91-407

ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E10-91-407

W.Dzwinel[1], Y.N.Pepyolyshev, J.Kitowski[1]

# PATTERN RECOGNITION APPROACH TO DEGRADATION DIAGNOSTIC OF NUCLEAR REACTOR

Submitted to the Technical Committee Meeting on Utilization of Condition Monitoring and Degradation Diagnostics Systems to Improve Nuclear Safety, Vienna, Austria, 7-9 October, 1991

[1]Academy of Mining and Metallurgy, Institute of Computer Science, Cracow, Poland

1991

disk and undergo the beginning processing i.e. the FFT transformation and statistical analysis. The filtered and transformed instant "noise image", together with all images processed before, constitute the objects for the pattern recognition process. Each of the spectral densities is treated as a point in the N-dimensional Euclidean space, where N is the number of frequency channels. Subsequent spectral density amplitudes determine the point position. As shown earlier in [4,5], the changes in reactor operation for properly selected kinds of the measured signals are reflected by the change of the pattern created by the respective spectral densities- points- in the N-dimensional Euclidean space. So that, e.g. two different reactor operation states should be represented by two separate clusters of N-dimensional points. The process of the clusters extraction- clustering- constitutes the main idea of our diagnostics system. The normal, stable reactor operation is characterized usually by the one or few clusters. When the subsequent (in time) point falls into one of them, knowing this cluster characteristics, one can immediately determine the instant reactor operation. Otherwise, when a new cluster appears, the anomalous operation of the reactor can be expected. The cluster analysis and features selection procedures help an operator to examine the reason of an anomalous reactor operation.

However, the long term degradations may disturb the clusters structure in different ways, so that some of them may be invisible for a single clustering method, especially when well established numerous cluster attracts single "abnormal" points of an incipient degradation. An approach to the detection of both the abrupt and slow degradations of the reactor operation are exemplified in the next sections of this paper.

<u>Main characteristics of the IBR-2 reactor and its diagnostics</u>

The system briefly described above is applied to the IBR-2 pulsed reactor (Dubna USSR) diagnostics. The IBR-2 reactor is used as a pulsed neutron source for performing the physical investigations on the neutron beams. Its main characteristics are as follows:

- average power regime: - 2 MW,
- maximum pulse power: - 1500 MW,
- frequency of reactor pulses: - 5 Hz,
- reactivity modulator: - two moving reflectors: the main (OPO) and additional one (DPO).

The pulse energy (reactivity) is the most general reactor parameter. Its fluctuations are measured by means of the vacuum and ionization fission chambers placed mainly in the center of the reactor core and on the neutron beam. The signals are transmitted by means of the respective CAMAC blocks. The statistical error of the power spectral density (PSD) for the measured time series length equal to 8192 and 256-points PSD discrete channels, is estimated at 13%. As the sampling frequency of the pulse signals is given by the reactor pulse frequency (i.e. 5Hz) the reactor control period must be not less than 30 minutes, and the width of PSD discrete channels ≈0.01 Hz. The control period and statistical PSD characteristics turn out to be, the optimal ones to obtain appropriate results for the following



clusters analysis. The regime of the long term reactor operation is periodical one i.e. in the single cycle it works non- stop two weeks then waits one week with zero power.

In the applied diagnostics system two clustering algorithms are used. The first one, namely the mutual nearest neighborhood hierarchical agglomeration method (MNN), was described first by Gowda and Krishna in [6]. The second one, the ISODATA non-hierarchical clustering algorithm is presented by Tou and Gonzalez in [4]. Both of them were used independently in the IBR-2 diagnostics [2,3,5]. The required number of clusters for the incipient degradations detection can not be strictly determined using some of the well known criteria, because the information about their appearance may be hidden in the early stage of clusters agglomeration process. The reasonable interval i.e. 3-10 clusters are examined in this paper in accordance with the noises level which is considered, and the authors experience.

