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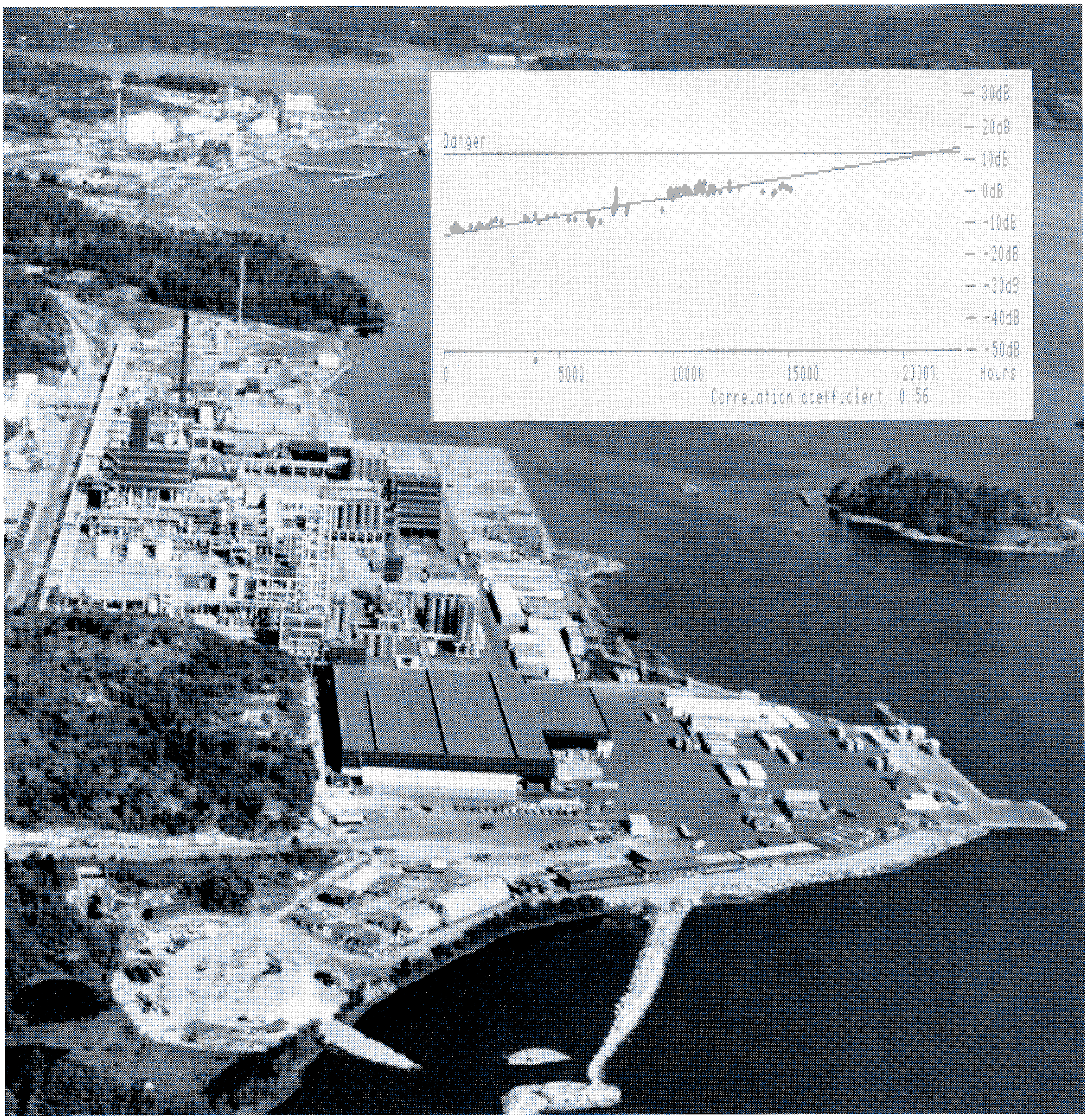
Machine-Condition Monitoring Using Vibration Analysis

A Case Study from a Petrochemical Plant



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Machine-Condition Monitoring using Vibration Analysis

A Case Study from a Petrochemical Plant

by *D.N.Brown & J.C.Jørgensen*
Brüel & Kjær

Introduction

This Application Note describes in detail the computer-based vibration monitoring system installed at a petrochemical plant at Bamble, Norway. The plant, which is operated by Statoil the Norwegian state-owned oil company, produces Polypropylene and Low- and High-Density Polyethylene at a rate of 300000 tons a year.

At plant conception, a decision was made to employ vibration measurements for condition monitoring of the plant's critical rotating machinery. Initially, the measurement program consisted of taking broadband measurements of vibration level and employing vibration analysis as a diagnostics tool. After this successful introduction to vibration monitoring, a periodic vibration analysis system was set up, using an FFT analyzer and tape recorder. This system was finally upgraded to a computer based system, employing both on-line permanent monitoring and off-line periodic monitoring. The on-line system continuously monitors both broad and narrowband vibration levels from critical production units. The off-line system, which covers a number of other important machines, is based on tape recorded measurements taken at 1 to 4 month intervals.

Experience with the monitoring system has shown that, although the periodic measurement programme enabled a number of potential failures to be discovered well in advance of breakdown, continuous monitoring was necessary to detect sudden developments that could lead to breakdown in a relatively short period of time. The system also allowed an accurate diagnosis of faults to be made at a very early stage in their development. The successful identification of a number of potential failures are documented here.

Since installation, the number of unexpected breakdowns on permanently monitored machines has been greatly reduced, and the savings gained from this computer-based system (savings associated with lost production, maintenance costs etc.) enabled a pay-back on investment within 18 months of installation.

The cover photograph, with the Statoil petrochemical plant at Bamble Norway shown in the foreground, has been reproduced with the kind permission of Statoil, who are operators of the plant. The authors are also grateful for the assistance of Superintendent Mechanical Dept. Olaf Andersen and Senior Inspection Engineer Tor Inge Nomme who are responsible for the vibration monitoring programme at Statoil Bamble.

The Monitoring System

The Monitoring System, shown schematically in Fig. 1, can be considered as made up of a number of sections: the vibration pickup section; the monitoring section that continuously monitors vibration levels both broadband and narrowband; and the data

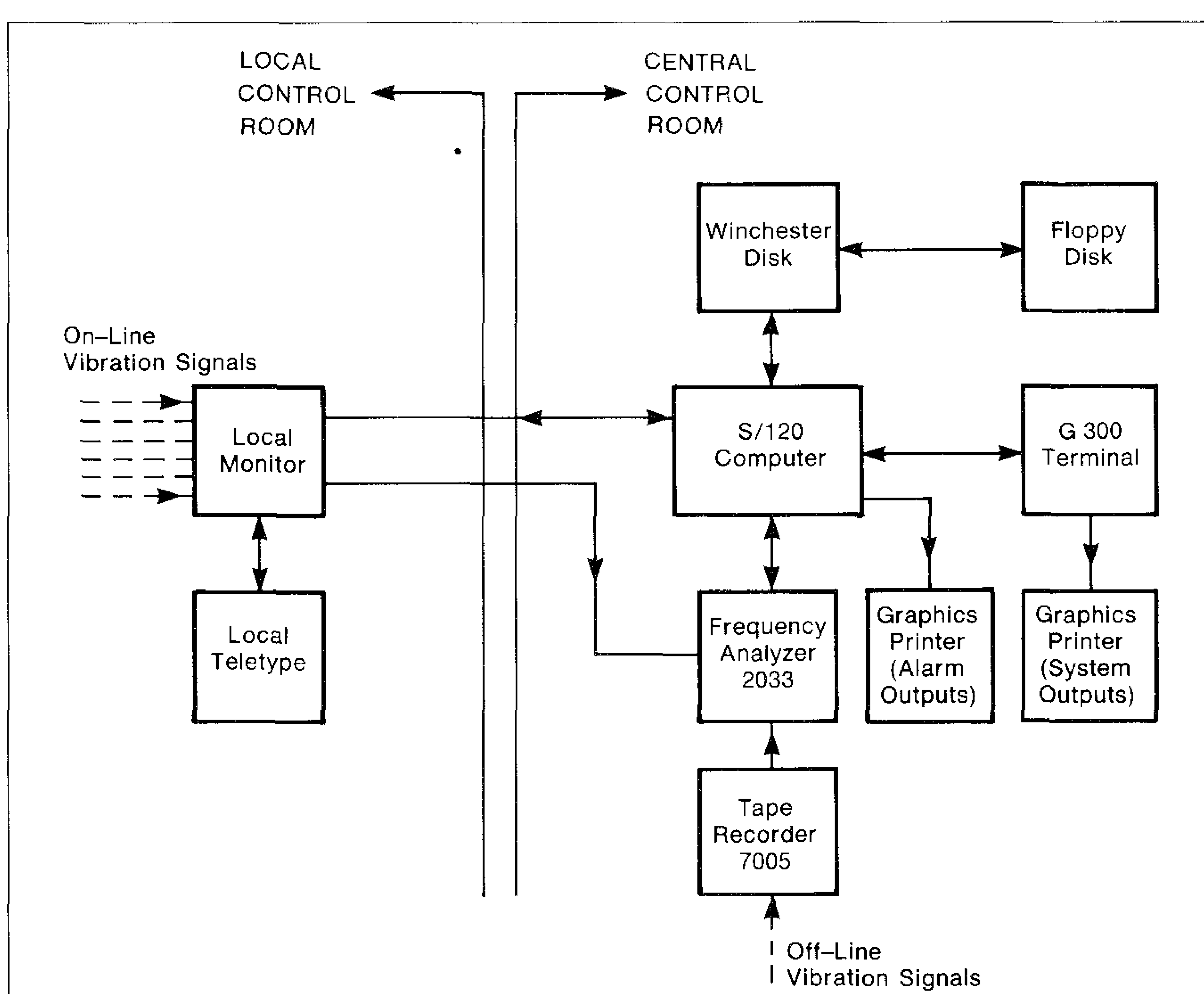


Fig. 1. Layout of the permanent monitoring system developed for the Statoil Bamble plant

section that is used for data storage and management of the machine condition data. Off-line data can be entered into the system from a tape recorder for periodic monitoring.

The system was developed by the Brüel & Kjær System Development Group, specifically for the needs of Statoil. It is not a standard production item.

Vibration Pickup

Vibration pickup is made by accelerometers permanently mounted on the monitored machines. These are highly sensitive, rugged transducers capable of withstanding long periods in "harsh" environments. The accelerometers are certified as intrinsically safe for use in the potentially explosive atmosphere present in the petrochemical plant. Signals from these accelerometers are routed via preamplifiers to a local control room.

Broadband Monitoring

Vibration signals are routed first to a number of Local Monitors, located in the local control room, where the broadband monitoring is carried out. Each monitor has 16 parallel vibration channels and 4 logic inputs. The logic inputs are used to automatically activate and passify vibration channels on machine start up and shut down.

