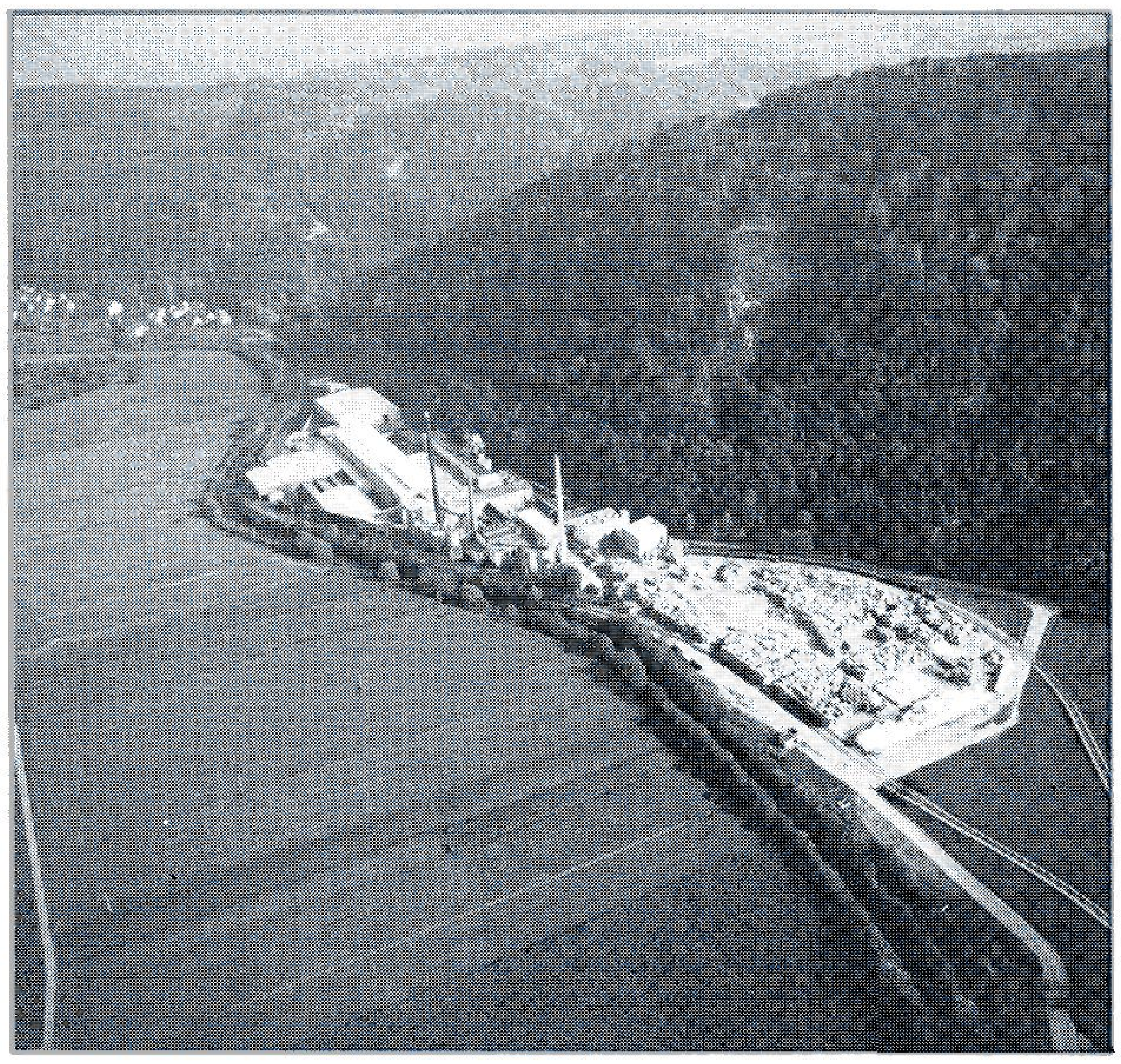
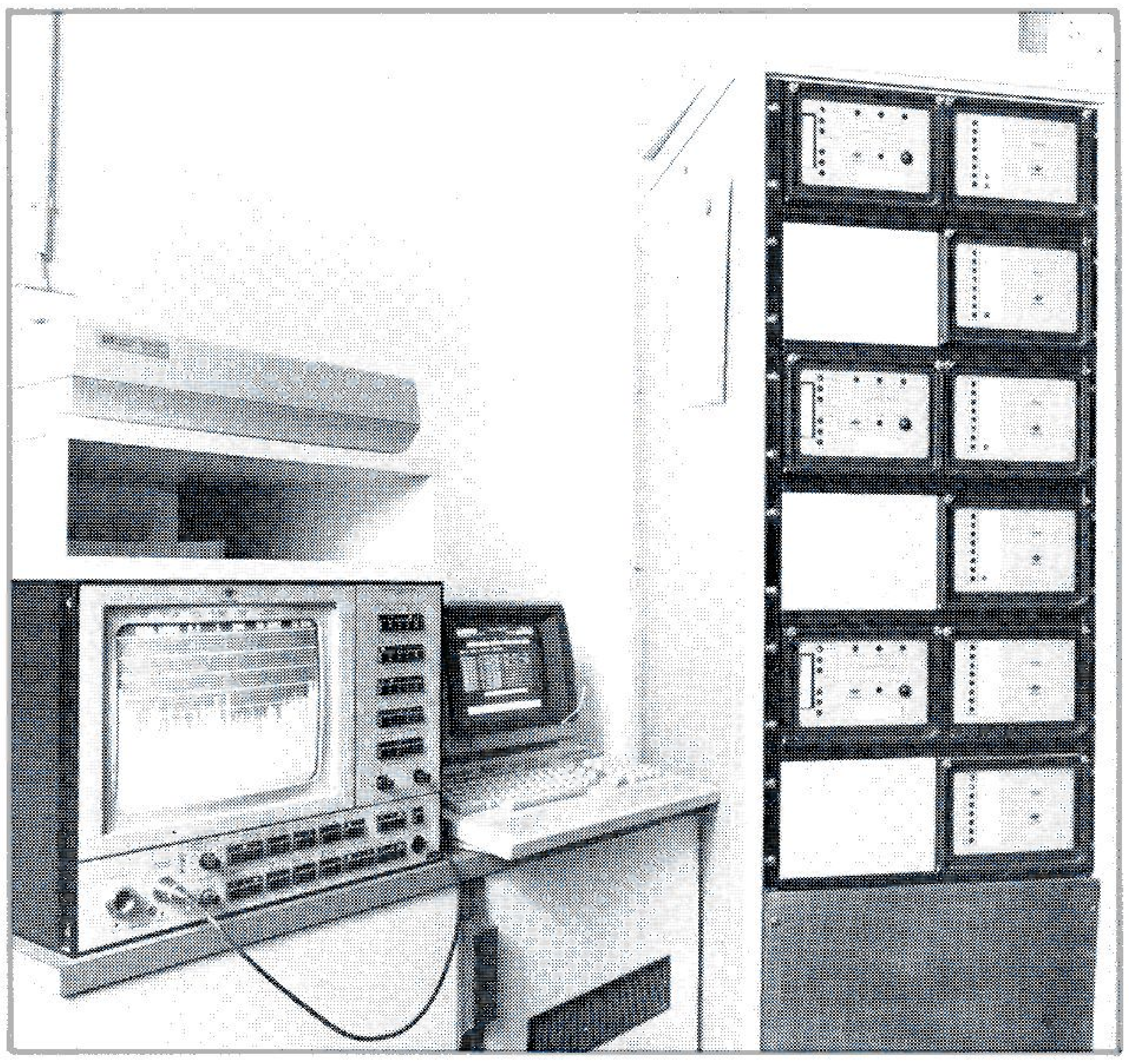
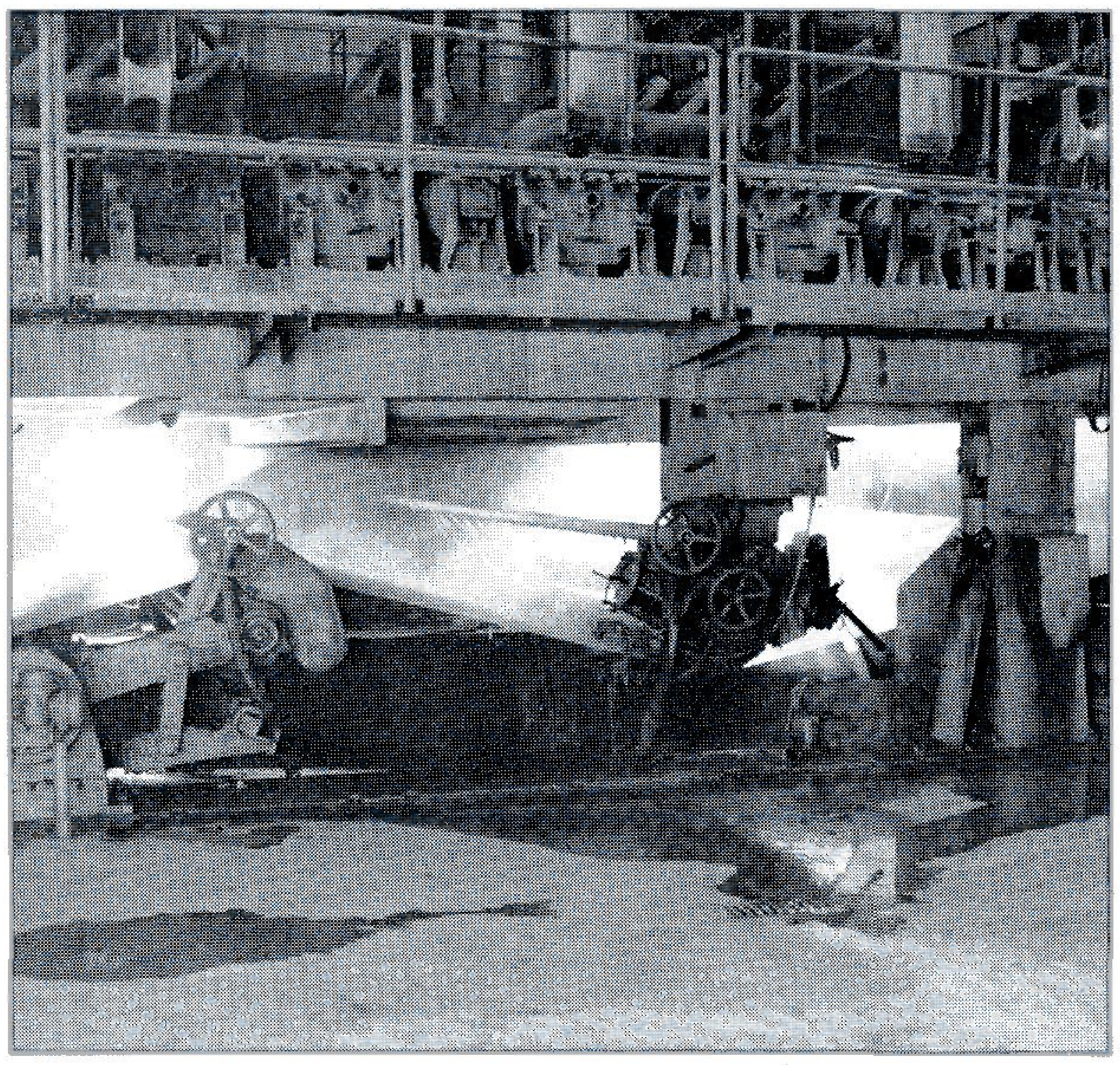
Brüel & Kjær application notes

