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PREDICTIVE MAINTENANCE OF ROTATING MACHINERY IN NPP „PAKS" BASED ON VIBRATION DIAGNOSTIC EXPERT SYSTEM

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ABSTRACT

A recent study of the Predictive Maintenance Program for approximately 300, different types of rotating machinery in NPP „Paks" is reviewed. The program is based on an automated vibration analysis expert diagnostic system. The data measurement and evaluation methods, the fault identification accuracy, the expert system analysis steps and the rule-base development techniques are reviewed. The process of order normalization of vibration data, the accumulation of average data as a baseline for automated analysis and the bearing wear detection are presented. The fundamental assumption used in expert system is that the health of the machine as a whole can be assessed by isolating the spectral data pertinent to each major component. Details of machine configuration such as minor component arrangement, types of bearings, gearbox details and coupling types are stored in knowledge base via a component coding scheme. The major component groups are defined and the proper identification of the major components of a given machine and the location of the test points are shown. The method of fault diagnostics using the expert system rule-base, the fault severity assessment and fault severity trending are demonstrated through concrete practical examples of machines (motor-coupling-gearbox-coupling-pump, and high-pressure turbine- low-pressure turbine-generator, etc.) of NPP „Paks".

INTRODUCTION

A three-year long project was begin in NPP „Paks", Hungary to introduce and acquire the techniques of Predictive Maintenance for rotating machinery in NPP. The supervision of the chosen machines was organized using the DC-7b type vibration analyzer, and the ExpertALERT PdM expert system, developed by PredictDLI Corporation.

Part of the machinery belongs to the safety systems of NPP, part of them have very large importance in the energy production. The Maintenance Strategy for this two machinery groups will remain Preventive, but the Maintenance Planning Organization will receive more information about the condition of this machines too. The third - largest - part of rotating machinery belongs to that group, for which will be realized the Predictive Maintenance Strategy (Condition Dependent Maintenance). This year is the first in introduction of the PdM strategy, but we obtained good results.

VIBRATION TEST AND ANALYSIS GUIDE

The Vibration Test and Analysis Guide (VTAG) contains the necessary technical information of each specific machine type, on which the vibration analysis and data acquisition are based.

