF" which has the following structure:

Table 3

The structure of table with resulting data

Channel	Modified Count	Energy	Origin	Peak width	K_p	K_k	Activity

However, as the task of the expert system is to identify all of the peaks, and also those that correspond to peaks with yield that is less than 10%, the user can set a task for the expert system to try to identify those peaks. The problem which appears here is the fact that those peaks have smaller intensity and can be covered by a noise. Because of that, the expert system here begins with reverse process. From the table with natural radionuclides, using the Pascal program, the expert system loads energies from those peaks one by one. After that, the expert system will check in the spectrum if there is a peak on the corresponding channel. In the case the peak is found on appropriate channel, the expert system in the field "ORIGIN" writes the mark 3 that corresponds to decay whose possibility is less than 10%.

In the final phase of its work, the expert system calculates activity for all the peaks that in the process of analysis were classified as peaks which arise from physical events i.e. that in the field "ORIGIN" have mark 1 or 3.

Pascal's program calculates an activity of found radionuclides in the spectrum using the following formula:

$$A = \frac{Net}{p\,m\,t\,e} \tag{4}$$

where:

- p is a yield that is constant for a particular isotope.
- m is mass of sample
- t is a measurement time.
- Net is the total number of counts of photopeak
- e is the detector efficiency.

Beside the values that were set at the beginning of this phase of the expert system work and which are constant (detector efficiency and yield for particular isotopes), in order to be able to continue with its work, the expert system have to ask a user to input data that are connected with concrete sample whose spectrum is analyzed, for instance, the time of measurement, t, and the mass of the sample, m.

As was already mentioned, the activity is determined for every peak which in the field "ORIGIN" has mark 1 or 3. In that way the expert system positions itself on those peaks, and then for each peak the procedure is repeated. The expert system need to calculate the value named "Net" that represents the sum of photopeak counts on the channels range which represents their width. The peak width is calculated for each peak separately. The reason for this is that experience teaches us that, although all peaks have normal distribution i.e. there are represented in the Gaussian form which is symmetrical, presence of superposed peaks disturbs aforementioned form.

The aforementioned value "Net" is calculated by a program that uses an algorithm for checking the values and ratio of counts at every side of Gaussian form, but it must also take into account a possibility that there can emerge superposed peaks which stem from a noise or insufficiently expressed peaks of other transitions. It has been shown in practice that a presence of superposed peaks on a main peak disturbs a "bell" form of Gaussian function on both sides, but at three channels at most; so Pascal's program has algorithm created to deal with this. If a superposed peak is found the program will treat the width of this peak as integral part of width of chosen main peak. Process will be repeated for left and right side of main peak, and will yield the two values ΔX_l and ΔX_d that represent a left and right width of a main peak. Total width of peak, ΔX, will be obtained as a sum of these two calculated widths:

$$\Delta X = \Delta X_l + \Delta X_d \tag{5}$$

Full range, i.e. initial and final channel of peak's width is given as:

$$K_p = X_{fp} - \Delta X_l \tag{6}$$

$$K_k = X_{fp} + \Delta X_d \tag{7}$$

In "Eq.(6)" and "Eq.(7)" X_{fp} is a channel where the given peak is, ΔX_d and ΔX_l are the calculated right and left peak's widths, while K_p and K_k represent the values of initial and final channel of peak's width.

Values K_p, K_k and ΔX will be written in the appropriate field in table "RESULT.DBF".

When the initial and final channel of peak's width have been determined, the expert system can perform a summation of appropriate counts O_i, of all channels that lie in the peak's range:

$$Net = \sum_{K_p}^{K_k} O_i \tag{8}$$

When the "Net" have been calculated the expert system determines the activity of a given radionuclide.

When the activities of present radionuclides in a sample are finally obtained, it is possible, if necessary, to calculate the relative ratios between activities of each of the radionuclides found.

6. Conclusions

The expert system for analysis of the spectra of natural radionuclides is one more the expert system that we developed for purpose of analysis of discrete spectra. This one, like the one before, has shown that using the expert systems in process of analysis of spectra is justifiable.

The practice has shown that the process of analysis is faster, and also that both quantity and quality of obtained results are better than those obtained by standard procedures. The subjective factor has been completely removed, and also all of the structures that emerge in a spectrum will be analyzed.

The concrete spectra of natural radionuclides are very interesting because natural environment and its protection are one of most important tasks that we have to deal with. The expert system can be used for the control of environment or samples from specific locations and also in the case when there is a contamination of land and materials.

Acknowledgments

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