Machine-Condition Monitoring using Vibration Analysis

Permanent Monitoring of an Austrian Paper Mill







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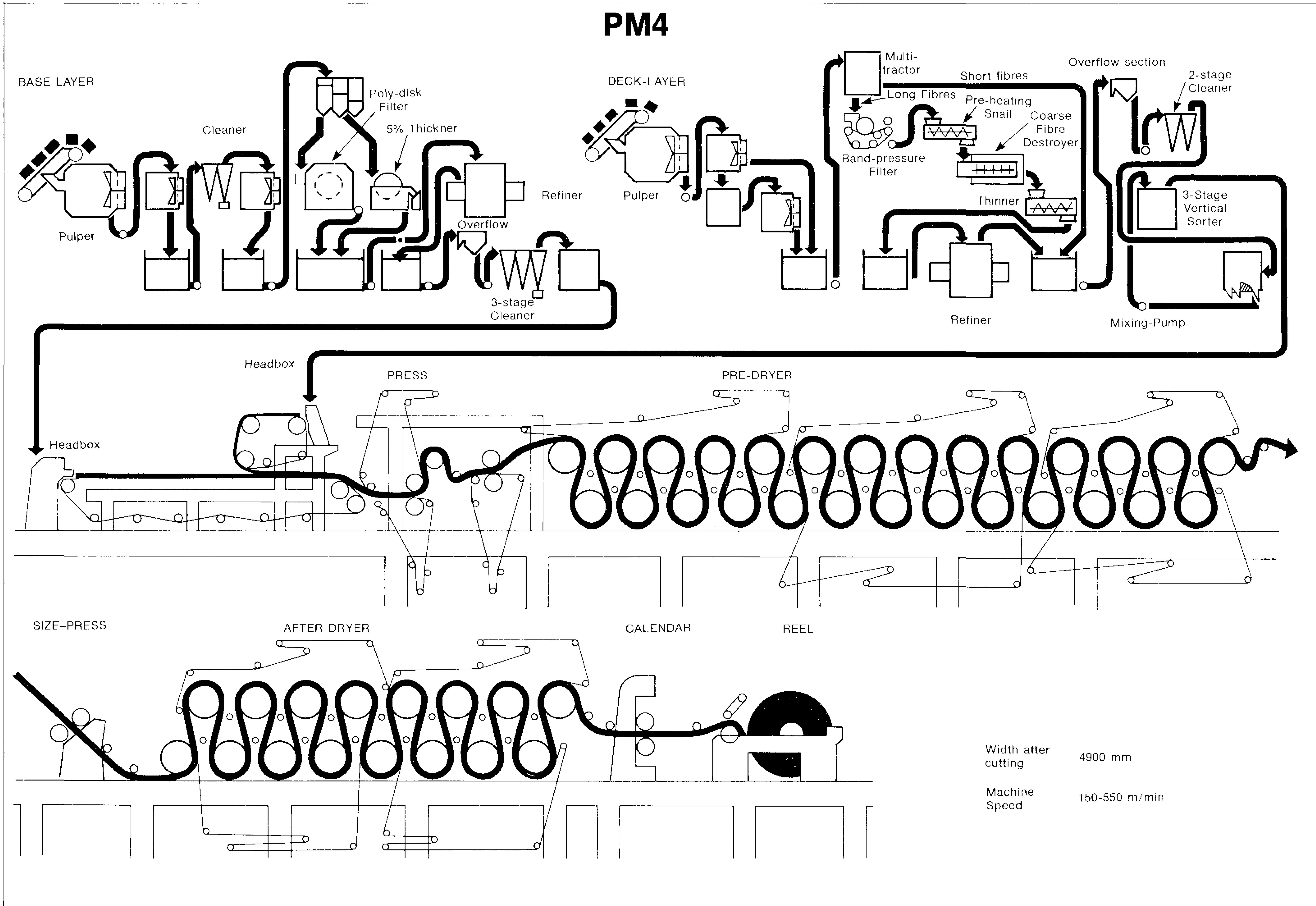

Fig. 1. A schematic layout of the Voith paper-machine used by Hamburger AG. The monitored bearings are in the dryer-section (both PRE-DRYER and AFTER DRYER) at the bottom of the figure

Introduction

In any continuous manufacturing process, maintenance is of the upmost importance. Loss of production due to forced outage of the production facility, or even part of the production facility, can have considerable effects on profitability. Specifically, in the pulp and paper industry, with its inherently high production costs and small operating margins, the need for efficient, cost-effective and practical monitoring systems is more pronounced than ever before.