The Local Monitor registers the vibration signals at one second intervals, and compares the RMS, Peak and Spike Energy levels with preset limits. If any of the preset limits are exceeded, a message is sent to the central computer and a warning given on an alarm printer.

In addition to monitoring the signal levels every second, the Local Monitor compiles and stores 1 minute and 24 hour average levels. The 1 minute average is used for a trend alarm, where the percentage increase of the average value is compared with a preset limit, a warning being given in the event of the limit being exceeded. Both the one minute and 24 hour average values can also be called up from the central computer for trend curve displays.

Narrowband Monitoring

For narrowband monitoring, the system's FFT analyzer transforms the time signal into a spectrum of narrowband frequency components. This allows monitoring with a far better resolution than with broadband monitoring.

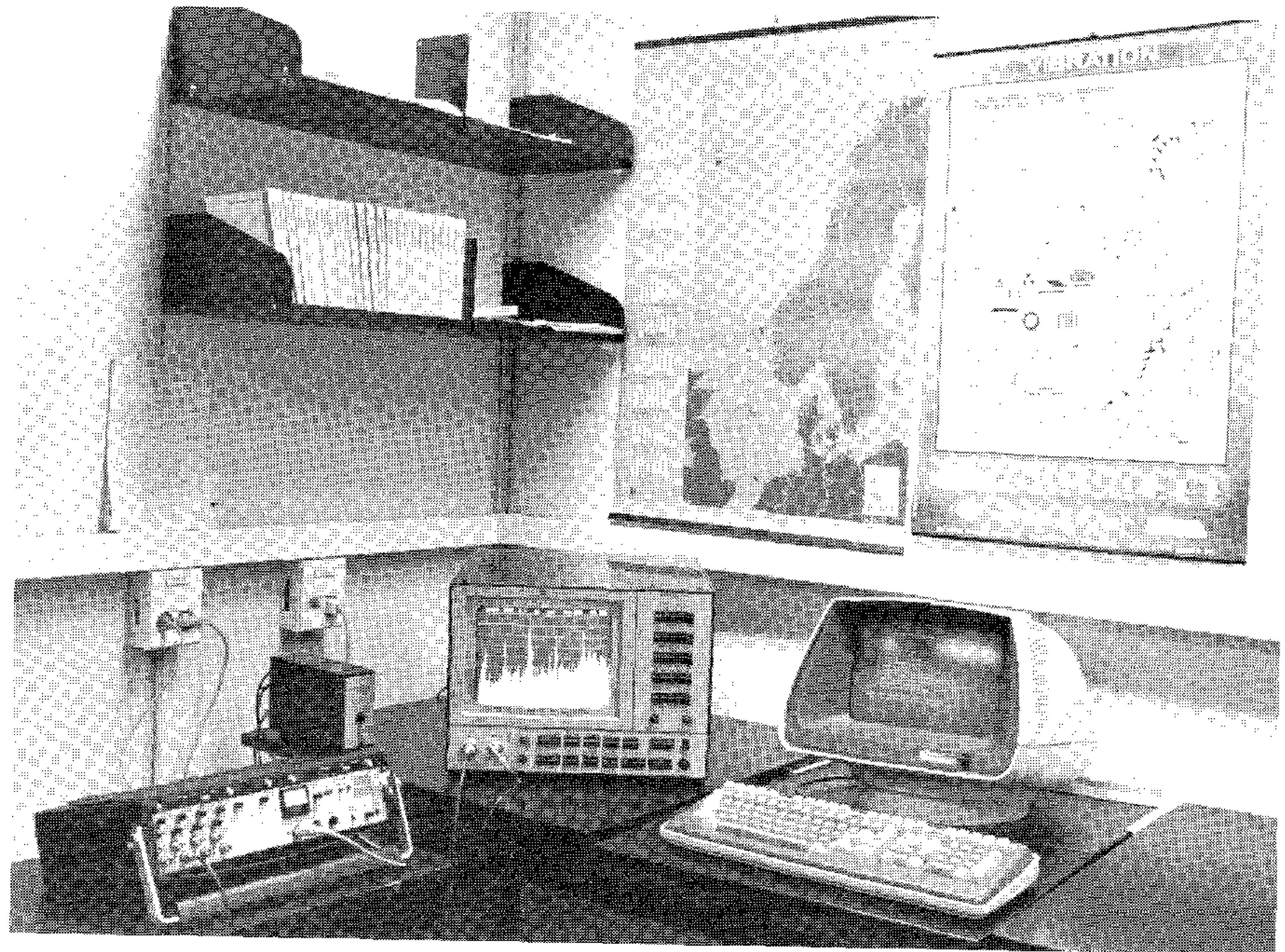


Fig. 2. The computer terminal and FFT Analyzer are placed in the engineer's office next to the central control room. An alarm printer is placed in the actual control room

The central computer directs analogue signals from the Local Monitors to the system's Frequency Analyzer. To obtain a sufficient frequency resolution in the high as well as low frequencies, the system takes a number of narrowband spectra and combines them together to form one constant-percentage-bandwidth spectrum. In such a spectrum the bandwidth is a percentage of the centre frequency, and the same resolution (user chosen between 4% and 23%) is obtained over the whole frequency range.

By recording one of these constant-percentage-bandwidth spectra when the machine is in "good" condition (this is then called the Reference Spectrum) and adding a tolerance, a Reference Mask is formed. Subsequent spectra are then compared to this Reference Mask (a procedure called the Spectrum Comparison), and any frequency components that increase to a level above the Mask will be reported. Fig. 3 illustrates the principle, showing a spectrum compared with its Reference Mask.

Automatic spectrum comparison normally takes place every 3 hours for each monitoring point. However, in the event of an alarm, the analysis speed will automatically be increased to 1/2 hourly intervals for the appropriate channel.

To study the variation of the vibration levels with time, trend analysis can be performed. This can either be carried out at single frequencies or over frequency ranges. The system's large data-base allows a large number of spectra to be stored and used in the trend analysis, thus giving a good overview of the behaviour of the vibration level and allowing predictions of when the levels will become critical. The lead time to a preset danger level is also calculated.

Having located a fault, the engineer in charge can interrupt the system's automatic scan mode and then use the high powered diagnostic functions of the FFT Analyzer to diagnose the cause of the fault.

Off-line Monitoring

Vibration data from the periodic measurement program are recorded on a 4-channel tape recorder for later play-back into the system. Play-back is carried out via the system's FFT Analyzer, and the vibration data is then handled as with the on-line (permanent) system, i.e. by performing spectrum comparison, trend analysis etc.

Measurements are made at 1 to 4 month intervals, depending upon the type of machine.

Data Storage

The central station hardware consists of a 16-bit computer with 512 kbyte of main memory and a 15 Mbyte hard disk.

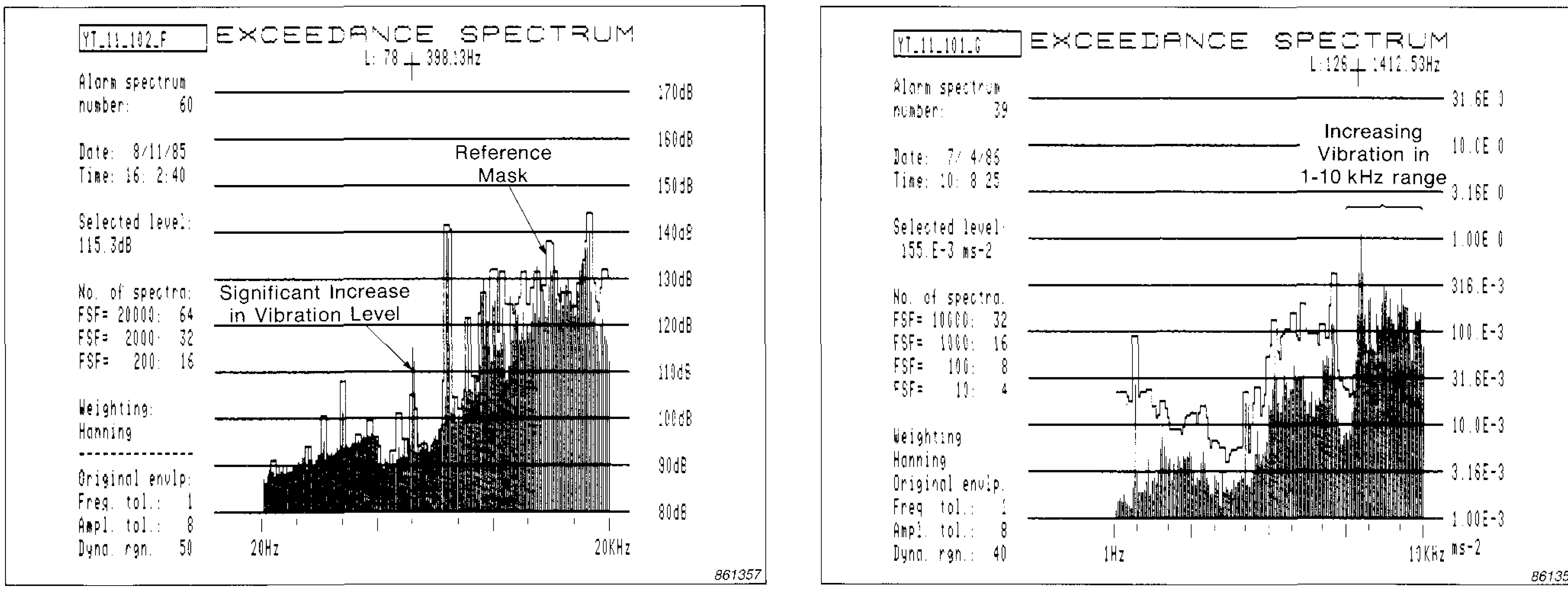


Fig. 3. Principle of spectrum comparison. Any frequency components that exceed the Reference Mask will cause an alarm. The spectrum to the left shows increases at discrete frequencies, whilst the spectrum to the right shows increases in a broad band of frequencies

Case 1 – Agitator

One particularly critical machine is the agitator in the main reactor of one the plants. Due to its importance to production, the agitator was chosen as one of the units to be monitored continuously. A sketch of the agitator is shown in Fig. 4.

In the past, breakdowns have occurred with considerable costs as a consequence (lost production, damage of machine parts etc.). Since the introduction of permanent vibration monitoring, however, no unexpected breakdowns have occurred. Also, in a number of cases, minor damage has been prevented from developing, possibly into potentially serious failure, as early vibration alarms have allowed appropriate action to be taken in good time.

Example 1

Shortly after installation of the permanent monitoring system, a Spike Energy alarm was registered from the transducer mounted on the seal/roller bearing assembly at the top of the mixing shaft. This bearing was not normally changed when overhauling the seal.

Fig. 5 shows the RMS and Peak trends, which give steady readings (the x-axis scale refers to the number of weeks before the trend curve was drawn). Fig. 6 shows the long term Spike Energy trend from this transducer. This can be seen to increase at the time when the fault was discovered (between approximately –16 and –14 weeks on the trend time-axis).