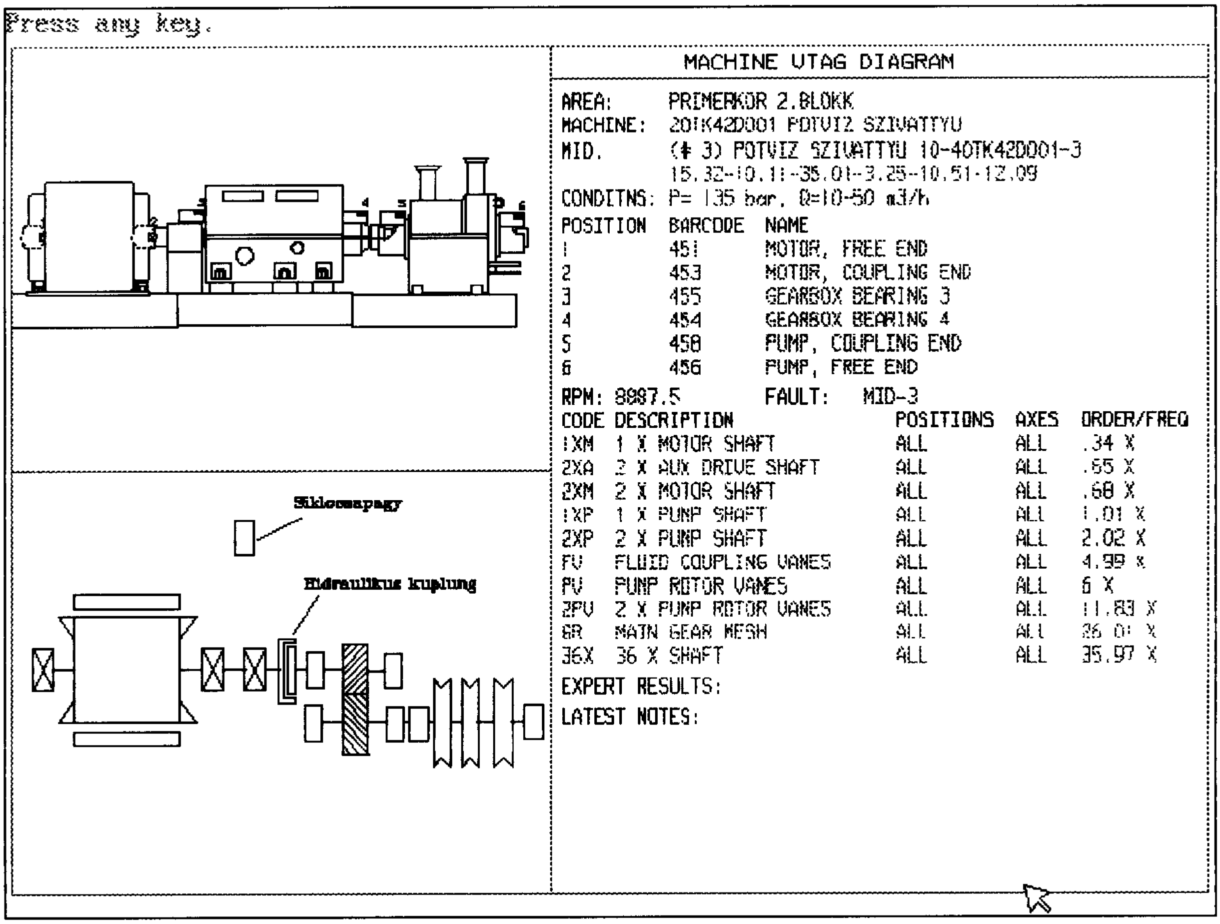

Fig 1.

The main important information:

- External schematics, showing locations of vibration test points, and their orientation.
- Internal schematics, showing the most important components of machines and characteristic frequencies relative to the reference shaft speed.
- Bearing types and specifications.
- Rated operating shaft speed (RPM).
- Reference RPM for order normalization in case of multiple shaft machine.

- Two frequency ranges for spectra (as multiples of the reference shaft speed, usually 10x and 100x RPM).

The expert system analysis not required all possible information of component forcing frequencies, but its more detailed knowledge lead to increased accuracy of ExpertALERT results.
Fig. 1. presents the VTAG for a feed water pump in the primary circuit of NPP „Paks".

TRI-AXIAL VIBRATION DATA AQUISITION

We acquire data for all three axes at each test point (A - axial, R - radial, T - tangential). Usually we use one test point for small, or two test points for major elements (sometimes more) per machine components, isolated by a flexible coupling.