The collected M=182 PSDs, which constitute the data objects (N=256 dimensional points) for the pattern recognition processing, cover the reactor operation time period from the end of 1987 to the beginning of 1991 i.e. the reactor operation period with the PO-2 version of the moving reflector. The region 1 in Fig.1 shows the power fluctuations -the average power standard deviations- and the MNN-clustering time diagram during this period. The clustering time diagram presents the cluster number each subsequent -in time- PSDs belong to. The last spectra [183-199] (region 2) refer to the reactor operation with artificial disturbances. Their role will be explained in the

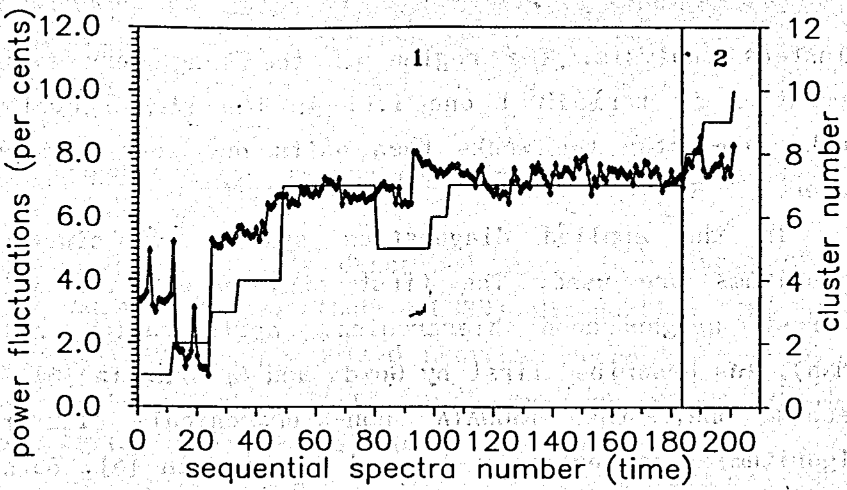


Fig.1 The clustering time diagram (the staircase diagram) and power fluctuations during the reactor operation period with the PO-2 moving reflector version. The region 1 represents the normal reactor operation and the region 2 refers to the reactor operation with artificially introduced reactivity disturbances.

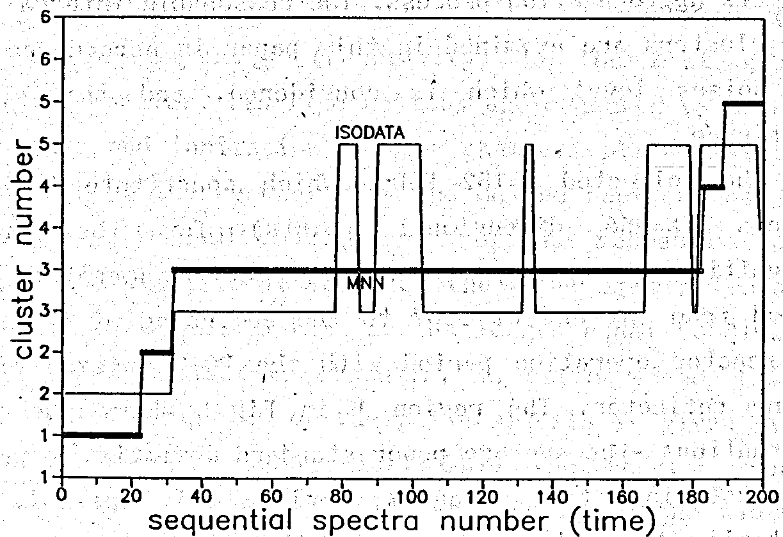


Fig.2 The ISODATA and MNN clustering time diagrams during considering reactor operation period.



next section. As shown in Fig.1, during stabilization period (≈6 months) the subsequent PSDs fall into small (in quantity), four "transition" clusters. This part of diagram reflects the stabilization period of the reactor noises after altering the moving reflector version from the PO-1 to the PO-2 one. The cluster No.7 in which almost all further points fall to, represents the roughly stable reactor operation regime. What is the meaning of these two underlined terms?

As is shown in Fig.1, the MNN-clustering time diagram reflects the changes of the IBR-2 reactor power fluctuations. The main difference is that the former extracts more distinctly both the subsequent reactor transition states and the moment of stabilization. Additionally, the new clusters in the disturbances region (region 2 in Fig.1) are apparent too. The violations of the stable operating regime, which are represented by the clusters 5th and 6th appearance in Fig.1, and their disappearance for the less detailed clustering represented by the time diagram in Fig.2 (thick line), signal that a "subtle" structure of the stable 7th cluster (or 3rd one in Fig.2) exists.