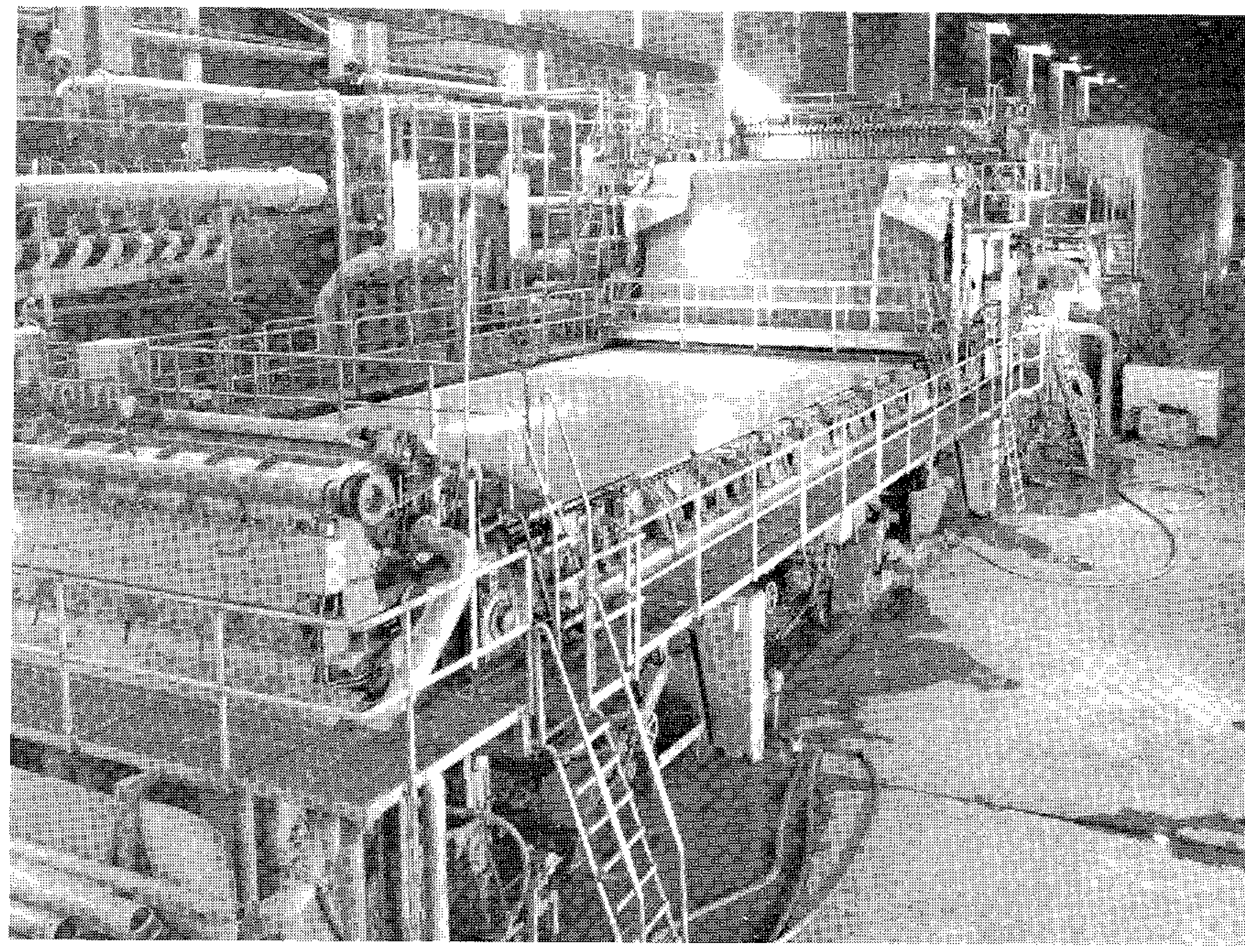

Fig. 2. The Voith paper-machine in use at Hamburger AG, Pitten, Austria

Maintenance Techniques

Traditionally, machine maintenance was on a *run to breakdown* basis, this meant allowing the breakdown to occur, shutting the production facility down, and repairing the fault. This was not an economic method of maintenance, the financial losses from a single bearing failure on one of the paper-machine's at the plant featured in this Application Note can exceed 35 000 ATS (approx. 3 000 USD) per hour.

Nowadays, one of the most widely used methods of machine maintenance is *time-based preventive maintenance*, using planned production stops to replace all critical components, at regular intervals. While this method is an improvement on the previous one, the planned production stops still generate financial penalties due to lost production and critical components are often replaced regardless of having a considerable life-expectancy. Further, no amount of regular, planned maintenance, can remove the threat of catastrophic failure of a component between checks.

A third method of machine maintenance involves regularly monitoring the machine while it is in a good condition, employing more advanced maintenance methods while the machine is deteriorating and using the collected data to predict when the machine is about to fail. It is called *condition-based maintenance*. Condition-based maintenance can accurately identify incipient rolling-element failure before the component reaches a catastrophic condition, allowing the production manager/maintenance team to decide when *he/they want* to replace worn components and alleviating the necessity for stripping-down machines in search of faults.

Condition-Based Maintenance at Hamburger AG

The condition-based monitoring system described in this Application Note is designed to monitor rolling-element bearings in harsh environments, such as those found throughout the pulp and paper industry. The necessity for installing the system was the unusually high failure-rate among bearings on the dryer section of Hamburger AG's, Voith paper-machine. Between 1980 and 1985 these sudden failures cost the company in the region of 21 mil. ATS (approx. 1,75 mil. USD) in terms of lost production alone. Inclusion of the costs incurred in overtime payment to the maintenance personnel, ancillary damage caused to other components by a sudden bearing failure and financial losses due to inability to deliver on schedule would considerably increase the estimate of the losses given above.

In the following sections of this Application Note, descriptions are given of how the system was designed, how it is used and how it has performed in practice. The most important criteria on which to judge a monitoring system of this type is its success, or lack of it, in eliminating sudden failure of bearings and associated production losses. In the case of Hamburger AG's monitoring system, since its installation in 1986, there has been *no loss of production due to sudden bearing failure on the monitored section of the machine.* While it is difficult to estimate the exact savings to the plant in terms of increased production, a conservative estimate would place them in the range of 2 mil. ATS (approx. 170 000 USD).

Hamburger AG

Hamburger AG, situated in Pitten, Austria, was founded in the year 1853 by Wilhelm Hamburger. The company is one of the constituent parts of a larger group comprising Mosburger AG, Brigl und Bergmeister AG and Hamburger AG. The company recycles waste paper, producing corrugated packing paper. They run 1 Voith and 1 Erwepa paper-machine, manufacturing 24 hours a day at full capacity. They employ 250 people and produce 150 000 tonnes of corrugated packing per year. Fig. 1 shows a schematic layout of the monitored paper-machine at Hamburger AG.

The Development of a Monitoring System

The Machine

The monitored Voith paper-machine was installed in Hamburger AG in 1978 at a cost, including installation, of more than 500 mil. ATS (approx. 41 mil. USD). The paper-machine contained over 1 500 bearings of which 400 were deemed *critical* from the outset, a failure amongst any of these bearings would result in the immediate shutdown of the whole machine. The monitoring system used initially, involved 3 to 4 personnel who listened regularly to the critical bearings using a stethoscope. The average down-time of the machine was about 5% per annum and the number of maintenance personnel engaged in down-time repairs was 6.

After a period of time, it became apparent that particular difficulties were being encountered in monitoring the bearings attached to the heated cylinders in the drying section. These 43 cylinders are 1,5 m in diameter and 6 m long, rotating at a speed of 100 rpm. Steam, at a temperature of 150° C, is fed into the cylinders at one side of the machine, passed along the length of the cylinder, and extracted at the same side again. The paper is passed over the cylinders and dried.