By listening to the channel, a "ticking" sound could be heard once per revolution. The automatic spectrum comparison showed an increase at approximately 17 Hz. By calculating the relevant bearing frequencies, this

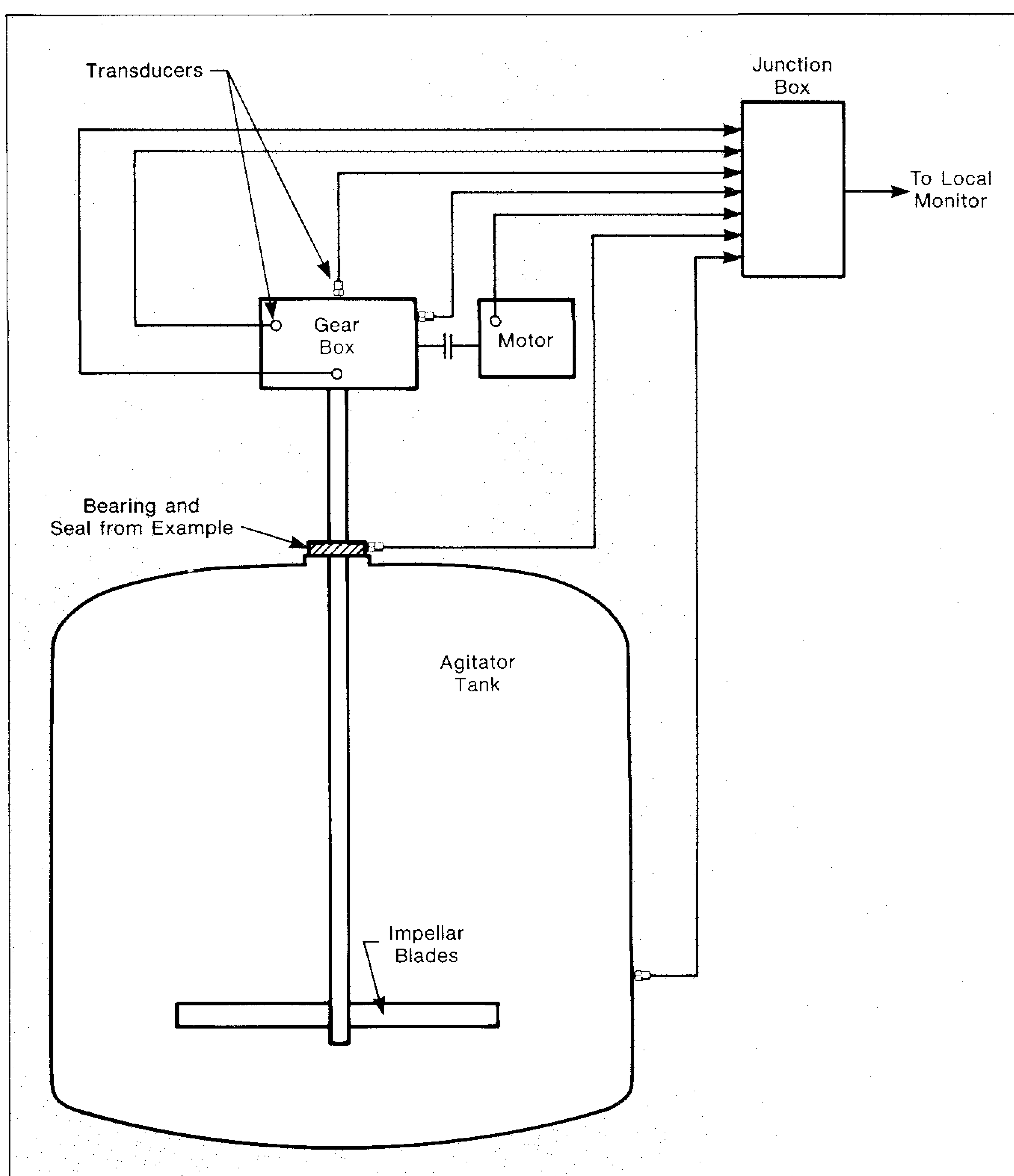
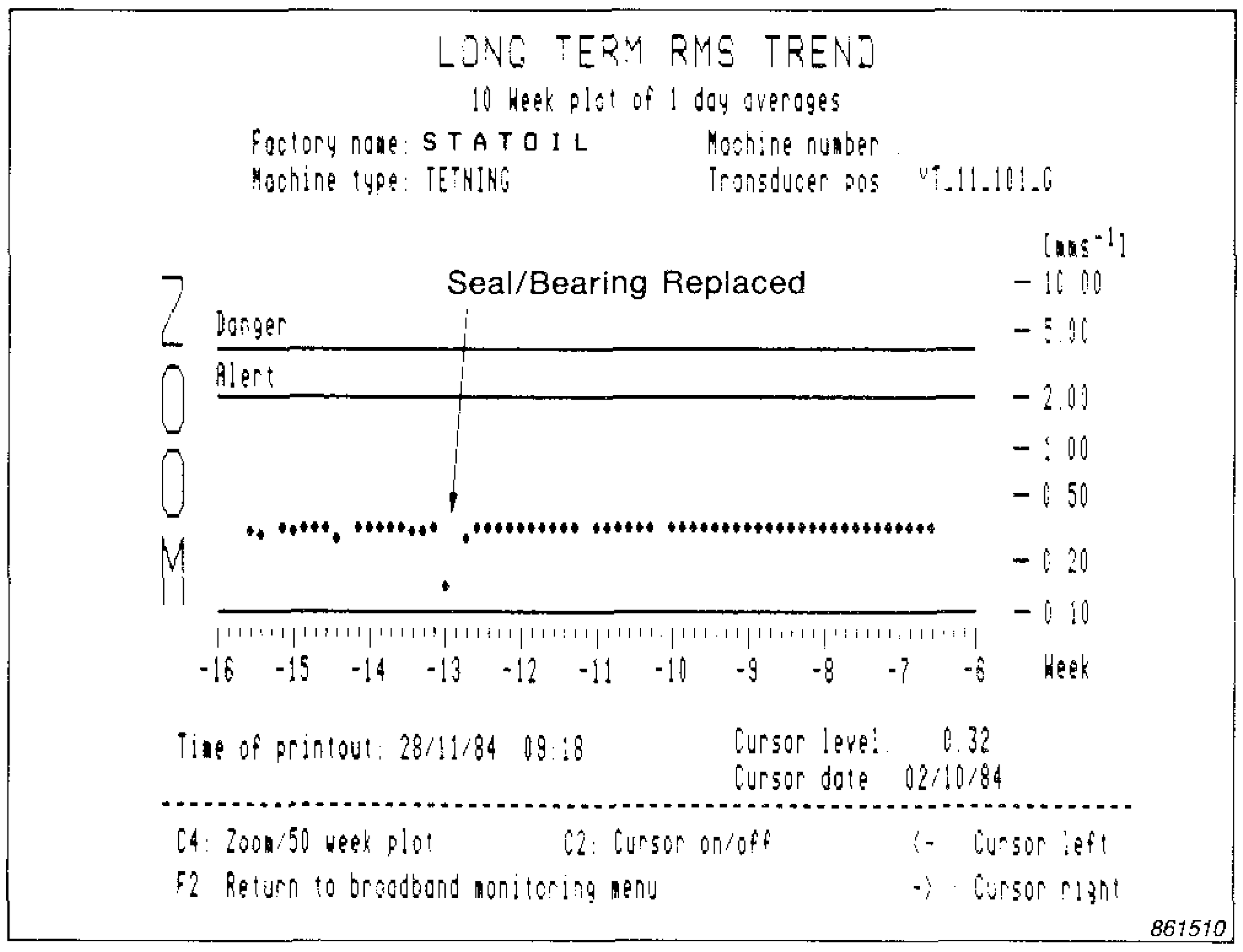


Fig. 4. Schematic layout of the agitator showing the position of the transducers



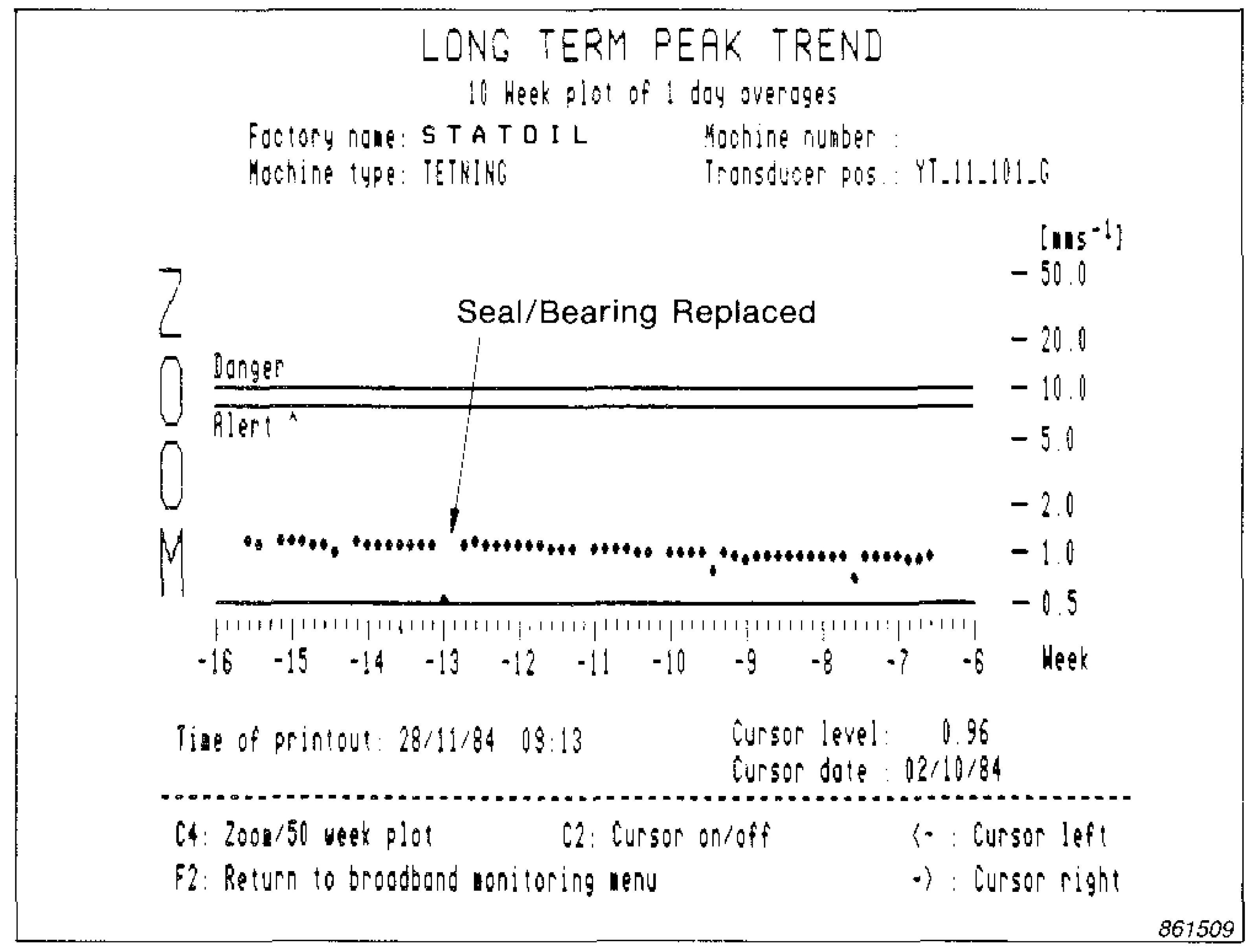


Fig. 5. RMS and Peak trends from the agitator showing no change. The low readings between weeks –13 and –12 were due to the production stop when changing the seal/bearing assembly (the –xx weeks refers to the number of weeks before the trend curve was printed out)