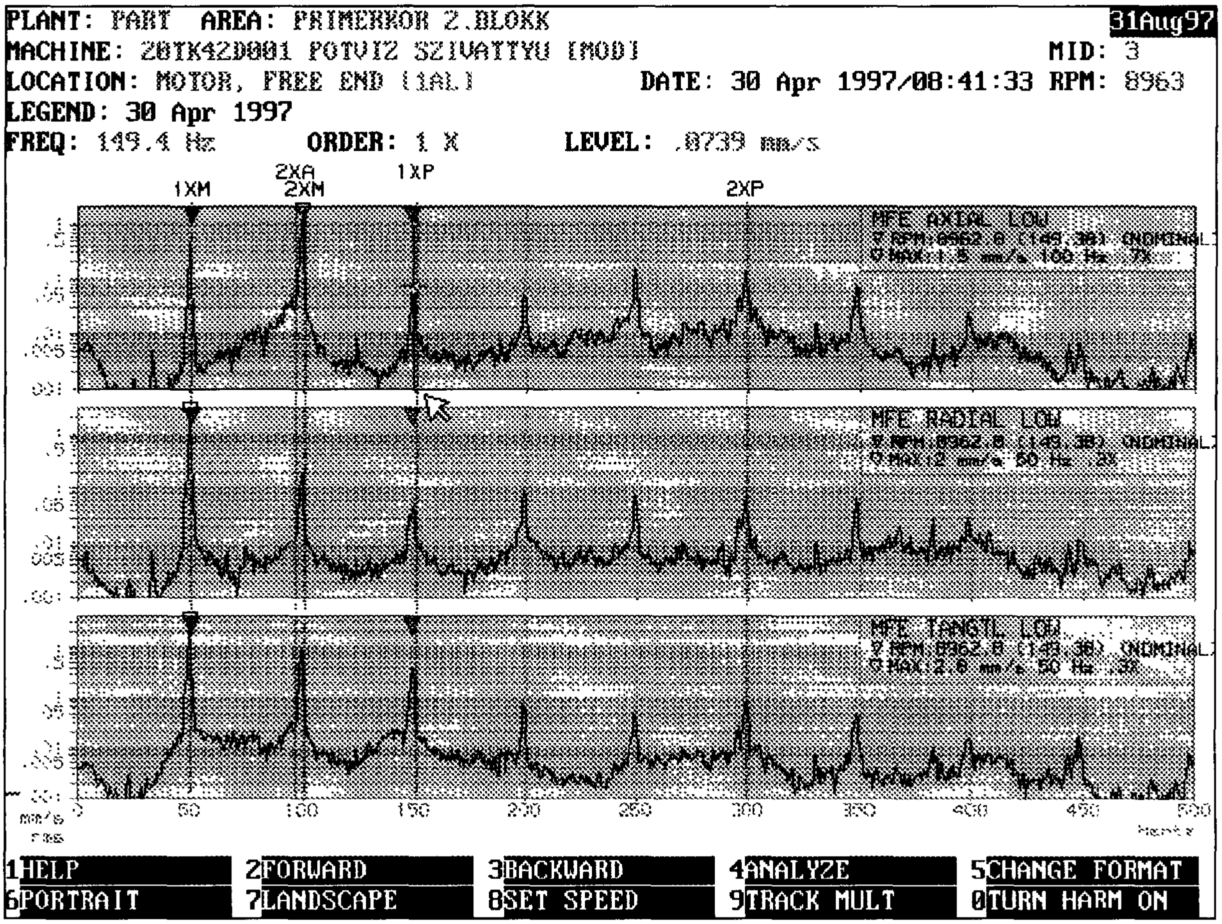

Fig 2.

Without tri-axial data a significant number of mechanical faults will be undetected, misdiagnosed or given an improper degree of severity.

Velocity is the best representation of the damaging forces associated with rotating machinery. Vibration magnitudes are presented on logarithmic scales in VdB, which is a log scale referenced to 10^{-8} m/sec rms (USA NAVI), or 10^{-9} m/sec rms (ISO).

Fig. 2. Shows low frequency range triaxial FFT plots for feed water pump, which VTAG is shown on fig. 1.

ORDER NORMALIZED SPECTRA

The abscissa of an order normalized spectrum is in multiples of machine fundamental speed rather then Hertz or CPM. Spectra for each test point and each axes are measured in two ranges:

- low order range: 0 to 10 times rotational rate,
- high order range: 0 to 100 times rotational rate.

In order normalized spectra the machine components generated vibration peaks lie at the same point on the frequency scale. For multiple shaft machines the basis of order normalization is the speed of reference shaft, and the frequencies related to the other shafts are determined by knowing relationships.

The expert system automatically finds the running speed of each machine. After order normalizing the analyst, or the system quickly identifies peaks at machine characteristic frequencies that are at fixed multiples of rotational rate. Order normalization allows expert, or expert system to identify probable bearing tones and detect rotational rate sidebands.

REFERENCE DATA-BASE

The order normalization allows the creation of an average data file for each specific machine type. Vibration signals for different identical machines measured at different times in slightly different operating speeds can be accumulated statistically and represented by a single set of averaged narrow band spectra. Comparing the actual spectral peak's amplitude to the corresponding peak of averaged spectrum, we can determine the changes.

The expert system uses reference database for automated analysis. The reference spectra made up of accumulated average of spectra measured at machinery in „good condition". Using this approach, we can define an acceptable level of vibration.