The clustering time diagram obtained using the ISODATA algorithm (Fig.2) shows more distinctly than the MNN algorithm, the substructure of the -so called- roughly stable regime of the reactor operation. The Niemann nonlinear transformation [7] of the 256-dimensional space into two dimensional one, lets one to observe in Fig.3 the main features of the clusters structure with the respective clustering results. The solid line divides this structure into the two parts ST-A and ST-B respectively. The ST-A represents the stabilization period of the reactor noises with the new moving reflector version. Two tendencies (clusters 1 and 2 in Fig.3) invisible for the ISODATA algorithm (see Fig.2) are extracted by the MNN method. On the other hand, the ST-B shows the clusters representing the last two years operation period of the IBR-2 reactor. Unlike the former one, this structure is more compact and spherical, that confirms the correctness of treating it as roughly stable. However, the substructure of the third cluster (3a and 3b in Fig.3) revealed by the ISODATA algorithm and degradation disturbances represented by the 4th and 5th clusters require more detailed examination in order to determine both the reasons of such a behavior and their influence on the reactor operation.

Degradation diagnostics of the IBR-2 reactor

Two kinds of the reactor operation degradations are examined in this paper using the pattern recognition diagnostics system. The first one refers to the case when a floating reactor long time trend undergoes the abrupt change or a new trend appears. The second kind, concerns the trend of its own i.e. when continuous and slow trend reflects the reactor operation degradation. Both the first and the second kinds of degradations are examined splitting the full PSD frequency interval [0,2.5]Hz or [1.256] frequency channels, into three ones (see Fig.4). The spectral densities in each of them reflects the main sources of power fluctuations. The low frequency interval [0.01,0.78]Hz (or [1,80] frequency channel number interval) corresponds to the cooling flow noises, the following [0.78,1.65]Hz to the moving reflectors



supporting construction vibrations, and in the last one the narrow peak [1.7,1.8]Hz reflects the moving reflectors vibrations. The PSDs in each of these frequency windows undergo pattern recognition processing separately.

In order to exemplify the first kind of degradations recognition, the new trend to the normal reactor operation was introduced by artificial reactivity modulation using the rod of the power automatic regulation. The three groups of disturbances with various respective modulation frequencies were introduced. The modulation frequencies are selected in such a way that their contributions to the PSDs are being revealed close to the wide peak in the region 1 in Fig.4 ([1,80] frequency channel number interval). Additionally, the reactivity fluctuations in each of the group ranged from $1.6\cdot10^{-6}$ up to $1.7\cdot10^{-5}\,\Delta k/k$ of the power pulse energy e.g. 2-20 per cents of its average. As the time diagrams show (see Fig.5), both for the low frequency PSDs MNN- clustering and the full interval PSDs MNN- clustering, the new clusters appearance is signaled in the [183-199] subsequent spectra number interval.

As is shown in Fig.2, the abrupt degradations are revealed by the less detailed MNN clustering i.e. when the lesser number of clusters is assumed. It evidences that the introduced disturbances are well recognized by the MNN clustering method. On the other hand it seems to be strange that the ISODATA algorithm did not recognize -apart from the most extreme one- any others, even relatively significant disturbances. The explanation lies in the basic idea of the ISODATA algorithm, where the agglomeration process is performed concerning the established, average cluster centers. Such an approach enforces spherical shape of a

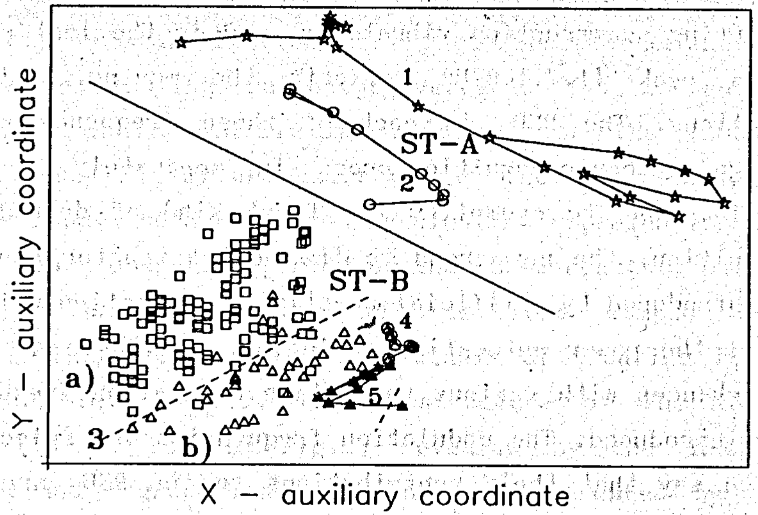


**Fig.3** The two dimensional clusters structure after the Niemann transformation of the 256-dimensional reactor spectral "noise images".