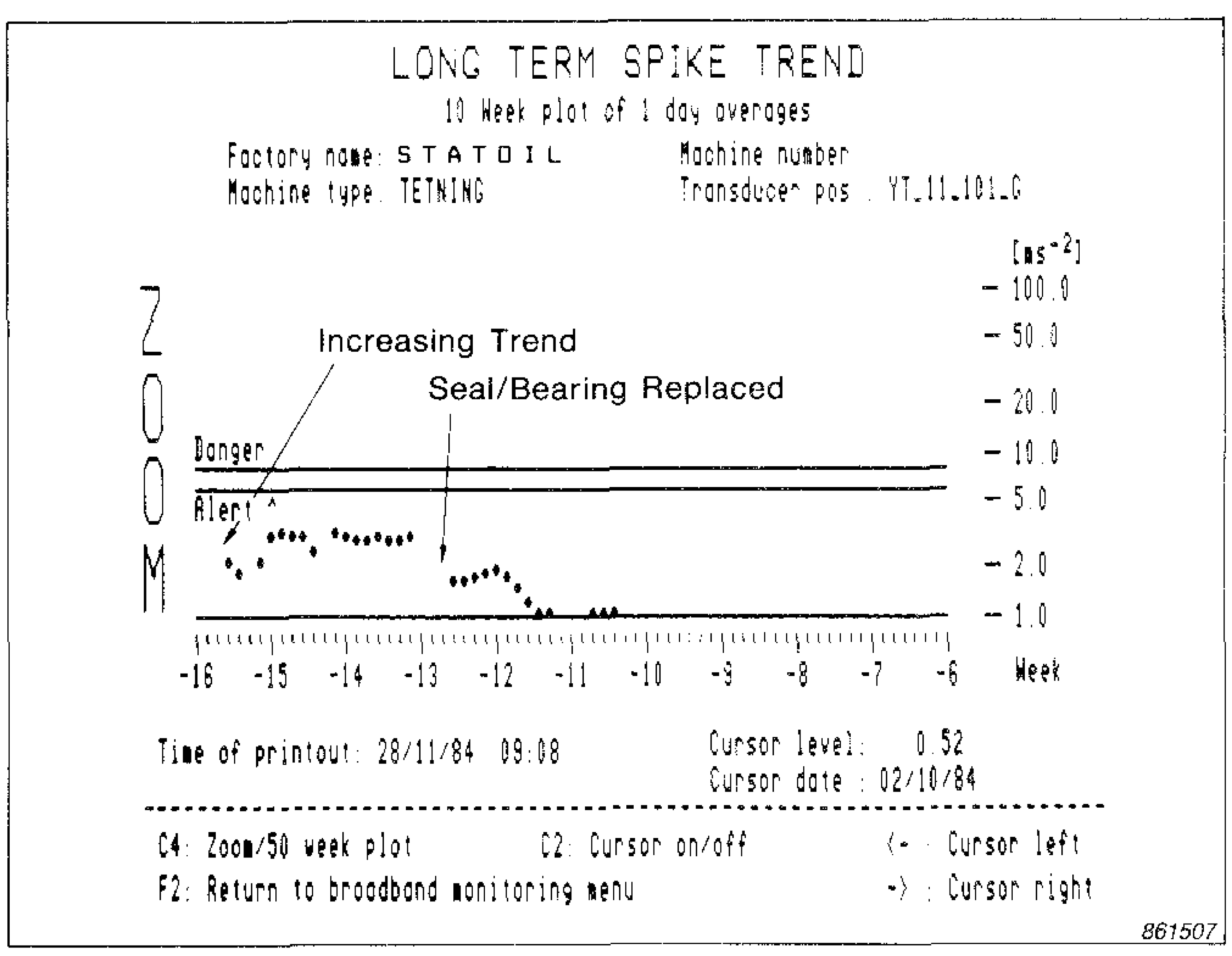


Fig. 6. Spike Energy trend from the agitator. This shows an increasing trend between weeks –16 and –15, and a drop after the seal/bearing assembly was changed in week –12

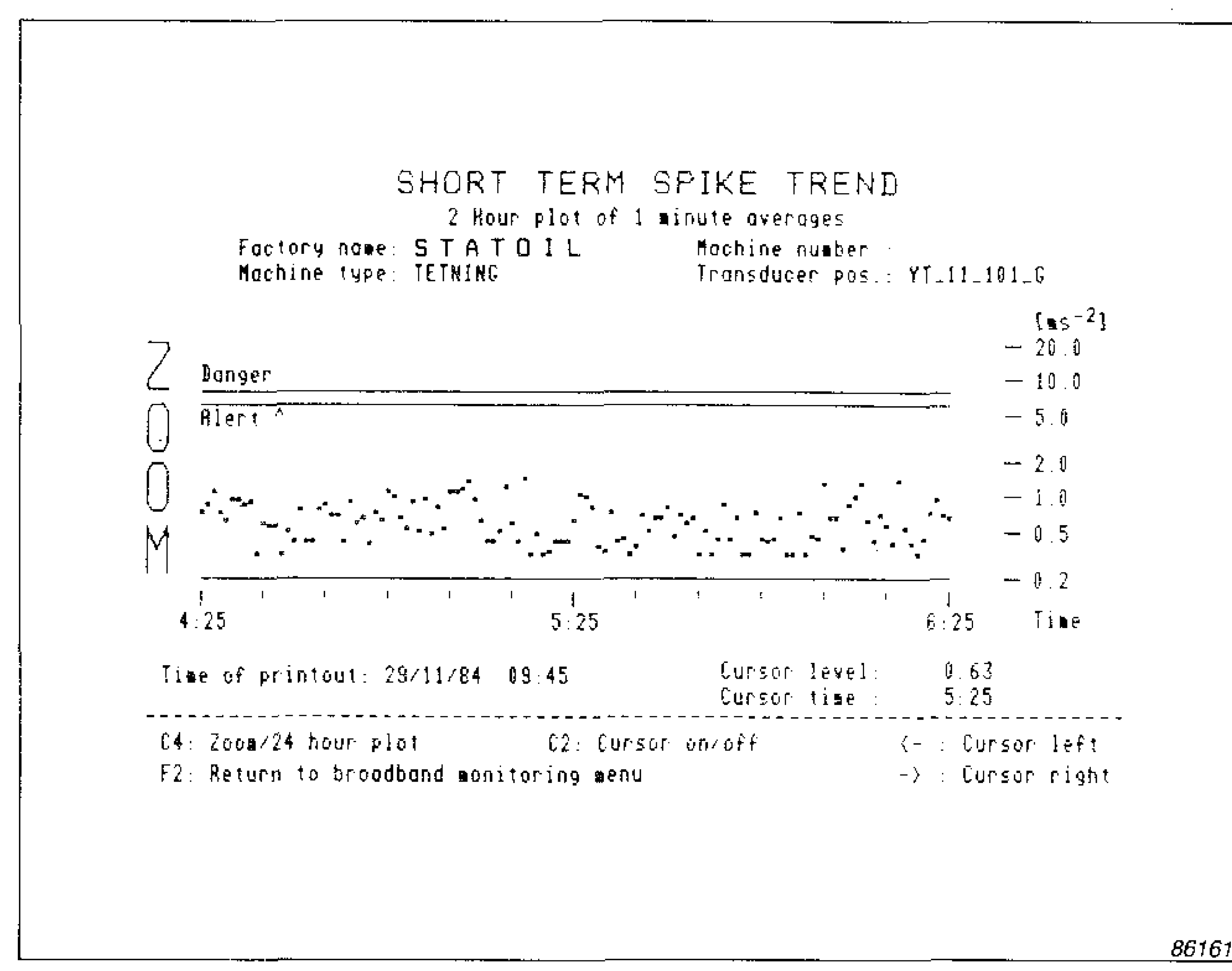


Fig. 7. Spike Energy trend after the seal/bearing renewal, showing a very random spread

17 Hz increase was diagnosed as a discrete bearing fault, which appeared to be at a very early stage in its development. A work order for changing the bearing was then made for the next planned production stop. During the period up to the planned stoppage the fault was closely followed, during which time the 17 Hz component showed a slight increase.

At the planned production stop, the bearing and seal were replaced. On inspection of the bearing it was seen that there was a single spall in the outer race of the bearing, see Fig. 8. The fault was at such an early stage that it was estimated that the bearing could have run for a further 6 months without problem.