The Problem

Between 1980 and 1985, the bearings attached to these rollers exhibited a very high failure-rate. These bearings were all at the hot-end (the side at which steam is fed into and out of the rollers). The average down-time due to a bearing failure on this section of the machine was 30 hours (due to the difficulty in accessing them) at a cost of 35000 ATS (approx. 3000 USD) per hour in lost production.

Analyzing the Problem

Hamburger AG contacted Brüel & Kjær Austria, who recorded the vibration signals from each of the critical bearings using a Type 7005 Portable Tape Recorder. The data was returned to Denmark to be analyzed using a technique called envelope detection (described in a later section of this Application Note). Hamburger AG requested that the analysis be completed before the annual maintenance shutdown in August 1984, to allow them to assess the validity of the results while stripping the bearings down.

The Results

The analysis concluded that 2 of the bearings, TS 11 and TS 17, had rolling element faults and while not critical, they should be replaced at the next available opportunity. The rest of the bearings exhibited no signs of terminal wear.

At the annual maintenance shutdown in August 1984, all bearings on the paper-machine's dryer section were stripped down and examined by Hamburger AG maintenance personnel. While a number of bearings throughout the paper-machine were found to exhibit signs of advanced wear, only 2 of the bearings in the dryer section were deemed to be at such an advanced state of wear that replacement was considered necessary. These were bearings number TS 11 and TS 17. Hamburger AG then requested Brüel & Kjær to design and install a permanent monitoring system.

System Requirements

The following 3 sections are taken from the original design specifications for the monitoring system and give a brief introduction to the ideas behind it.

1. Permanent monitoring by means of the Type 2505 Monitors and Type 2514 Multiplexers will monitor the overall vibration level of the bearings. It is expected that the overall vibration level would increase dramatically in the last few minutes of bearing life. The permanent system can then be used to shut the machine down before catastrophic failure.

2. Automatic spectrum comparison of each vibration signal with an appropriate reference spectrum should occur at least every 3 to 4 hours. Systematic monitoring of an increase in the vibration level at one of the bearing resonance frequencies should give at least several weeks warning of an impending failure. Operator-supervised trend analysis will aid in estimating the lead-time to failure.

3. On detection of changes in the spectrum, or at any other time where a fault is suspected, an envelope analysis can be performed. Detected fault-repetition frequencies could then be compared with calculated fault-repetition frequencies for various bearing faults i.e. inner-race, outer-race etc.

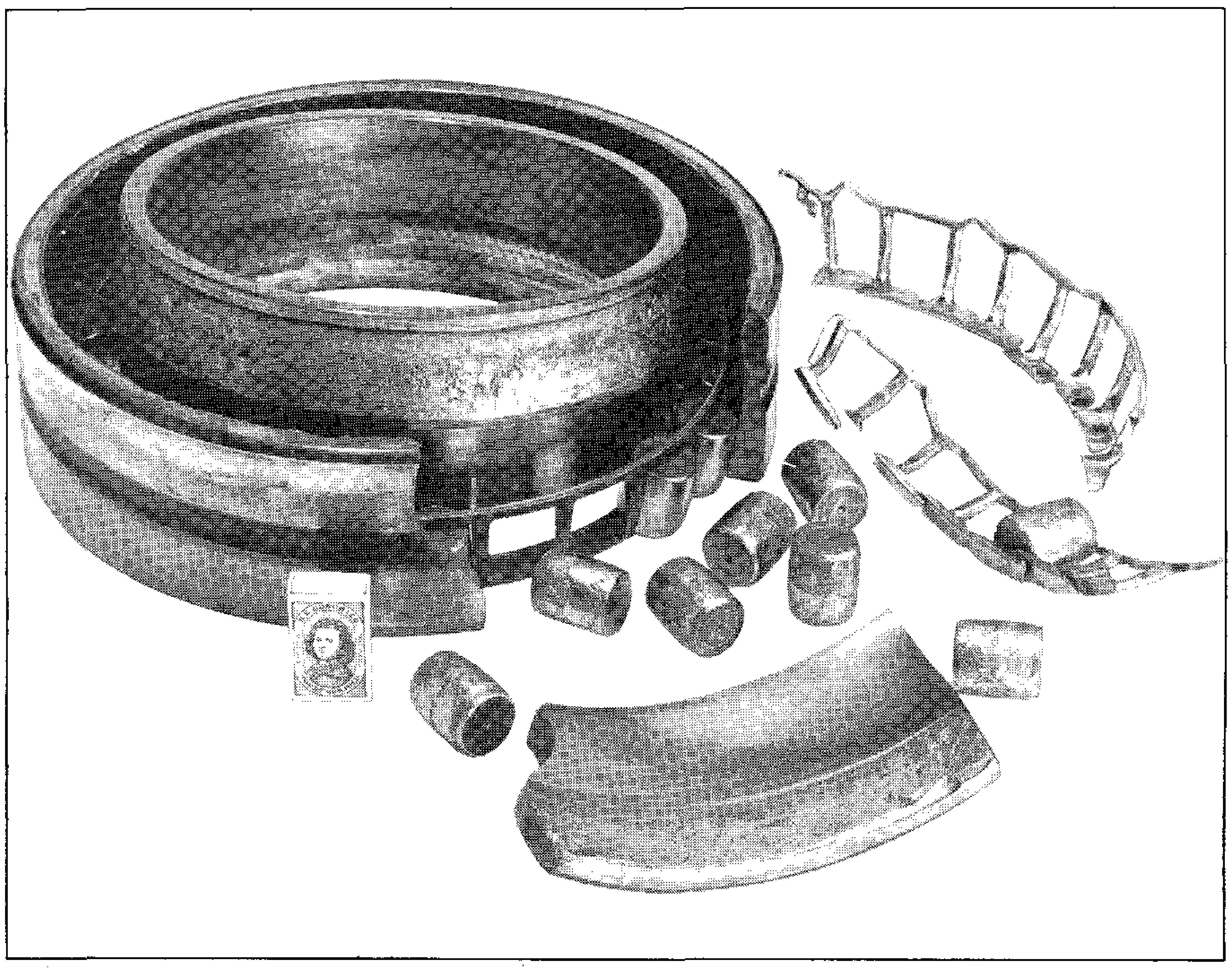

Fig. 3. Unexpected breakdown of a rolling-element bearing, such as the one shown above, can be an expensive surprise. Regular monitoring of the vibration signature from the bearing could have prevented it occurring