The average spectra composed of normalized vibration signals of technically identical machinery. In a set of 24 averageable signals (this number of signals enough for a good statistics), the average plus one sigma standard deviation values are computed for all 24, order normalized 500 line vibration spectra. There are 85% probability of that, a given peak in the spectrum not exceed the average plus one sigma value if the machinery is in „good condition".

VIBRATION DATA-MATRIX

Vibration data matrix, or screening table was developed for saving time of the analyst. This vibration data matrices serve as the basis of the work of expert system, which includes the next information for all test location and axis:

- Amplitudes at each ten pre-selected, specified orders, which are referred to as screening criteria or fault codes.

- Amplitudes and rotational rate order of two highest peaks in each of the low range and high range spectra, excluding the ten specified peaks, defined by fault codes.
- A „floor level" below which are the amplitudes of 75% of the remaining spectral lines of the high range spectrum.
- For each of the above, the change in amplitude from the previous survey and its deviation from average plus sigma.

We have 14 distinct peaks plus „floor noise level" at each axis for the analysis. In most of the cases the unspecified maximum peaks in the screening table are the bearing tones and rotational rate sidebands.

DLI ENGINEERING CORPORATION — PAGE 1
MACHINERY VIBRATION ANALYSIS SYSTEM — 20TK42D001 POTVIZ SZIVATTYU — 08-31-1997
SCREENING OUTPUT MATRIX — ExpertALERT

CURRENT SURVEY: 08-31-1997 ACQUIRED: 04-30-1997 08:41:33 CURRENT RPM: 3043/ 8952 MID: 3 SHORT NAME: 20TK42
SAMPLES IN AVERAGE FILE: 3 FILE SEQUENCE: 1

LOC	DATA SOURCE	SKI SLOPE ALARM	NOISE FLOOR 75%HR	VDB AT SPECIFIED ORDERS .34 1XN	.65 2XA	.68 2XN	1.01 1XP	2.00 2XP	4.99 FV	6.00 PV	11.99 2PV	26.01 GR	35.97 36X	MAXIMUM VDB AT UNSPECIFIED ORDERS LOW RANGE				HIGH RANGE			
1A	CURRENT	48	48	93	78	97	77	82	54	55	62	70	0	103	.67	83	1.67	81#	16.3	74	15 7
	d-SIGMA	-3	-12	-1	3	-6	-2	6*	-13	-18	-19	21	0	3*		3		-2		-12	
1R	CURRENT	47	50	106	69	79	74#	77	62	68	55	69	0	86	.67	79#	1.34	74#	12.7	74#	25 3
	d-SIGMA	-10	-9	2*	-3	-19	-7	4	0	-4	-26	13	0	-9		4		-21		15	
1T	CURRENT	47	51	108	75	90	91#	78	61	66	68	68	0	98	.67	77#	1.33	87#	16.3	87#	14.7
	d-SIGMA	0	-8	2*	-1	-10	-2	3	-3	-3	-3	0	0	-1		-3		8*		-6	
2A	CURRENT	42	55	89	74	96	85#	79	48	71	70	58	0	103	.67	81	1.33	78#	14.7	77#	12.9
	d-SIGMA	-6	-8	0	2	-6	2*	1	-17	-7	-2	-9	0	3*		2		2		7	
2R	CURRENT	44	51	106	67	98	81	75	67	71	50	49	0	78	1.34	71#	1 86	76#	14.7	74#	3 3
	d-SIGMA	-4	-9	2*	-5	0	2*	1	0	-2	-25	-25	0	0		9		5		2	
2T	CURRENT	41	54	111	94	94	86#	76	55	67	58	73	0	103	.66	93	1 00	83#	14 7	82	25 3
	d-SIGMA	-2	-6	1*	18*	-3	-9	-1	-9	-7	-11	-3	0	1*		-1		2*		-3	
3A	CURRENT	45	63	93	76	73	67#	59	66	79	82	75	0	82	.67	80#	1.98	102#	12 9	93#	25.7
	d-SIGMA	-4	-7	-1	7	-12	-27	-22	-22	-17	-10	-5	0	4		11		13*		19*	
3R	CURRENT	39	60	107	66	61	75	61	65	78	75	70	0	83	67	78#	2.97	97#	12 9	85#	25 7

Fig. 3.