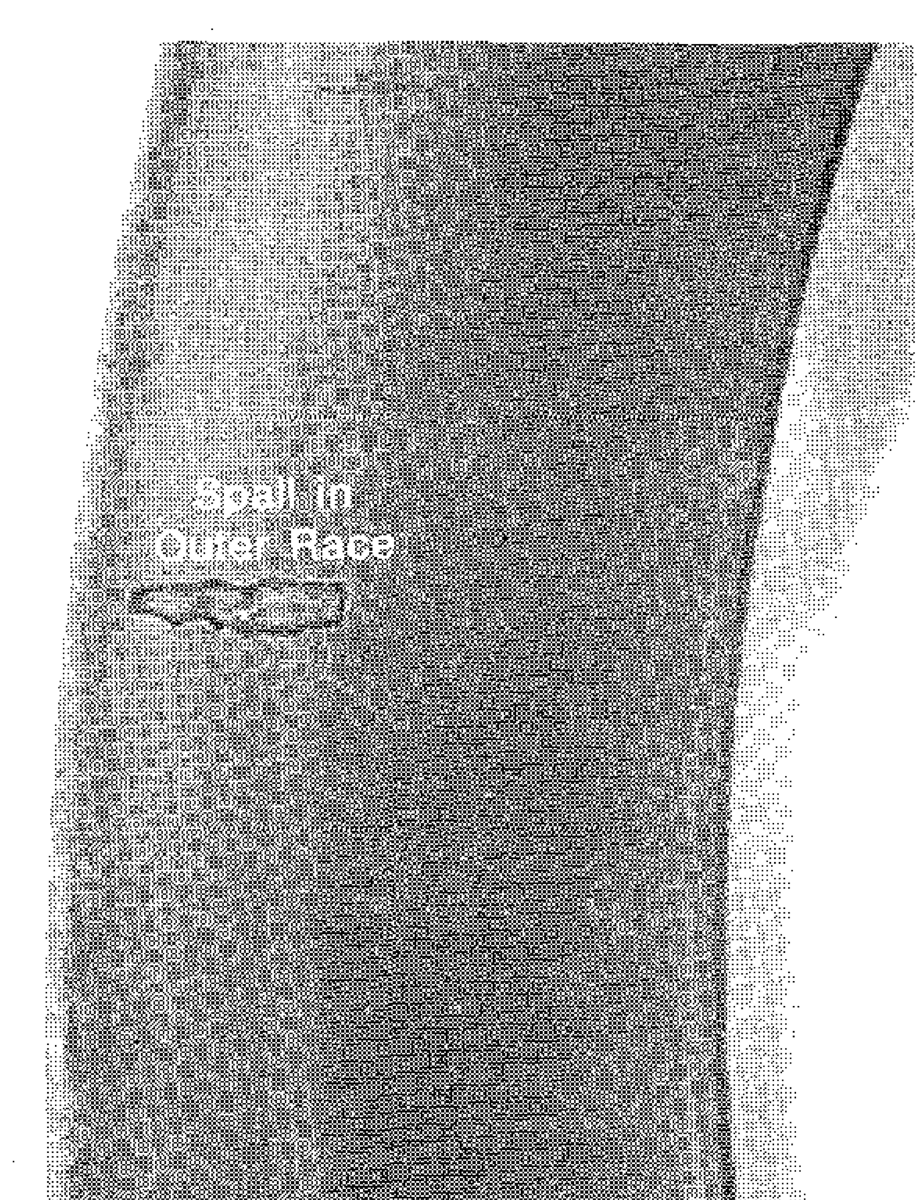


Fig. 8. Spall found on the outer race of the bearing

After a new seal/bearing assembly was mounted, the condition was checked in the usual manner. The RMS and Peak levels were steady, but the Spike Energy level (see Fig. 7) showed a very random spread and, by listening to the seal, a noise could be heared that was completely random. The reason for this noise, however, could not be traced, but was assumed to come from rubbing between two parts.

Normally, in such a situation, the agitator would be shut down and the seal replaced. However, after closely studying the vibrations levels for 1 day, a decision was made not to stop and change the seal, but to continue production and use the trending to

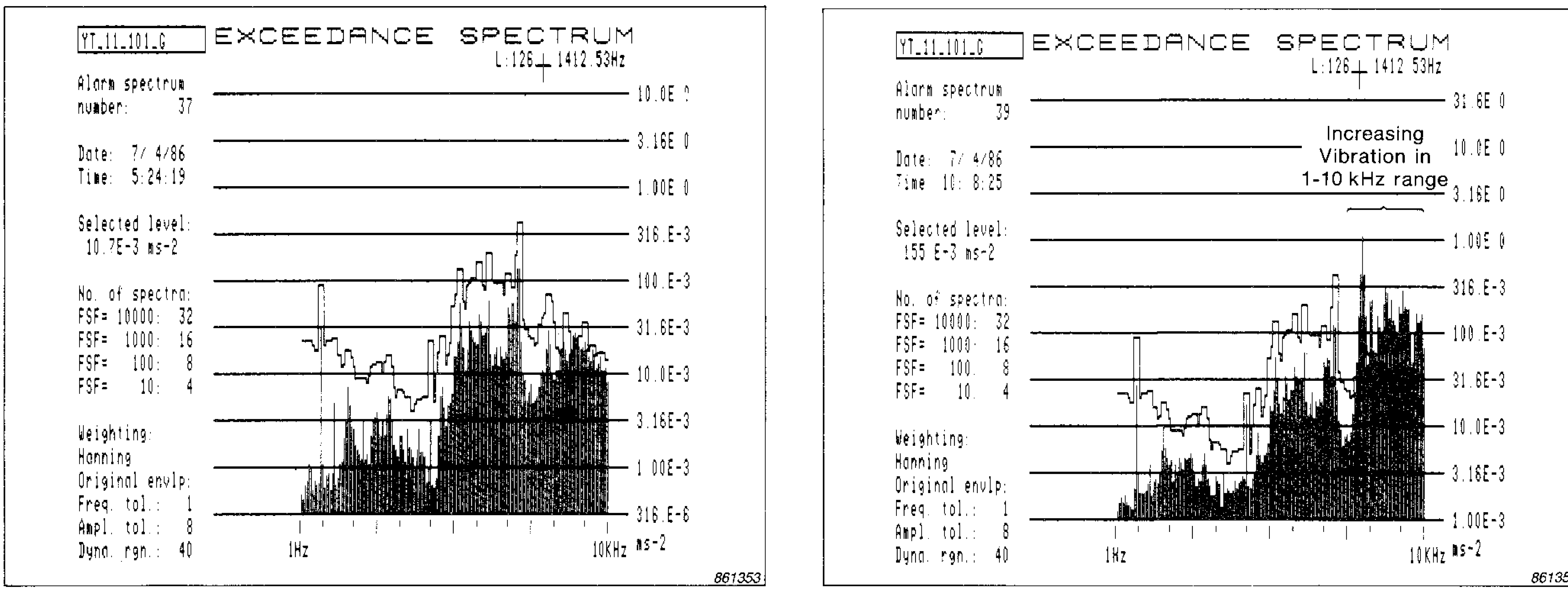


Fig. 9. Spectrum comparison from the agitator seal/bearing assembly showing the development of frequencies in the 1 – 10 kHz range. The spectrum to the right was registered approximately 4,5 hours after the spectrum to the left

check condition. In Fig. 6 can be seen the result of this patience, as the trend curve shows that the Spike Energy level dropped to a normal level shortly after (approximately between weeks –11,5 and –11 on the trend time axis). At this time the rubbing sound also disappeared.

Had the monitoring system with its trend analysis function not been employed, then an unnecessary production stop would have been carried out, with all the detrimental costs of lost production, increased maintenance etc.

Example 2

On a later occasion, during repairs on another machine in the production line, the seal/bearing assembly just above the agitator tank was changed as part of the plant's preventive maintenance programme. Shortly after production start-up, several alarms were registered from this bearing at the same measuring point as in example 1.

The automatic spectrum comparison showed a significant increase in vibration level in the 1 – 10 kHz region. This continued to develop over the relatively short time of just a few hours, see Fig. 9.

The problem was at first assumed to be associated with poor bearing lubrication. Grease was subsequently pumped into the bearing and the abnormal vibration levels were seen to drop to a normal level. However, after a few minutes the high frequency vibration returned and continued to increase.

This high frequency increase indicated classic symptoms of a damaged bearing and it was decided to stop production and inspect the bearing. On inspection it was found that the rollers were deformed, see Fig. 10, and on further investigation it was discovered that the bearing had in fact been mounted without grease. This very early stage damage, however, could clearly be seen in the spectra. The bearing was subsequently replaced and production restarted. The vibration thereafter dropped to a normal level over the whole spectrum.

It is very likely that a serious breakdown was prevented. The on-line spectrum comparison gave an alarm in good time before a serious problem occurred, even though the fault developed very quickly. At the same time, the spectrum comparison gave sufficient information about the fault to enable its cause to be effectively diagnosed.

Minor Changes Detected

Besides these two incidents, where major damage was clearly prevented, there is an added benefit from the system. Any changes in the frequency spectrum above a pre-defined tolerance, no matter how insignificant they may at first appear, are automatically reported and stored. In this way, mi-