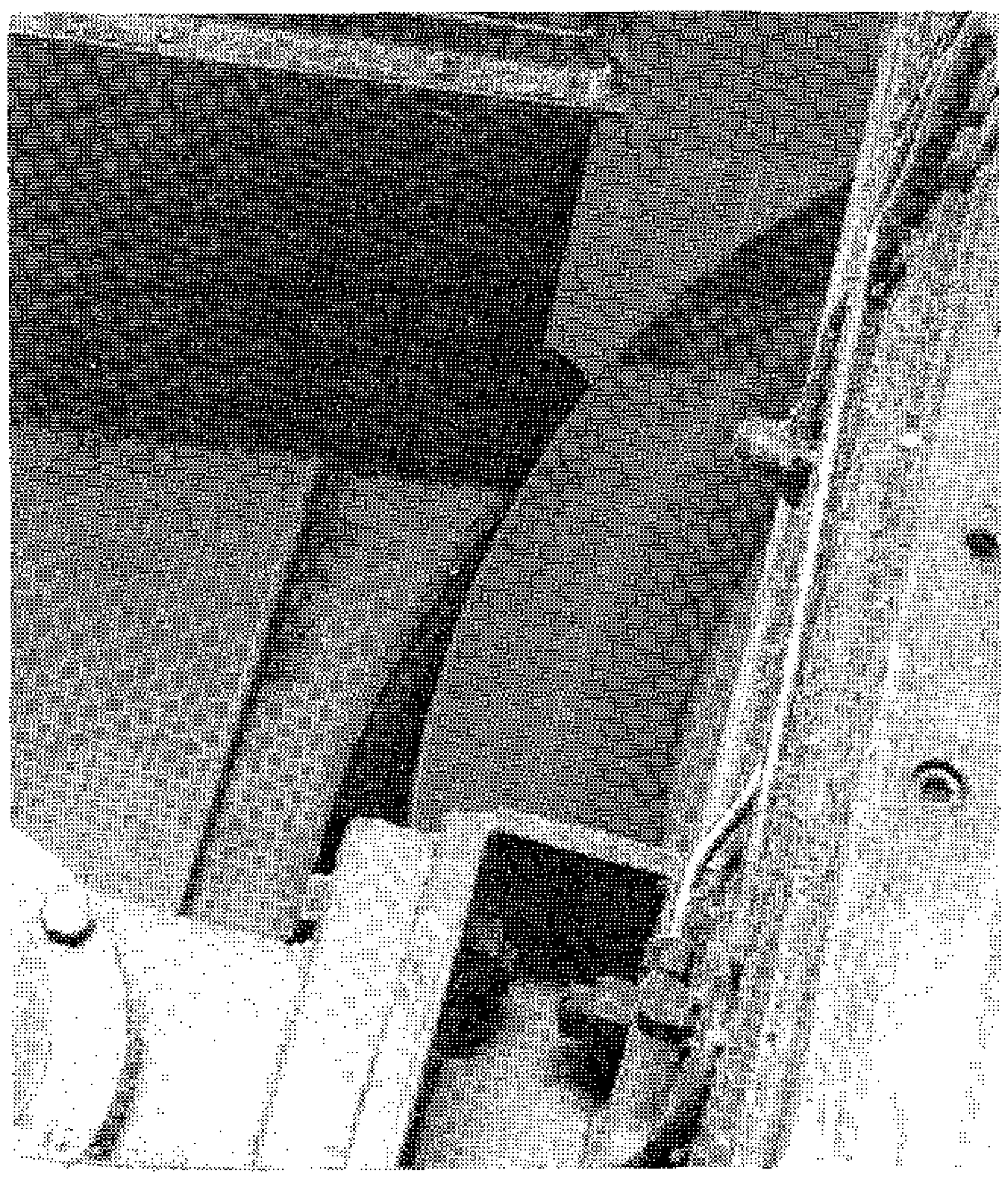

Fig. 4. A Brüel & Kjær accelerometer mounted on the bearing housing of one of the paper-machine's drying cylinders

Installing the System

The system was installed in the summer of 1985. The accelerometer mounting and routing of cables was done by Hamburger AG maintenance staff during regular maintenance shutdowns to minimize disturbance of production. When this work was finished, Brüel & Kjær service engineers completed the installation in 40 hours. During the entire installation period, production was not affected, and the system became fully operational in the Autumn 1985. Fig. 5 shows the layout of the monitoring system.

Does it Work?

Since the system was installed, *there has been no unscheduled production stops due to bearing failure on the monitored section of the machine at Hamburger AG.* Naturally, there have still been bearing failures. Three faulty bearings have been detected by the system since its installation, and dealt with at scheduled maintenance stops.

Is it used?

Presently, Hamburger AG operate a policy of shutting down production only when the Brüel & Kjær system indicates a serious bearing fault. They use a very simple chart, shown in Fig. 6, to calculate the bearing frequencies, and on cross-checking these calculated frequencies with the detected repetition frequencies, they can make a judgement on the seriousness of the bearing fault.

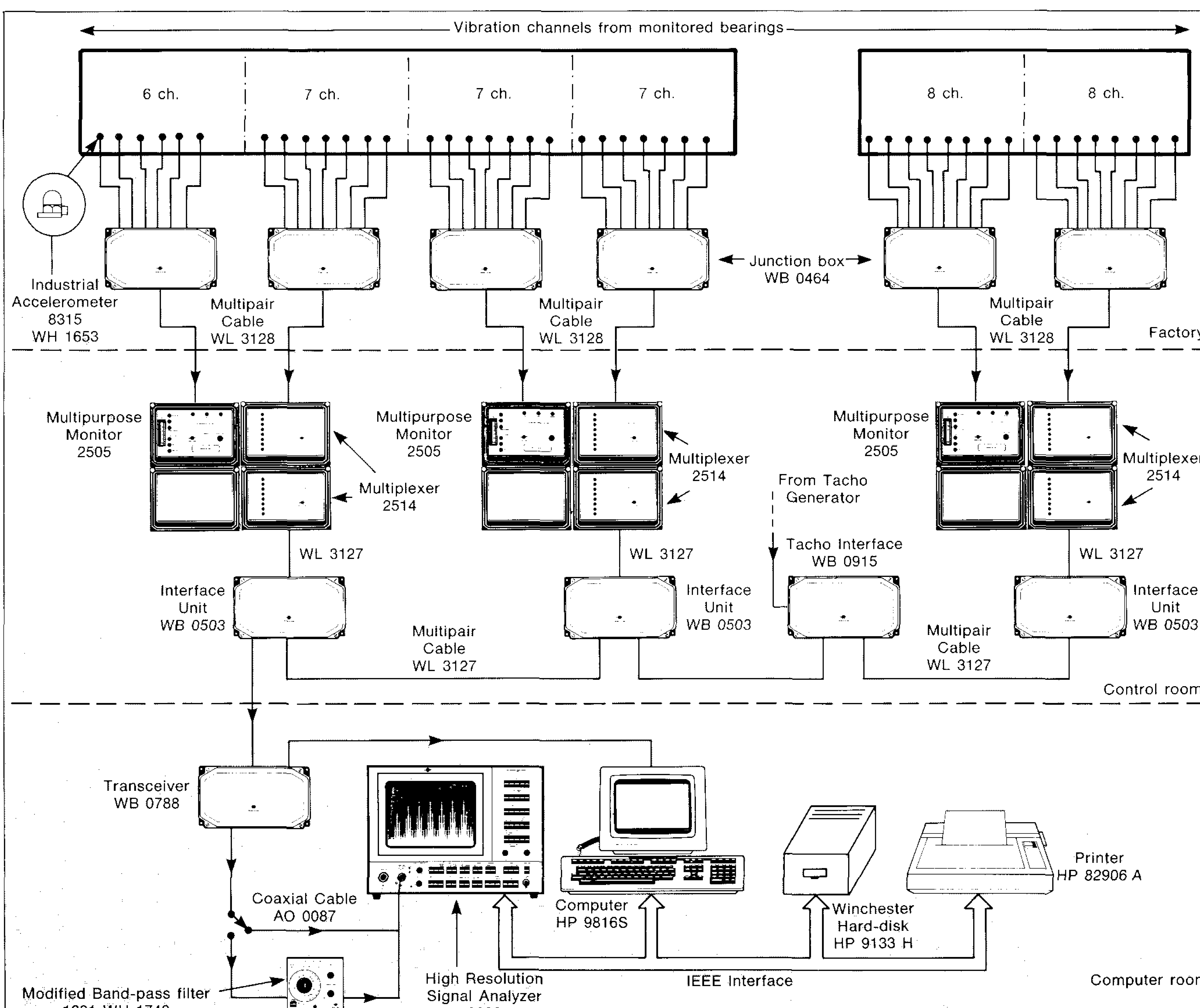

Fig. 5. The monitoring system in use at Hamburger AG

The Machine-Monitoring System

The monitoring system installed at Hamburger AG is based on the WT 9118 software package. The package is designed for fully-automatic, multi-channel, machine-condition-monitoring. The software runs on a HP 200 series desktop computer, using a Winchester hard disk for data storage. The data used by the package, vibration signals from the 43 critical bearings, is obtained from a permanently installed broadband monitoring system, operating in parallel with the software. The package analyzes the vibration data via a Type 2033 High Resolution Signal Analyzer.*

Broadband System

The broadband system cyclically scans the overall vibration levels of each of the critical bearings, providing them with the security of permanent monitoring. The broadband monitors quickly step through each channel (each channel in the system is connected to an accelerometer mounted on one of the critical bearings) comparing the overall vibration level of the channel against preset limits. Any increase in vibration above these limits will trigger relays to activate alarms, allowing the operator to shut the paper-machine down before the fault becomes critical.