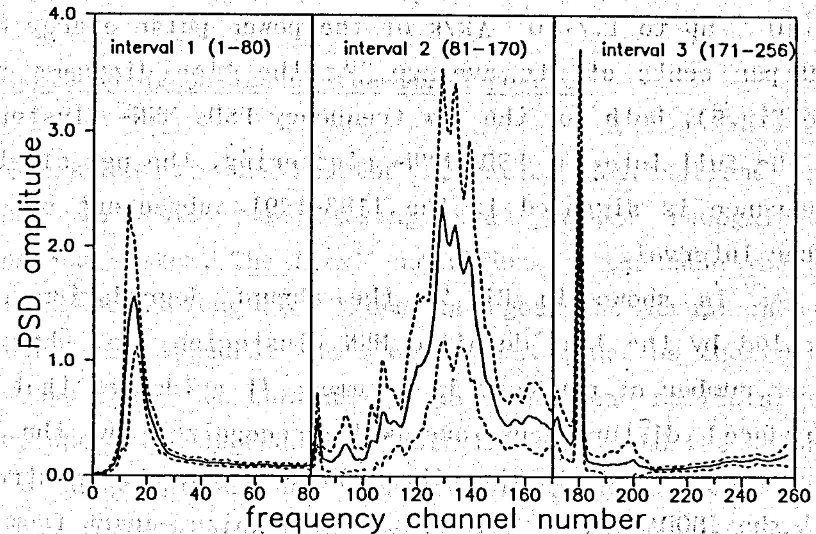


**Fig.4** The average power spectral density representing the 3rd (see Fig.2) cluster center (solid line) with ± standard deviation (dashed lines) in each of the frequency channels. Splitting the full frequency interval into three ones is shown.



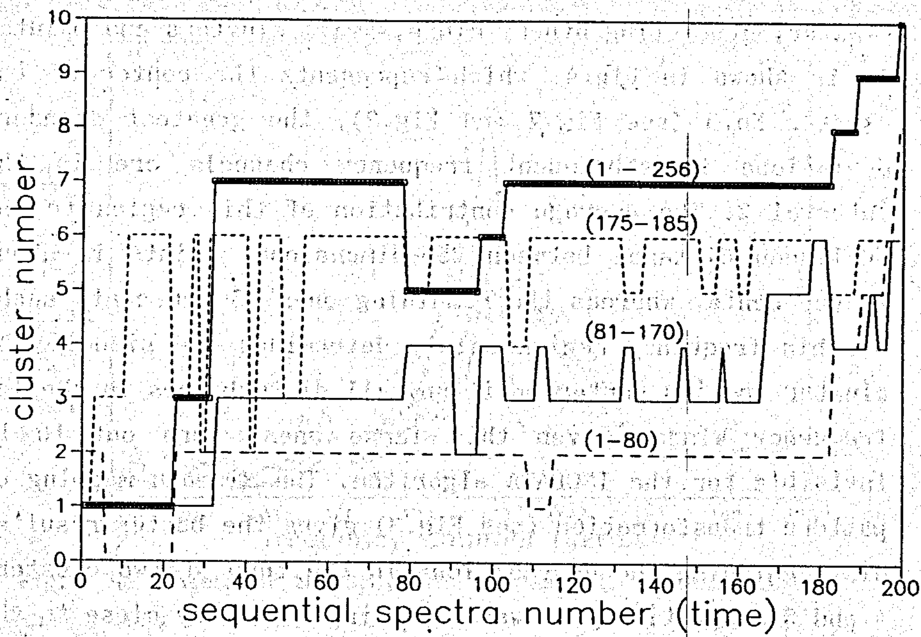


**Fig.5** The clustering time diagrams for the full frequency interval processing (thick line) and other ones. Both the low frequency ([1,80]) disturbances influence, on the 8th,9th,10th clusters appearance and the partial influence of the medium frequencies disturbances (belonging to the [81;170] interval) on the cluster 7 substructure existence (reflecting by the 5th and 6th clusters), are shown. A slow degradation in the medium frequencies window is shown at the end of the considered reactor operation period (the clusters 5 and 6 appearance, for the [81–170] interval time diagram).