CEPSTRUM ANALYSIS BASED BEARING WEAR DETECTION

Sometimes the computer, and the analyst have difficulties distinguishing between ball bearing tones and random peaks of lesser consequence. Using the cepstrum analysis one can detect and identify harmonics and sidebands in the frequency spectra. Cepstrum can be defined as the spectrum of a spectrum. Correspondence between the cepstral data and the spectral data in the screening table is checked systematically. If possible correlation is found, the corresponding peaks may be considered bearing tones if other criteria are met.

RULEBASE FOR DIAGNOSTICS

The specific peaks that reflect the faults generally are well represented in the screening tables. The tabular format of the program results make possible using a tabular approach applying diagnostic rules. For each fault diagnosis there are particular cells of data in the screening matrix, which alone or together with other cells provide influence in citing that diagnosis. The screening matrix and the knowledge of machine configuration give enough information to diagnose practically all mechanical faults that possible to diagnose using measured vibration spectra. The screened data are transformed into a suitable format using information about the component of machines, to be used as an input matrix for the diagnostic rules.

ANALYSIS BY COMPONENT

The expert systems uses the fundamental assumption that the health of the whole machine can be assessed by isolating the spectral data belonging to each major component and based on the data diagnosing faults by component. Assuming this, we concentrate to the test points of components, and its adjacent component and gather a set of data from the screening matrix pertinent to the analysis of that component. The comparison of the data belonging to the component, and the data of adjacent component, the expert system can determine which component may be the most possible source of the detected fault. This concept is very useful particularly for imbalance and bearing wear diagnoses.

The proper identification of major components of the machine and the location of test points in relation of each component is very important. Machine configuration such as component arrangements, bearing types, gearbox details and coupling types are stored in the knowledge base via a component coding scheme. Major component groups have been defined as follows:

- Close-coupled Machines
- Linked Drivers (belt or chain)
- Rotary Thread/Gear Pumps
- Rotary Sliding Vane Pumps
- Marine Propulsion Gearboxes
- Turbines
- Motors
- Gearboxes
- Fans
- Generators
- Centrifugal Pumps
- Reciprocating Pumps
- Centrifugal Compressors
- Reciptroc. Compressors
- Screw Compressors
- Lobed Browers
- Couplings
- Diesel Engines
- Purifiers
- Machine Tool Spindles

PROCESS OF FAULT DIAGNOSTICS

Analysis of each of major component group requires that a unique set of frequencies of interest be extracted from the screening table and examine. There are two basic expert system processes to gain diagnosis from screening data:

1. Transformation the screening matrix into a set of Component Specific Data Matrices (CSDMs),
2. Analysis of vibration data in each CMDS by passing the two dimensional array of numerical values (vibration amplitudes and exceedances of average) through a series of diagnostic rule templates that serve to pass or fail each individual fault diagnosis.