Automatic Spectrum Comparison System

The WT 9118 software package works in parallel with the broadband system. For each channel, it produces a frequency spectrum of the machines vibration levels for comparison with a similar spectrum taken when the machine was in a known "healthy" condition. As soon as a fault begins to develop, the shape of the frequency spectrum changes and this change will be detected by the spectrum comparison. The spectra are created by transforming the vibration signals into their frequency components, compounding the components into percentage bandwidths, and displaying the result on logarithmically scaled axes.

The "first" spectrum recorded for each bearing is stored as the "Reference Spectrum". The reference spectrum is then used to create the "Reference Mask". The mask is made by widening the bands of the reference spectrum (to allow for small speed fluctuations) and adding tolerances to the result.

The monitoring software steps contiguously through each channel and generates a new "Comparison Spectrum" which is compared with a mask of the corresponding reference spectrum. "Exceedances" over the mask by the comparison spectrum are noted by the on-line printer and the "Exceedance Spectrum" and measurement parameters are stored. See Fig. 7.

Speed Ranges and Speed Compensation

A paper-machine is run at different fixed speeds to produce different grades and/or thicknesses of paper. A bearing monitored at one speed will generate a dissimilar vibration spectrum when run at a different speed. The comparison of two such spectra may lead to spurious results. To avoid this, recorded spectra are classified into 6 speed ranges, bounded by fixed speed limits. Each speed range has an independant reference spectrum against which all comparison spectra, falling within that speed range, are compared. Since speed ranges are bounded by upper and lower limits, smaller speed differences will also occur within a speed range. WT 9118 compensates for these random changes in speed by normalizing all spectra to a fixed speed within a given range. The normalizing process involves shifting spectra within a speed range so that all speed-related components are concurrent.

Trend Analysis

The development of a particular exceedance over time can be manually investigated using a trend analysis plot. The plot returns a prediction of the time remaining before a pre-defined "danger" exceedance level is reached. The prediction is based on a trend curve of past exceedances by a frequency band over the reference mask. The correlation factor for the "fit" is also displayed. It is a measure of the accuracy of the curve-fit, the closer its value is to 1, the more reliable the prediction. Any points on the graph can be excluded from the curve and a new curve obtained. This allows a more accurate prediction to be obtained if the rate at which the machine is deteriorating changes significantly.

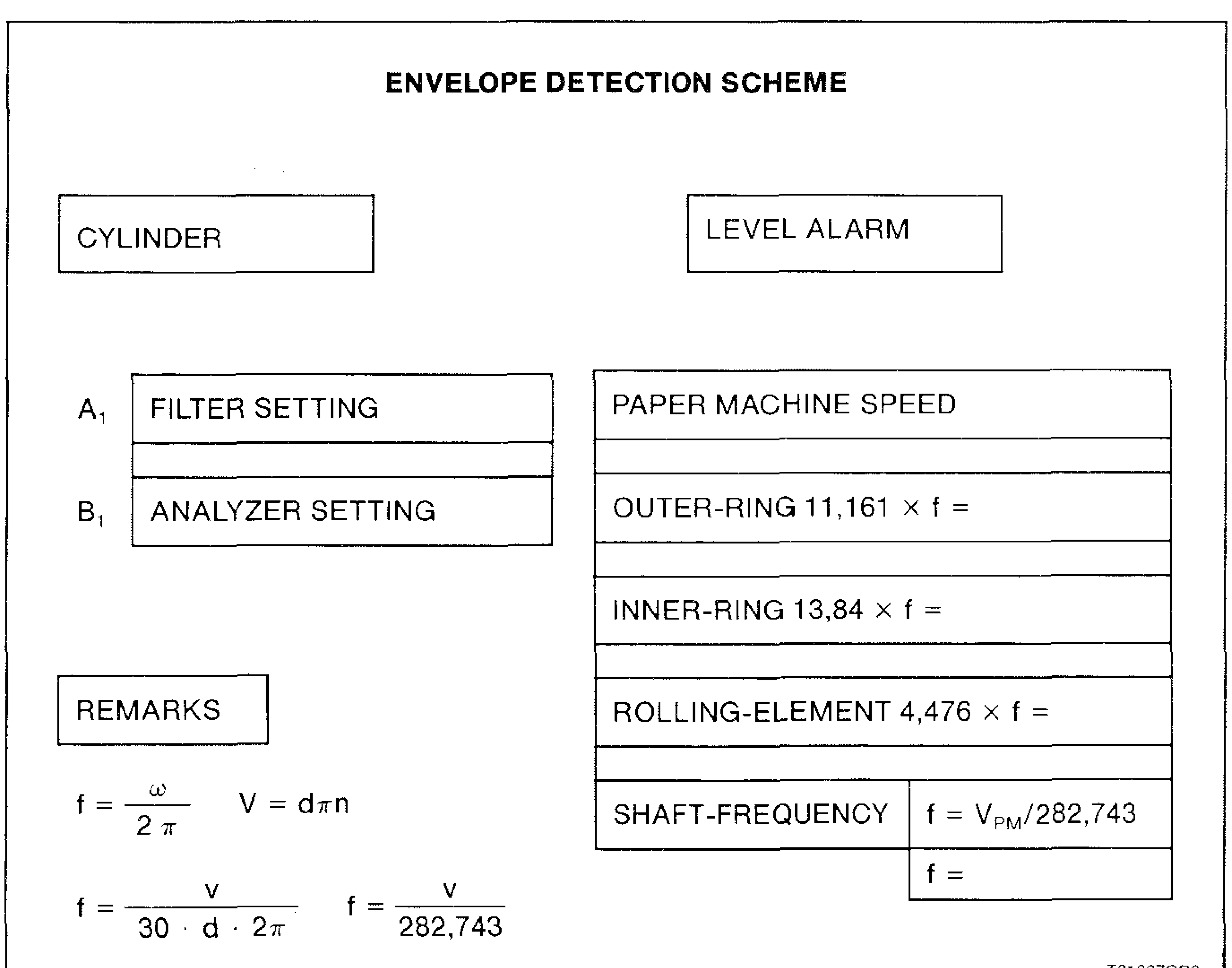

Fig. 6. The chart used by Hamburger AG for calculating bearing resonance frequencies. The multiplication factors are derived from the relevant equations given in the text. The speed of the paper-machine, in meters per minute, is converted into Hz before it is inserted in the formulae

* For full details of the monitoring system, ask your local Brüel & Kjær representative for publication number BU 0085.

Envelope Analysis

Local faults in rolling-element bearings produce a series of impacts which repeat periodically at rates dependant on bearing geometry. The different repetition rates are characteristic of faults in different components within the bearing. These repetition rates or bearing frequencies are: ball-passing frequency outer-race (BPFO), indicative of a fault in the outer-race; ball-passing frequency inner-race (BPFI), indicative of a fault in the inner race; ball-spin frequency (BSF), indicative of a fault on the rolling-element; fundamental train frequency (FTF), indicative of a fault in the bearing cage. These frequencies are calculated as follows:

$$BPFO = n \times \frac{f}{2} [1 - \frac{d}{D} \cos \phi]$$

$$BPFI = n \times \frac{f}{2} [1 + \frac{d}{D} \cos \phi]$$

$$BSF = D \times \frac{f}{2d} [1 - (\frac{d}{D} \cos \phi)^2]$$

$$FTF = \frac{f}{2} [1 - \frac{d}{D} \cos \phi]$$

where: n = number of balls or rollers
f = shaft speed (i.e. relative speed of outer to inner race)
d = diameter of balls or rollers
D = pitch diameter of balls or rollers
ϕ = contact angle from the radial direction

In a frequency spectrum, the first detectable signs of bearing deterioration is a general increase in the vibration level in the 2 kHz to 20 kHz region. This is because each time a ball passes a fault, the resulting impact will excite structural resonances which appear in this part of the spectrum. These impacts cause a modulation of the time signal, the frequency of the modulation being directly related to the fault causing it. The modulation frequency creates an envelope around the time signal which is detected by the envelope detector.