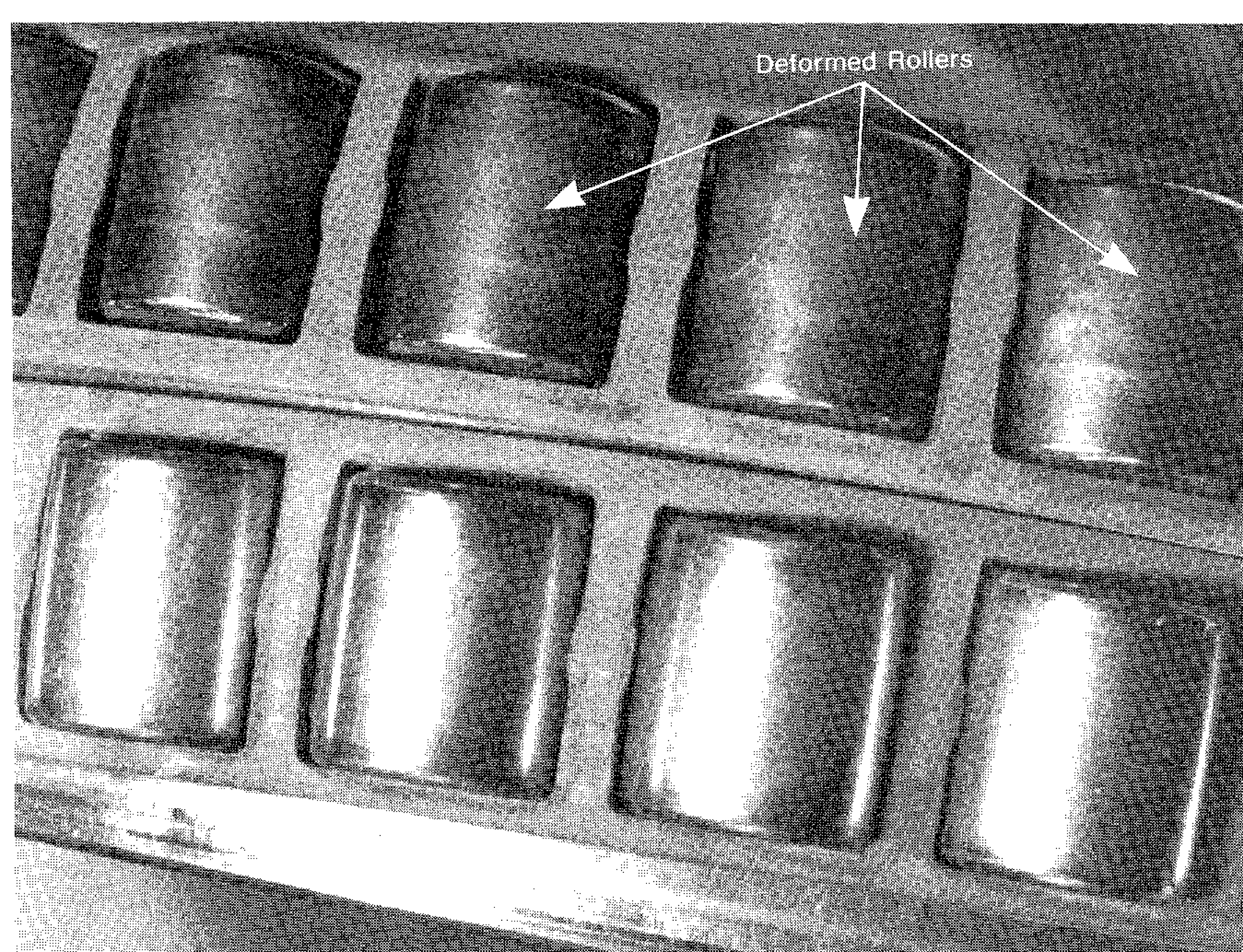


Fig. 10. Deformation of the bearing rollers

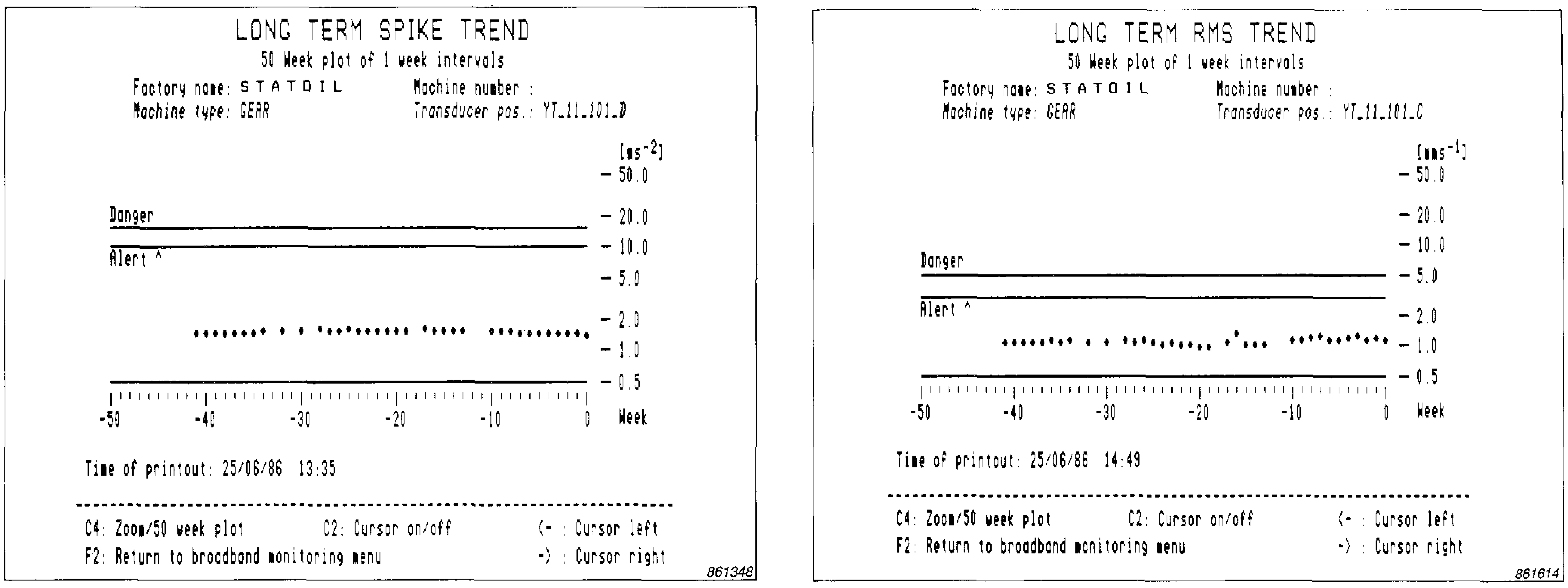


Fig. 11. Spike Energy and RMS trends from different places on the agitator gearbox. The values are seen to be stable

nor changes in condition can be followed and, together with information from other machines in the same production line, decisions can be taken well in advance about when to overhaul the machine. So, unless there is an indication of serious deterioration in condition, the machine can be kept in production for maximum time.

Advantages of Spectrum Comparison over Broadband Monitoring

For this type of detailed condition monitoring, the use of spectrum comparison is absolutely vital. The broadband monitoring of RMS, Peak and Spike Energy will certainly react if there is a serious immediate threat, but small changes in low energy components in the vibration spectra are not reflected in these parameters.

This is shown in an example were only a minor change in condition was detected, this time using measurements made on the gearbox of the agitator. The broadband values were seen to be stable on all measurement points on the gearbox (the Spike Energy and RMS trends are shown in Fig.11). However, studying the stored narrowband spectra revealed a positive trend in the 3 – 10 kHz range (see Fig.12), plus some small increases in low frequency components (see Fig.13). This suggests the beginning of deterioration of the gearbox bearings.

As these changes, however, were not considered dramatic, the agitator was kept running. A close check on the levels will be kept as the monitoring continues, and if the changes continue to develop, this will be reported by the system.

Another example of such a minor change can again be shown on the agitator, this time on the motor. Fig.14 shows a spectrum comparison from the motor, which indicated some high frequency components beginning to increase. The trend curve in Fig.15 shows the beginning of an upward trend in the 1,6 kHz to 1,8 kHz frequency range. The most likey cause of these increases was deemed to be from a bearing problem in its early stages. However, as the increases in level were not considered serious, the bearings were lubricated regularly to keep the levels down and the motor was run until the next scheduled shut-down. At this shut-down, the motor's bearings were examined and, on one of them, traces of pitting were found on the outer race.

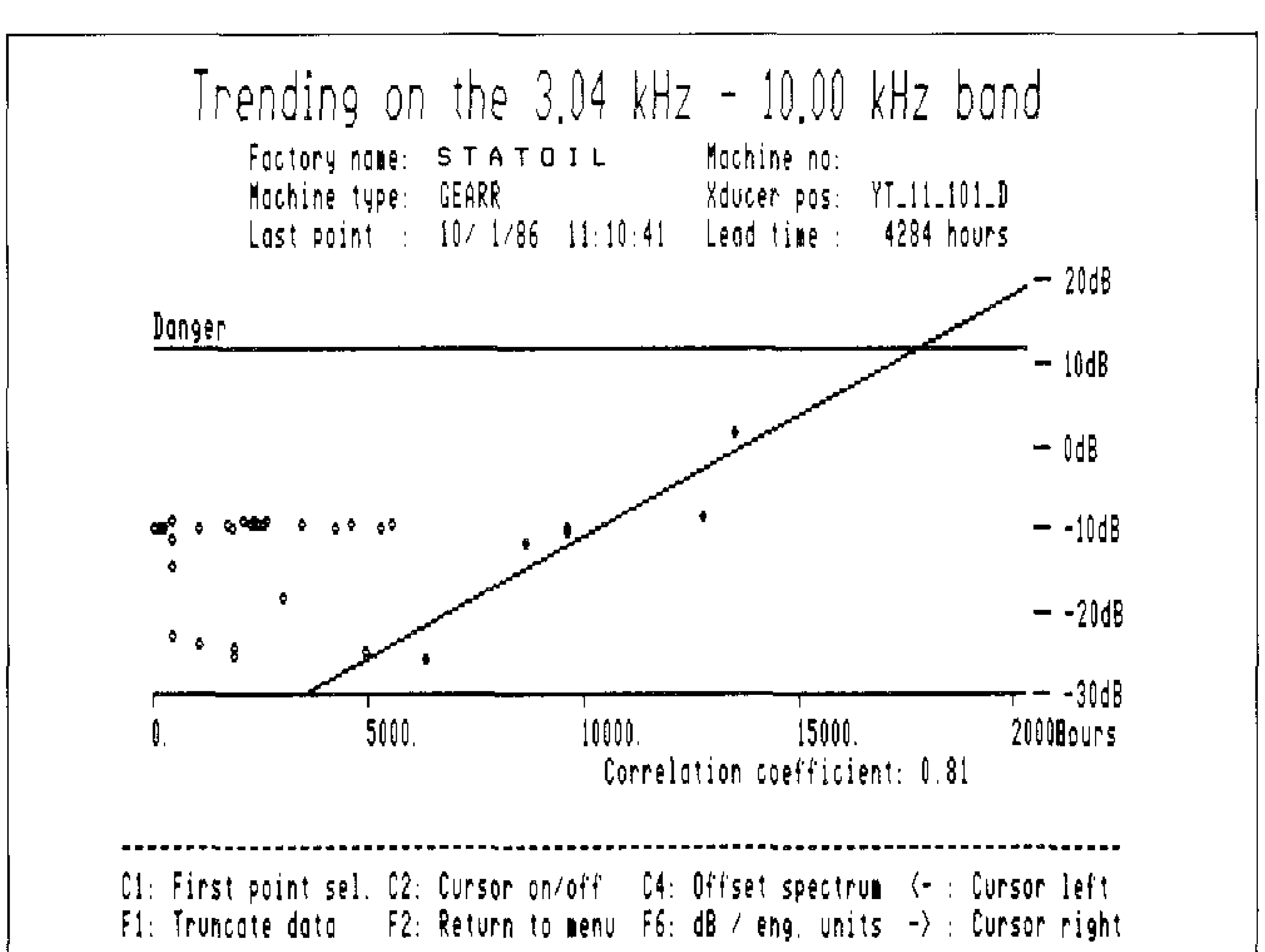


Fig. 12. Trend curve from the agitator gearbox in the 3 – 10 kHz range showing the beginnings of an upward trend