cluster, attracting other, close, small clusters and points. As is shown in Fig.4, which represents the center of the cluster No.3 (see Fig.2 and Fig.3), the greatest standard deviations in subsequent frequency channels are in the interval 2. The average contribution of this region to the Euclidean distance between 256-dimensional points is about 70 per cents, whereas the remaining ones 15 per cents each. As this frequency region mainly determines the size of the cluster and its center position, all disturbances in the low frequency window, even this large ones, turn out to be invisible for the ISODATA algorithm. The Niemann mapping of pattern transformation (see Fig.3) gives the better results, distinguishing the degradations in the form of two clusters 4 and 5 respectively, however placing them very close to the cluster 3b.

As is shown in Figs.1,2,3,5, apart from the abrupt degradations caused by the reactivity modulation in the low frequency region, recognized as separate new clusters at the end of the clustering time diagram, additional substructure of the 3rd (in Figs.2,3) cluster exists. The ISODATA clustering time diagram for the medium frequency interval (interval 2 in Fig.4) presented in Fig.5 shows that the fluctuations in just this interval are responsible for the substructure appearance. It shows also, that after relatively stable operation period represented by the alternately occupied 3rd and 4th clusters, the new clusters 5th and 6th have appeared recently. The centers of these clusters shown in Fig.6 are quite different than the previous ones. The peaks are sharper and higher in amplitude. They evidence the resonance-like behavior caused by the moving reflector supporting device and jacket



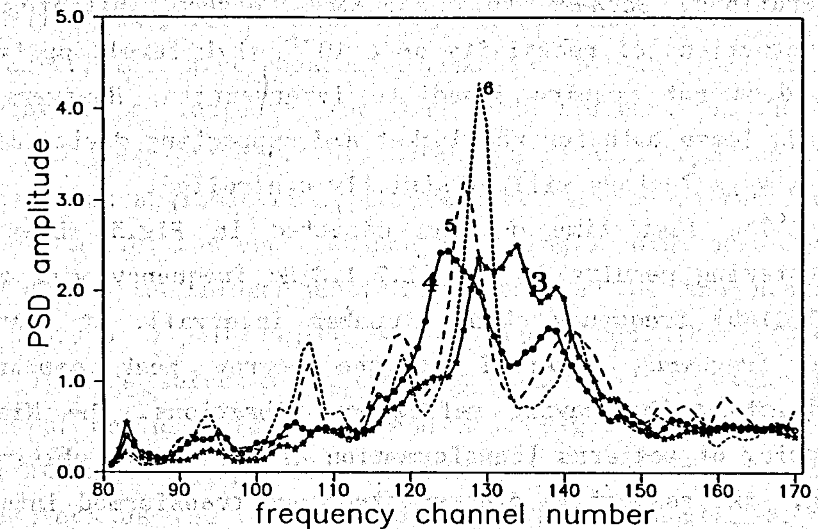


Fig.6 The centers of the 3rd, 4th, 5th and 6th clusters for the PSDs medium frequency window ([81,170]) ISODATA-clustering.