To detect the envelope, you must first find the region of general increase in vibration level, as described above. The envelope detector's band-pass filter is then tuned to the centre-frequency of the region of maximum increase. The detector smoothes and rectifies the time-signal before transferring the altered signal to the analyzer. The signal displayed by the analyzer contains the fundemental and harmonics of all frequencies related to the bearing fault. These frequency components can then be cross-checked with the calculated bearing frequencies to ascertain the type of bearing fault.

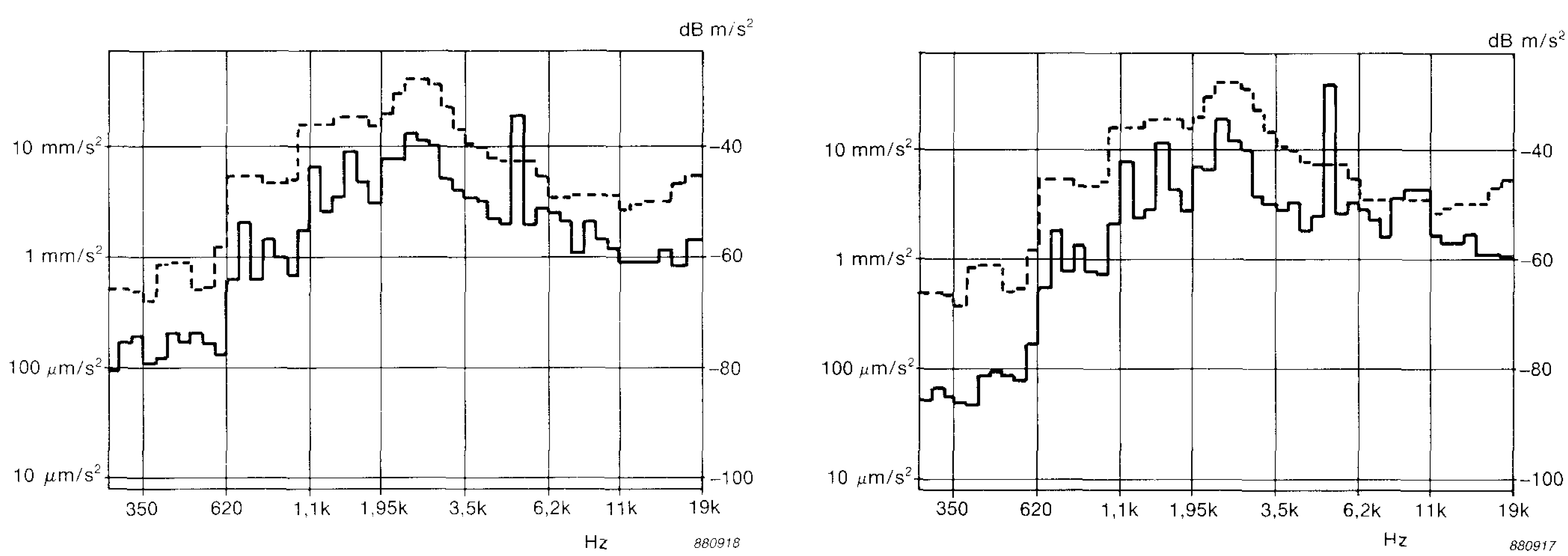

Fig. 7. Two Exceedance spectra generated by bearing TS 20. The general vibration-level increase is in the high-frequency region to the right of the peak which exceeds the mask (dotted line). The spectrum to the right was recorded 1 week after the spectrum to the left

Case Study

The following case study is of a fault detected and repaired in December 1986. The fault was on the inner-race of bearing TS 20. The method used in detecting this fault was identical to the method employed in detecting the other two faults which have occurred since the system was installed.

The first indications of a problem with bearing TS 20 were exceedance warnings given by the on-line printer, which were in the 2 kHz to 20 kHz range. Fig. 7 shows two separate exceedance spectra which were generated during this period. When the exceedance level reached 10 dB, the engineer in charge of maintenance decided to perform an envelope analysis. The bearing frequencies were calculated using the method outlined above.

For the type of bearing used in this section of the paper-machine the relevant figures are:

$n = 25$, $d = 36$ mm,
$D = 326$ mm, $\phi = 15°$,
$f = 1{,}35$ Hz, this gives:

BPFO = 15,1 Hz, BPFI = 18,7 Hz,

BSF = 6,0 Hz, FTF = 0,6 Hz.

As can be seen from the plot of the envelope spectrum in Fig. 8, the fault was identified as a flaw in the bearing's inner-race. A trend-analysis was then performed to give an estimate of the remaining life of the bearing, it is shown in Fig. 9. With this information at their disposal, Hamburger AG scheduled the bearing for replacement in December 1986 at one of their regular maintenance shutdowns. When the bearing was dismantled, the maintenance team verified that it did have an inner-race fault.

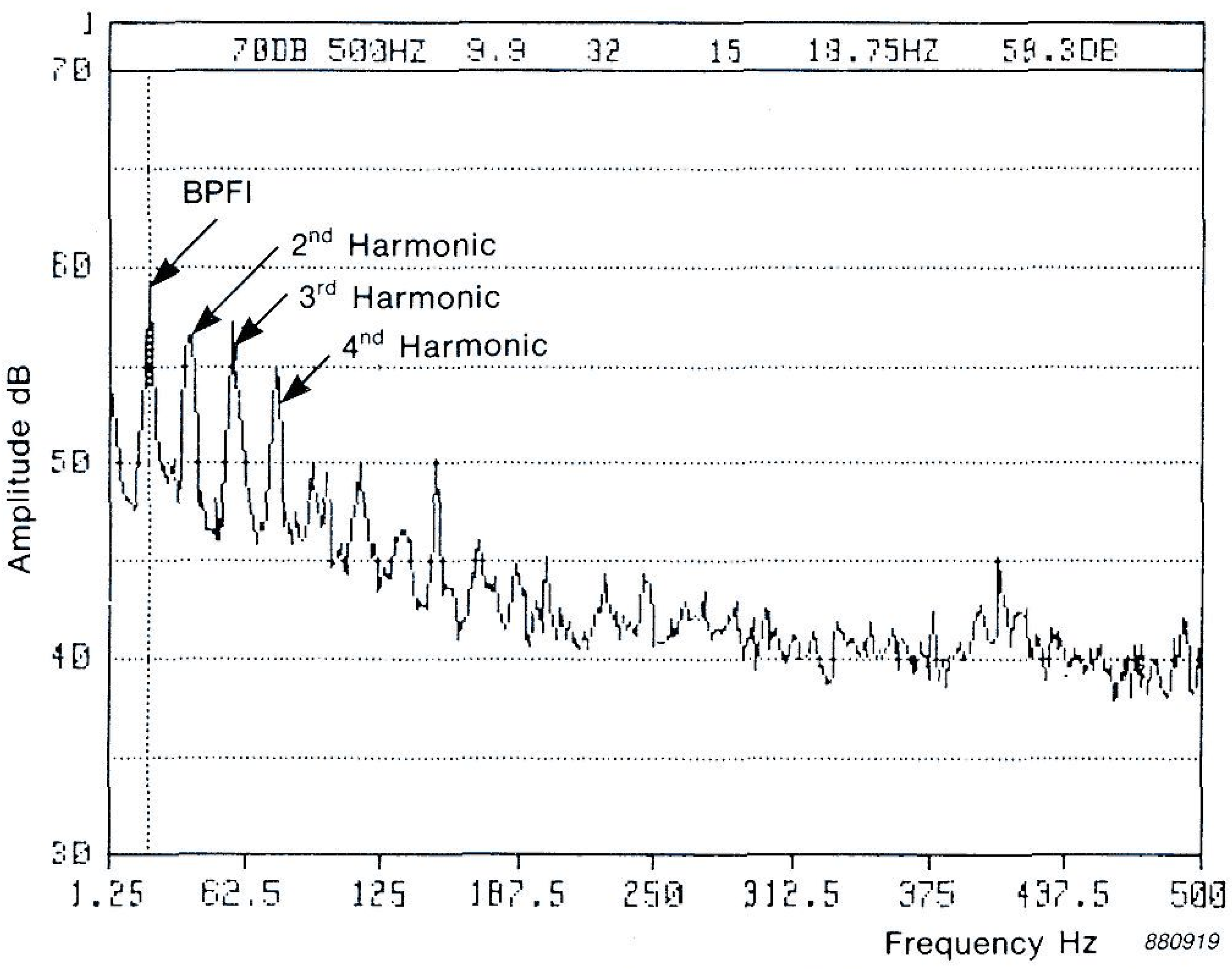

Fig. 8. The envelope spectrum for bearing TS 20. The cursor (dotted line) is positioned at the peak (18,75 Hz), where the inner-race fault is readily identifiable