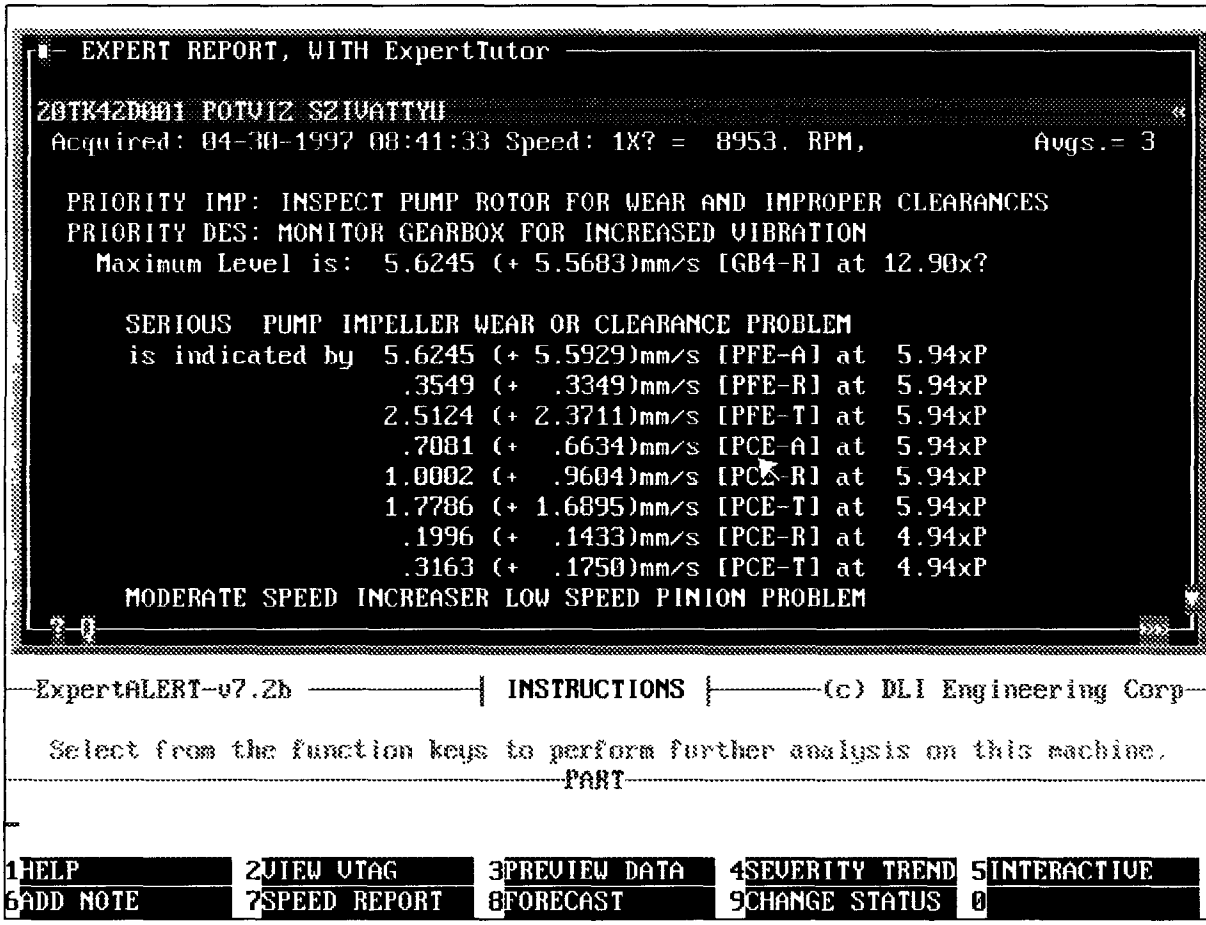

Fig 4.

FAULT SEVERITY ASSESSMENT AND TRENDING

After declaring a fault, a relative severity needs to be determined. A linear numerical scoring system is used to determine fault severity. It is well suited to provide trending of severity over time, from survey to survey. All fault diagnosis that is detected at least to a „slight" degree for a given machine, the severity score can be plotted as a function of time.

The ordinate does not directly reflect the numerical score. Dividing the trend plot into horizontal bands of „slight", „moderate", „serious" and „extreme" serves to normalize the severity scores among the various diagnoses. Thus multiple faults can be trended independently for a machine on the same graphical plot. Repair decisions can be made based in part on a combination of absolute fault severity and its rate of increase, and in part on the type and number of indicated faults.