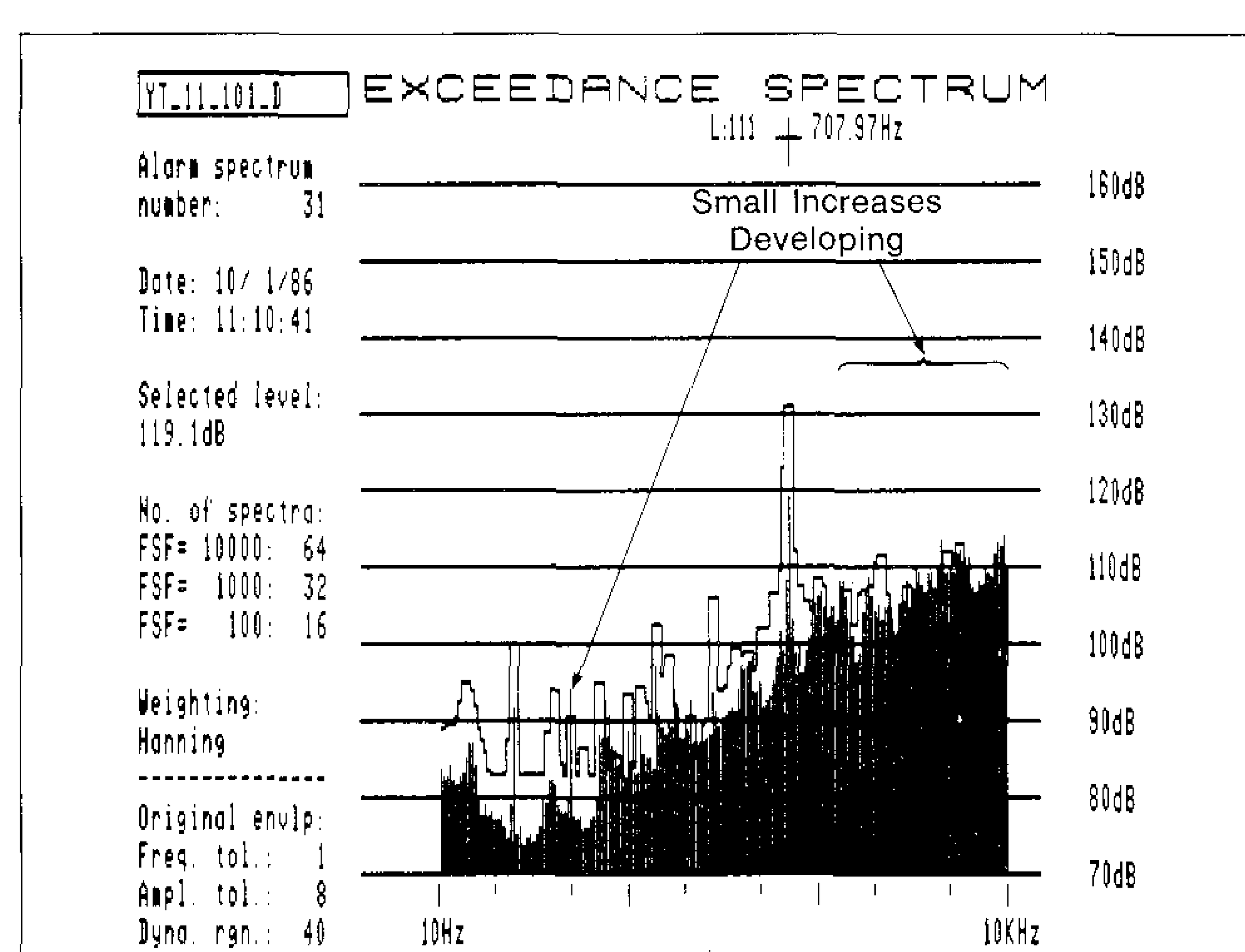


Fig. 13. Spectrum comparison from the agitator gearbox showing some small increases in both the low and high frequencies

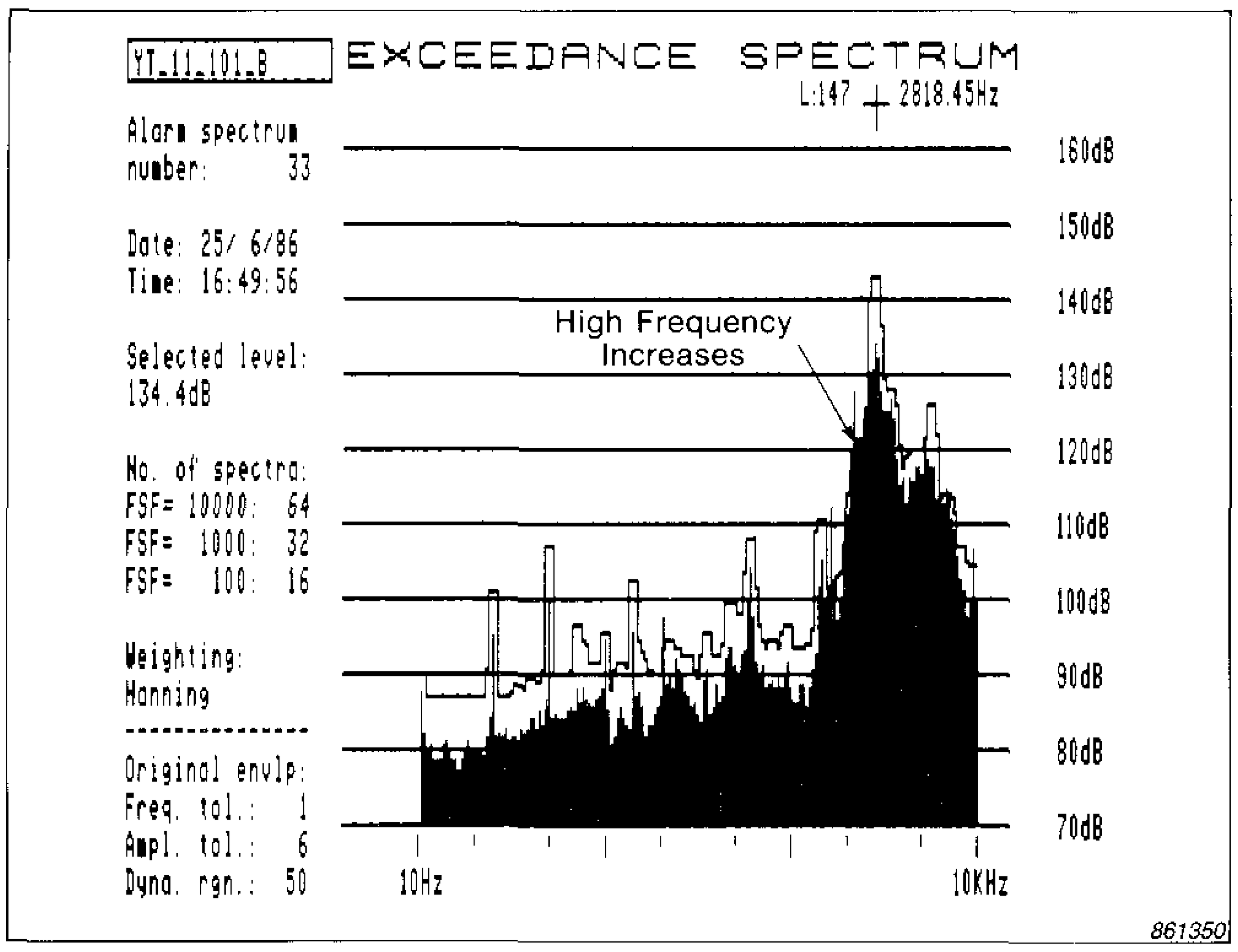


Fig. 14. Spectrum comparison from the agitator motor showing small increases at the higher frequencies

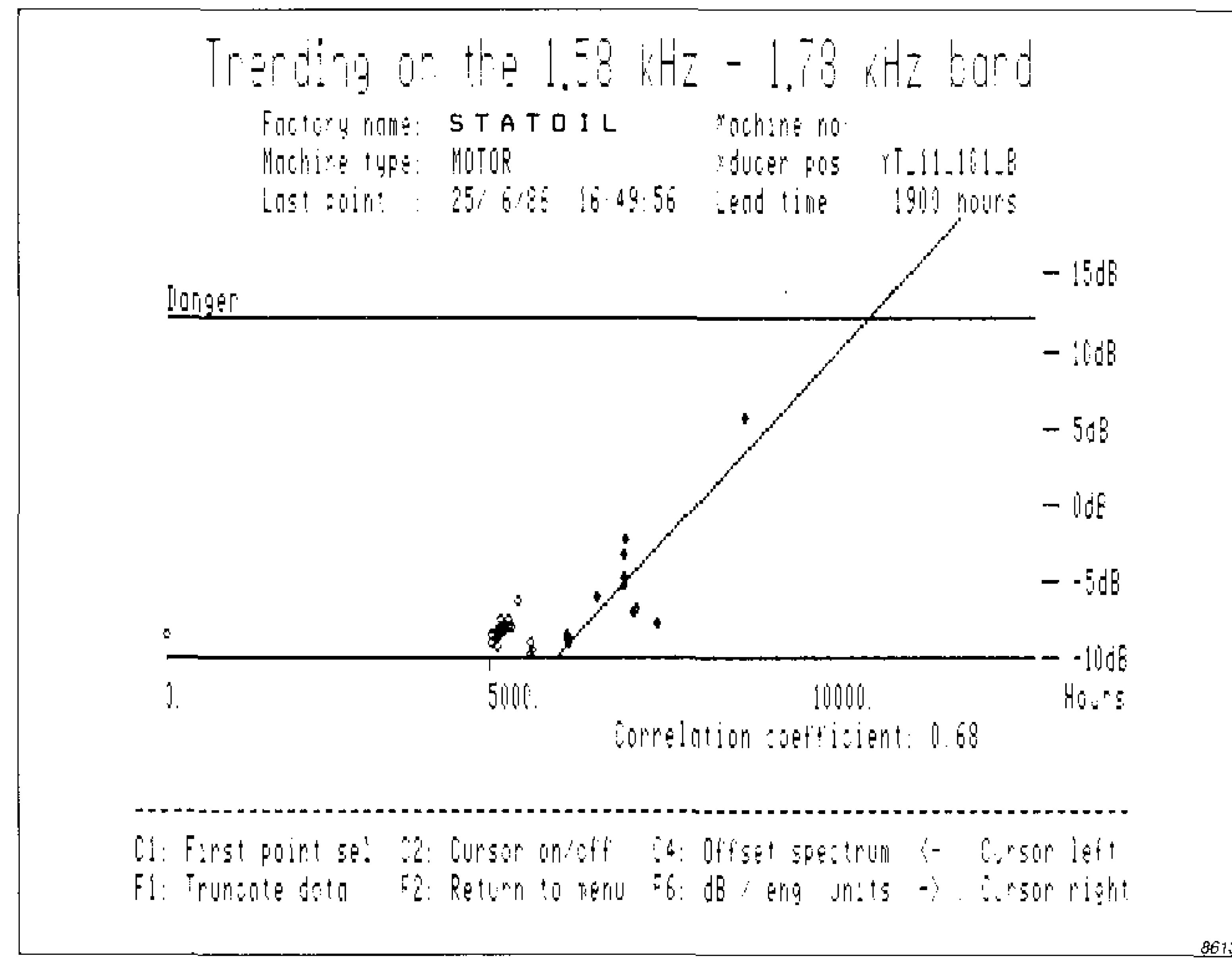


Fig. 15. Trend curve from the agitator motor showing the beginning of an upward trend in the 1,6 kHz to 1,8 kHz range

Case 2 – Screw Compressor

A screw compressor is a so-called positive displacement compressor, where the gas is compressed by two intertwining screws, the lobes working very much like a gear mesh, see Fig. 16. The vibration signature from such a machine is also very much like a gear, with the harmonics of the lobe frequency, that is the number of lobes times shaft frequency, dominating the frequency spectrum.

The screw compressors in question are in critical service, and therefore connected into the permanent monitoring system. A schematic layout is shown in Fig. 17.

One such screw compressor showed, for a period of time, an increase in vibration at the lobe frequency (398 Hz) and its harmonics. The spectra in Fig. 18 clearly show these increases, together with increases at the high frequencies. Fig. 19 shows the trend curve at the lobe frequency, and Fig. 20 a trend in the 7 – 13 kHz range. These increases indicated wear or possibly minor damage to the compressor's screws which, if left to develop, could have led to more serious damage.

At this stage, since the machine was permanently monitored, it was decided to let the machine run until further alarms indicated that repair was necessary to avoid a breakdown. The system, therefore, enabled a difficult decision to be avoided; whether to shut down the machine and suffer a considerable loss of production, or run the risk of an unexpected breakdown.