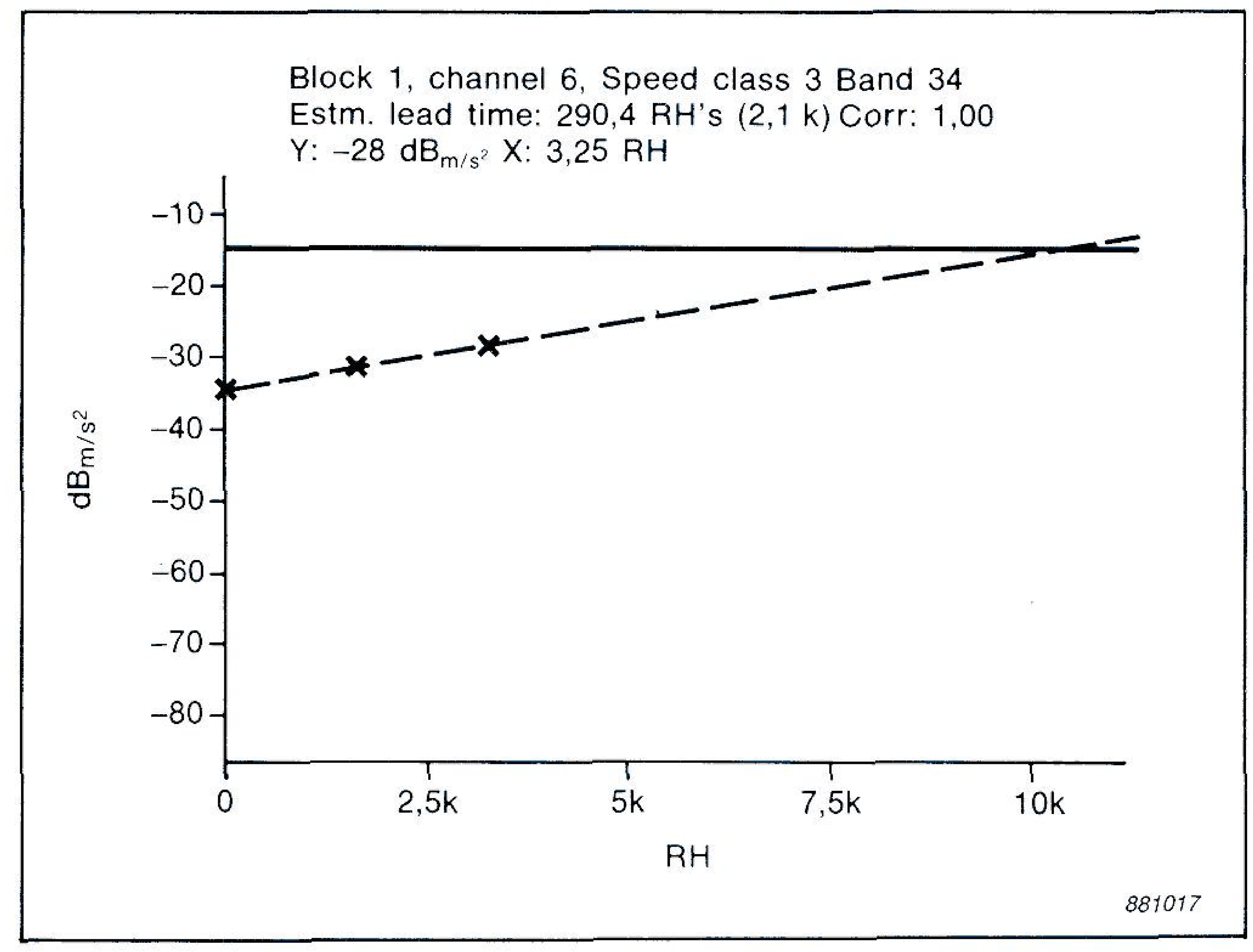

Fig. 9. A trend analysis plot performed on the exceedance spectra from bearing TS 20. The estimated time before breakdown is given as 290,4 running hours

Predictive Maintenance - A Worthwhile Investment?

When investing in a monitoring system, numerous methods of assessing the viability and economic benefits of the investment can be used. One method is the "payback period" which gives the investor information on whether he can expect his initial investment in the system to pay for itself within the period of time he expects the system to be in service. The investment will only prove worthwhile if the payback period is shorter than the expected lifetime of the system.

The payback period (t_p) can be calculated using the formula given below. It takes into account the rate of return which the investor expects from his investments.

$$t_p = \frac{\log a - \log(a - i \cdot G)}{\log(1 + i)}$$

Hamburger AG invested 2 mil. ATS (approx. 170 000 USD) in equipment for the monitoring system. Including their installation costs (in this case 5% of the total), the initial investment of capital was 2,1 mil. ATS. A single bearing fault on this section of the paper-machine takes about 30 hours to repair, if it fails suddenly. Each hour of machine down-time costs Hamburger AG 35 000 ATS (approx. 3 000 USD) in lost production. In the two-year period since the system was installed, it has detected 3 bearing faults before they became critical. The savings in terms of increased production are therefore 3,15 mil. ATS (approx. 263 000 USD). This yields a saving of 1,575 mil. ATS (approx. 130 000 USD) per year. This gives :

a the annual expected savings as 1,575 mil. ATS

i the interest rate demanded, say 14% = 0,14

G the initial investment as 2,1 mil. ATS

Inserting these figures in the above formula gives a payback period of 1,57 years for the Brüel & Kjær system at Hamburger AG. This means that the system has already payed for itself. Assuming a minimum expected lifetime for the system of 5 years, it has proved a very "safe" investment.

The relative benefits to Hamburger AG from investing in the system (as compared to not investing) can be assessed directly by calculating the *difference* between the present values of the two alternatives (investing as against not investing). If A stands for investing in the system and B stands for not investing, then A is a better alternative than B if the present value of A is greater than the present value of B ($PV_{A-B} > 0$).

PV_{A-B} can be calculated as:

$$(G_A - G_B) + (a_A - a_B)\,\frac{(1+i)^n - 1}{(1+i)^n \cdot i}$$

Using the investment, savings, expected life time (n), and interest rate from the Hamburger AG figures:

$$(-2.1 - 0) + (1{,}57 - 0)\,\frac{(1 + 0{,}14)^5 - 1}{(1 + 0{,}14)^5 \cdot 0{,}14}$$

This gives a PV_{A-B} of 3,298 mil. ATS which means that the investment has proved very worthwhile – with a present value which is 3,3 mil. ATS (approx. 280 000 USD) greater than would have been the case if they had not invested.

The authors would like to thank the plant manager at Hamburger AG, Herr Ing. Grill for allowing us to visit and report on the plant. We would also like to extend a special thank you to Herr Schrammel, maintenance manager at the plant, for his invaluable help.

Brüel & Kjær

WORLD HEADQUARTERS: DK-2850 Nærum · Denmark · Telephone: +45 2 80 05 00 · Telex: 37316 bruka dk · Fax: +45 2 80 14 05

Australia (02) 450-2066 · Austria 02235/7550*0 · Belgium 02 · 242-97 45 · Brazil 246 8149 · Canada (514) 695-8225 · Finland (90) 80 17 044 · France (1) 64 57 20 10
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