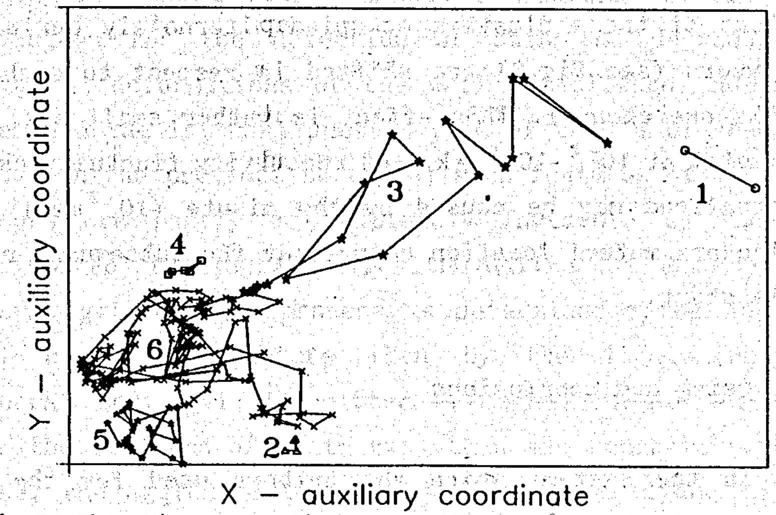


Fig.7 The Niemann pattern of the clusters structure determined by the peak, referring the moving reflectors vibrations in the [175,185] window. The clusters 5 and 6 reflect the recent (two years) reactor operation, while 1st,2nd and 3rd the stabilization period at the beginning of the reactor operation with the new moving reflector version.

vibrations. Because this anomalous effect initiates the fluctuations of reactivity on a $10^{-6}$ $\Delta k/k$ level, up to now it does not require immediate intervention. However, the bonds loose both for the jacket and supporting device of the moving reflectors will be strictly controlled.

The last time diagram depicted in Fig.5 shows the clustering results in the [1.7,1.8]Hz frequency window (or [175,185] frequency channel number interval). It embraces the frequency interval of the narrow peak appearance reflecting the moving reflectors vibrations. The Niemann mapping of patterns transformation allows one to observe in Fig.7 the respective cluster structure transformed into two dimensional space. After stabilization period represented by the "oblate" clusters 1 and 3, the well established, numerous and "spheric" clusters 5 and 6 appeared. The centers of these clusters occupied alternately during last two years (see Fig.8) are shifted in respect to each other by the one channel. This effect is rather small one and is estimated at $10^{-7}$-$10^{-6}$ $\Delta k/k$ of reactivity fluctuations. Such fluctuations may be caused by the minute ($10^{-3}$mm.) moving reflectors mutual location changes at the subsequent reactor cycle start.

## Discussion and conclusions

In the system, which the authors used for the IBR-2 nuclear reactor diagnostics, two clustering algorithms are built-in for two sorts of expected reactor degradations. As the results presented in the previous sections show, the MNN algorithm properly selects the abrupt trend changes in the reactor operation. This fact is apparent especially for



stabilization period of the IBR-2 reactor and for the period of artificial disturbances introduced by the reactivity modulation, reflected by the long, wide clusters 1,2 and 4,5 in Fig.3, respectively. This advantage results from the idea of clusters agglomeration performed by the MNN hierarchical algorithm i.e. the appurtenance of a single point or a small cluster to the bigger one, is determined by the nearest neighbors of a point which is just considered. That is why, the clusters selected by the MNN clustering may take the forms of chains (clusters 1 and 2 in Fig.3 or 3 in Fig.7) reflecting some operation trends. The algorithm control parameters as the cut-off radius and/or the number of the nearest neighbors taken into consideration, determines the level of different trends extraction. However, the advantage of selecting chain-like structures appears to be the disadvantage for the detection of both the degradations causing the deformations of the well established, numerous cluster and the internal substructure of such a cluster. As is shown in the previous sections, such features of clusters structure are partly or completely invisible by the MNN algorithm. For the ISODATA algorithm unlike the MNN one, the clusters agglomeration process is determined rather by the global clusters structure than by the local (nearest neighbors) one, and the pattern recognition subjects are rather the clusters of their own, than the separate points. Because, the agglomeration process is performed due to the clusters centers with determined separation between them, and the assumed size of the clusters, it enforces the spherical shape of clusters. Therefore, each deformation of this cluster shape or its grow in size is reflected by the cluster partition. This fact is exemplified in Fig.3, where the ISODATA clustering reveals the substructure of the cluster 3rd (subclusters 3a and 3b). The detection both of the reason of this substructure appearance and the small degradation in the [81,170] frequency channel number interval (interval 2 in Fig.4), shows the ISODATA-clustering advantages. However, as is pointed above, in order to preserve the spherical structure, the numerous clusters attract the smaller ones placed close to them. For example, the Fig.3 depicts, that the different clusters 1 and 2 are classified by the ISODATA as a single one (see Fig.2), and the clusters 4 and 5, reflecting significant reactivity fluctuations, are classified to the cluster 3b. Summarizing, we can conclude that the MNN and ISODATA clustering methods supplement each other, and for the degradation diagnostics they should be used concurrently.