Diagnostic Score	Severity	Repair Priority
0 to 10	Slight	No Recommendation
11 to 30	Moderate	Desirable
31 to 60	Serious	Important
≥ 61	Extreme	Mandatory

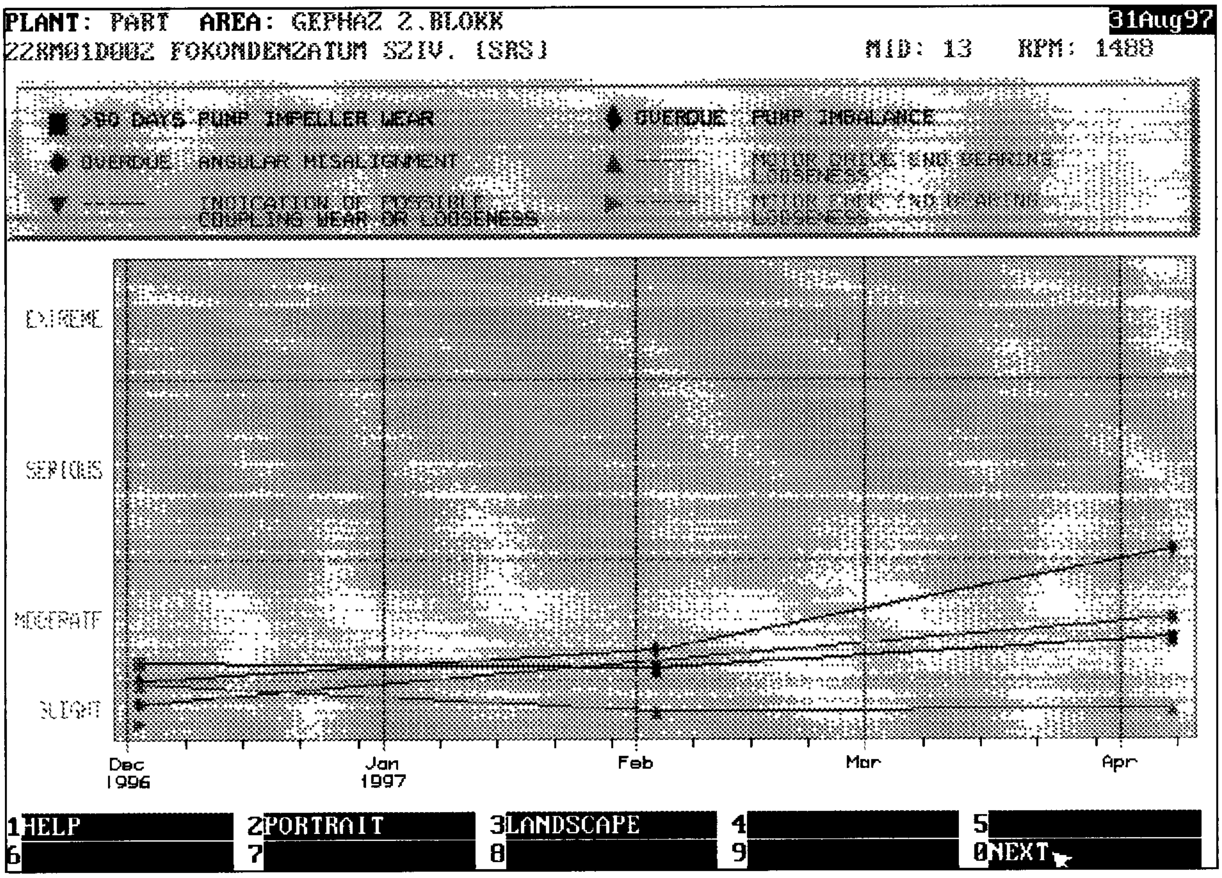

Fig 5.

SUMMARY AND CONCLUSIONS

The Predictive Maintenance Program in NPP Paks is in its first year, but there are a lot of positive results in diagnosing faults of rotating machinery. Using an automated expert system, called ExpertALERT with a high degree of accuracy increases the safety of operation and reduces the cost of maintenance.

ACKNOWLADGEMENTS

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BIBLIOGRAPHY

Glenn D. White, Introduction to Machine Vibration, Part Number 8569, ver.2.0, 1997 DLI Engineering Corp., Bainbridge Island, WA 98110

Bill Watts and **Joe Van Dyke, Sr.**, An automated Vibration -Based Expert Diagnostic System, Sound and Vibration, September 1993.

Joe Van Dyke, Expert System for Precision Machine Tool Diagnostics, Sound and Vibration, May 1994.