Splitting the PSDs data into the three frequency windows responsible for various sources of reactivity fluctuations, and clustering them separately, permits the authors to increase the system sensitivity by the order of magnitude. For the full PSD frequency interval processing, the reactivity fluctuations at a $10^{-6}$-$10^{-5}$ $\Delta k/k$ level are distinguishable, while for the separate frequency windows the $10^{-7}$-$10^{-6}$ $\Delta k/k$ degradations are apparent. It is worth to emphasize that such a splitting is indispensable, when some PSD frequency window contribution to the Euclidean metrics is considerably higher than the other ones.

In order to examine more carefully the degradation processes, the authors propose the mapping of patterns transformations application. The transformation of the N-dimensional pattern to the two or three dimensional ones, makes it possible to visualize the clusters structure and observe their changes during the reactor operation.



Although, the two (or three) dimensional patterns show disturbed- in comparison with the N-dimensional ones- clusters structure, the pictures like Fig.3 and Fig.7 give impressively correct results. The pattern recognition diagnostics system used by the authors has built-in two principally different mapping of pattern methods [1]: the Karhunen- Loeve and Niemann techniques. The diagnostics system enable one to combine both of them, and observe the resulting three (or two) dimensional clustering structures [3].

The positive effect of the degradations detection in some complex device operation (not only the nuclear reactor) at their very beginning stage depends on the proper selection of both the information source (data measured) and the method of its processing. The former requires the knowledge, where such degradations may be expected, and the latter, what kind of degradations are anticipated. Just these rules should be taken into account in construction of any reliable nuclear reactor diagnostics system.

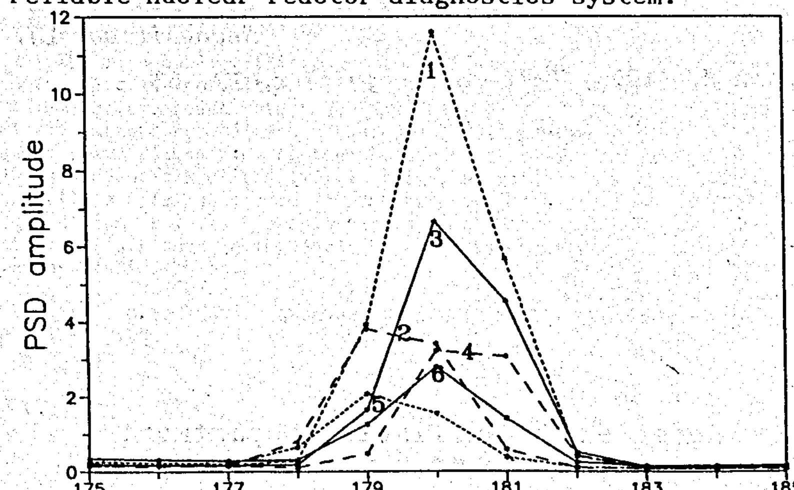


**Fig.8 The centers of clusters in the [175,185] frequency channel number interval.**

Acknowledgements

The authors wish to thank Mrs. T.A. Filimonycheva for her assistance in manuscript preparation.

## REFERENCES

1.Pepyolyshev Yu.N. and Dzwinel W. (1990) *Commun.JINR Dubna,* E10-90-323.

2.Pepyolyshev Yu.N. and Dzwinel W. (1991) *Ann.Nucl.Energy,* **18**, 117.

3.Pepyolyshev Yu.N. and Dzwinel W. (1991) *Proc. Symposium on Nuclear Reactor Surveillance and Diagnostics,* SMORN VI, Gatlinburg, Tennessee,USA, **2**, 61.01.

4.Tou J. and Gonzalez R.C. (1974) *Pattern Recognition Principles,*Addison -Wesley, Reading, Mass.

5.Bargiel M.,Kitowski J.,and Pepyolyshev Yu.N. (1988) *Commun.JINR Dubna,* P13-88-345 (in Russian).

6.K.Chidananda Gowda and Krishna G. (1978) *Pattern Recognition,* **10**, 105.

7.Niemann H. (1980) *Pattern Recognition,* **12**, 83.

Received by Publishing Department
on September 6, 1991.