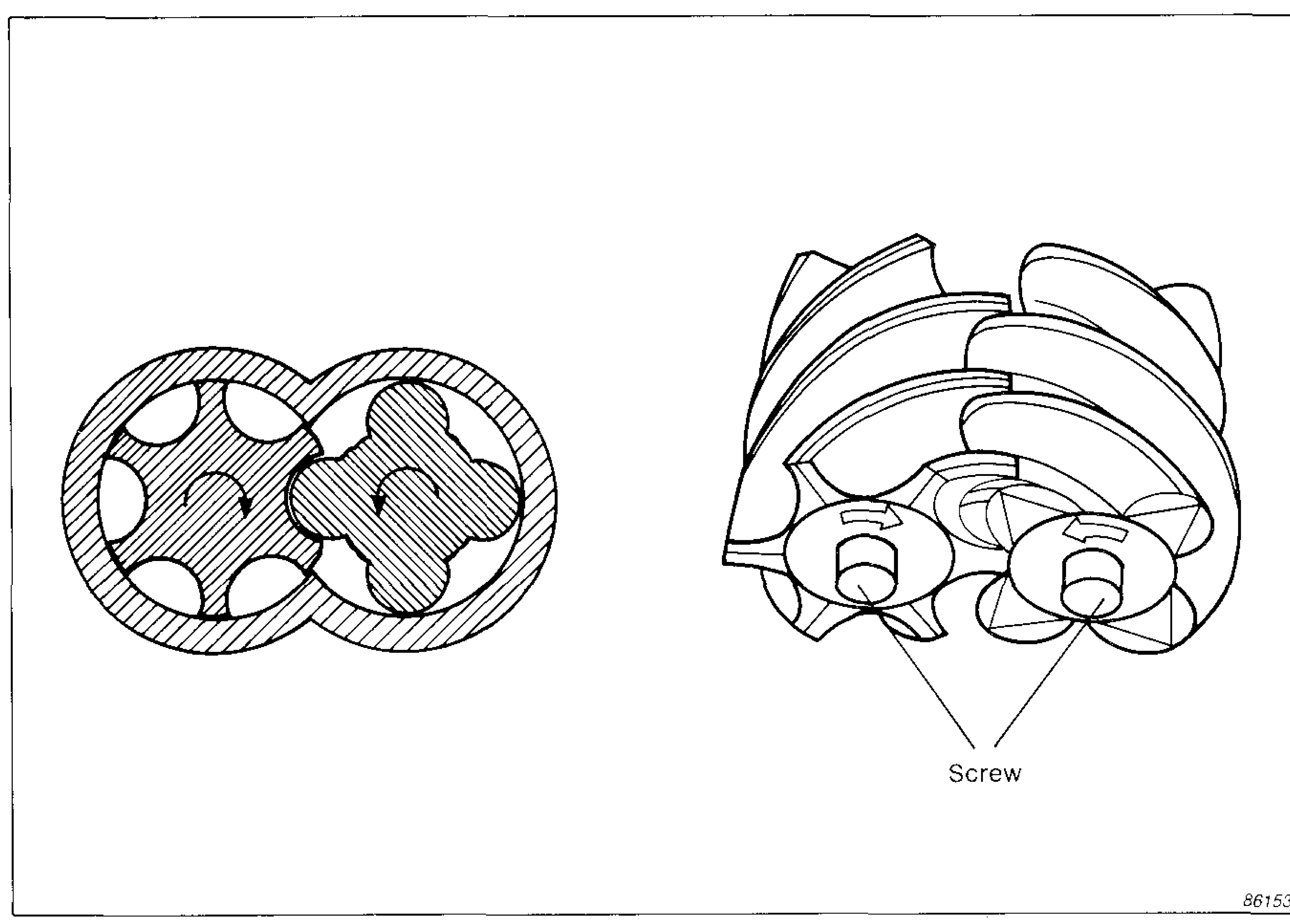


Fig. 16. Principle of the screw compressor

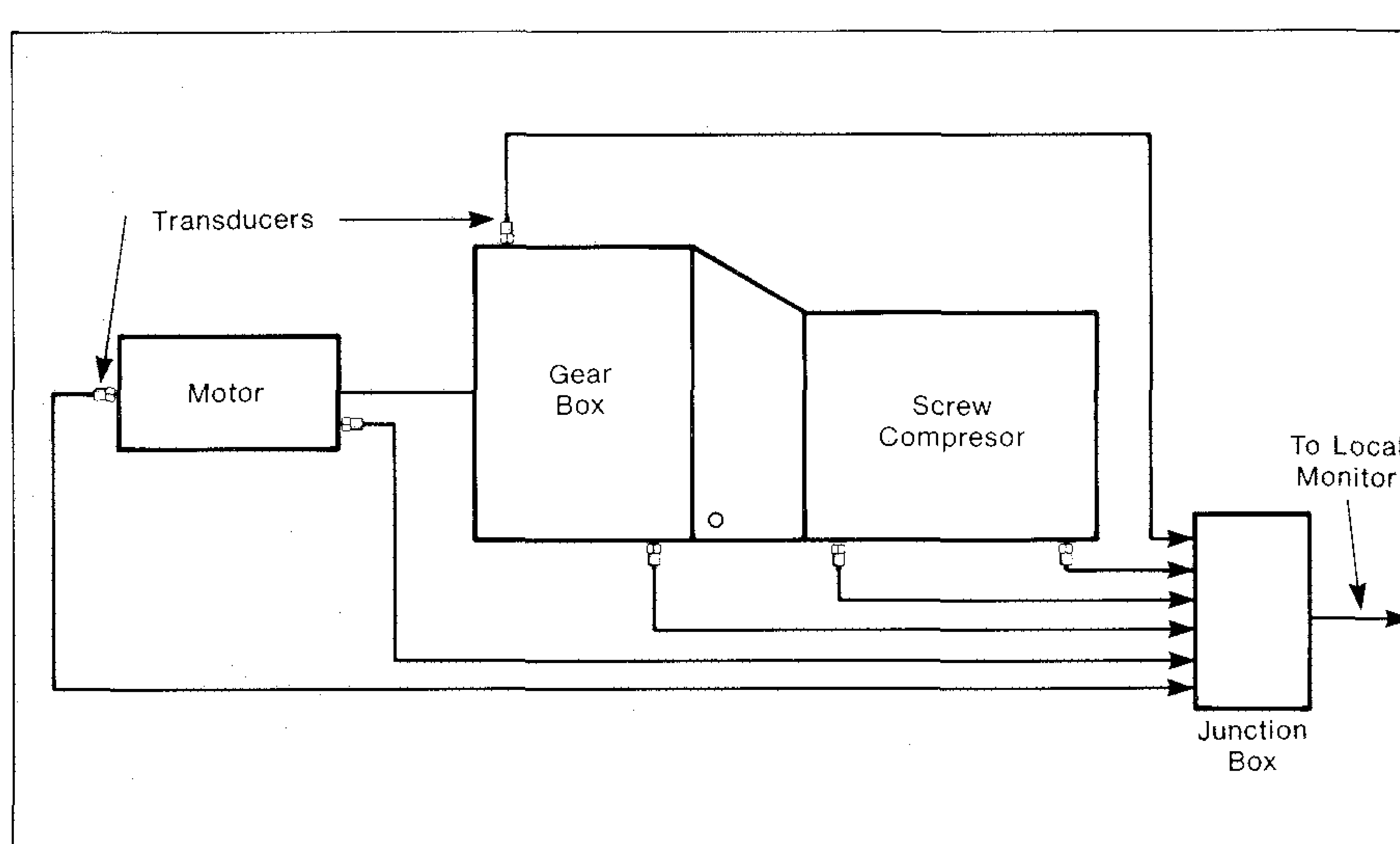


Fig. 17. Schematic layout of the screw compressor unit

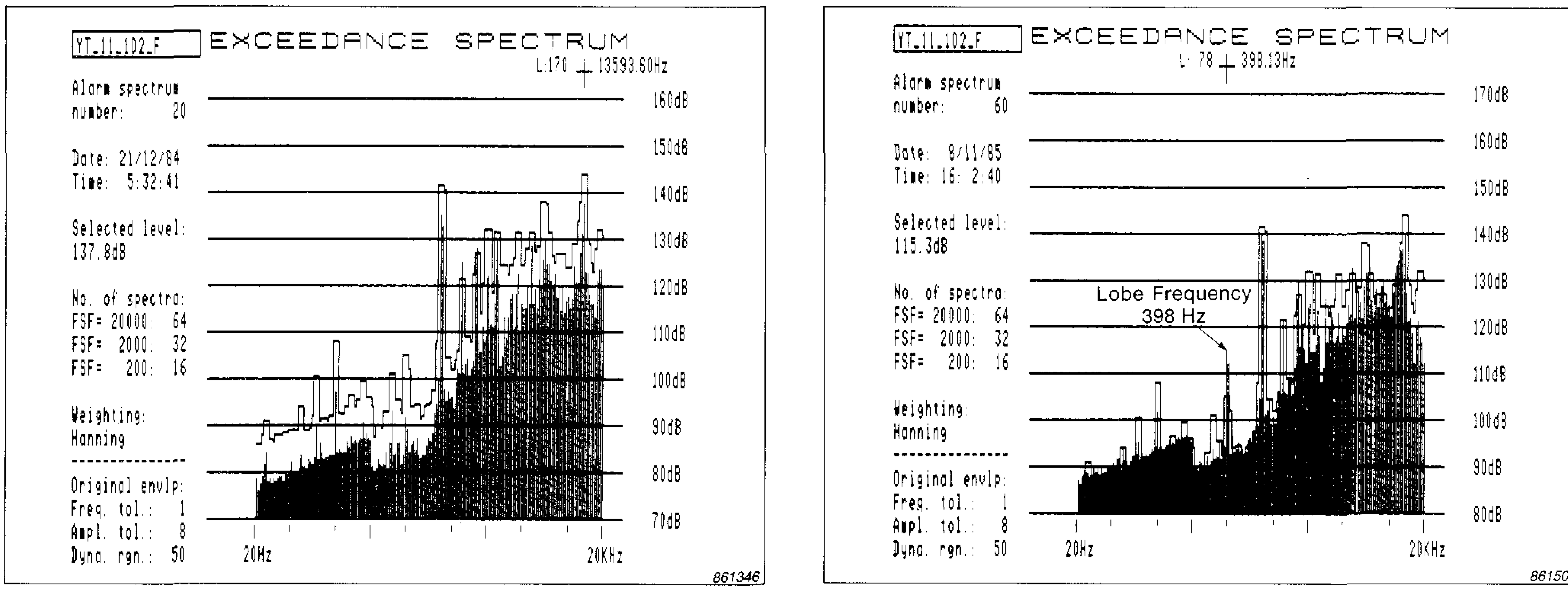


Fig. 18. Spectra from the screw compressor showing an increase at the lobe frequency (398 Hz). The spectrum to the right was registered approximately 1 year after the spectrum to the left

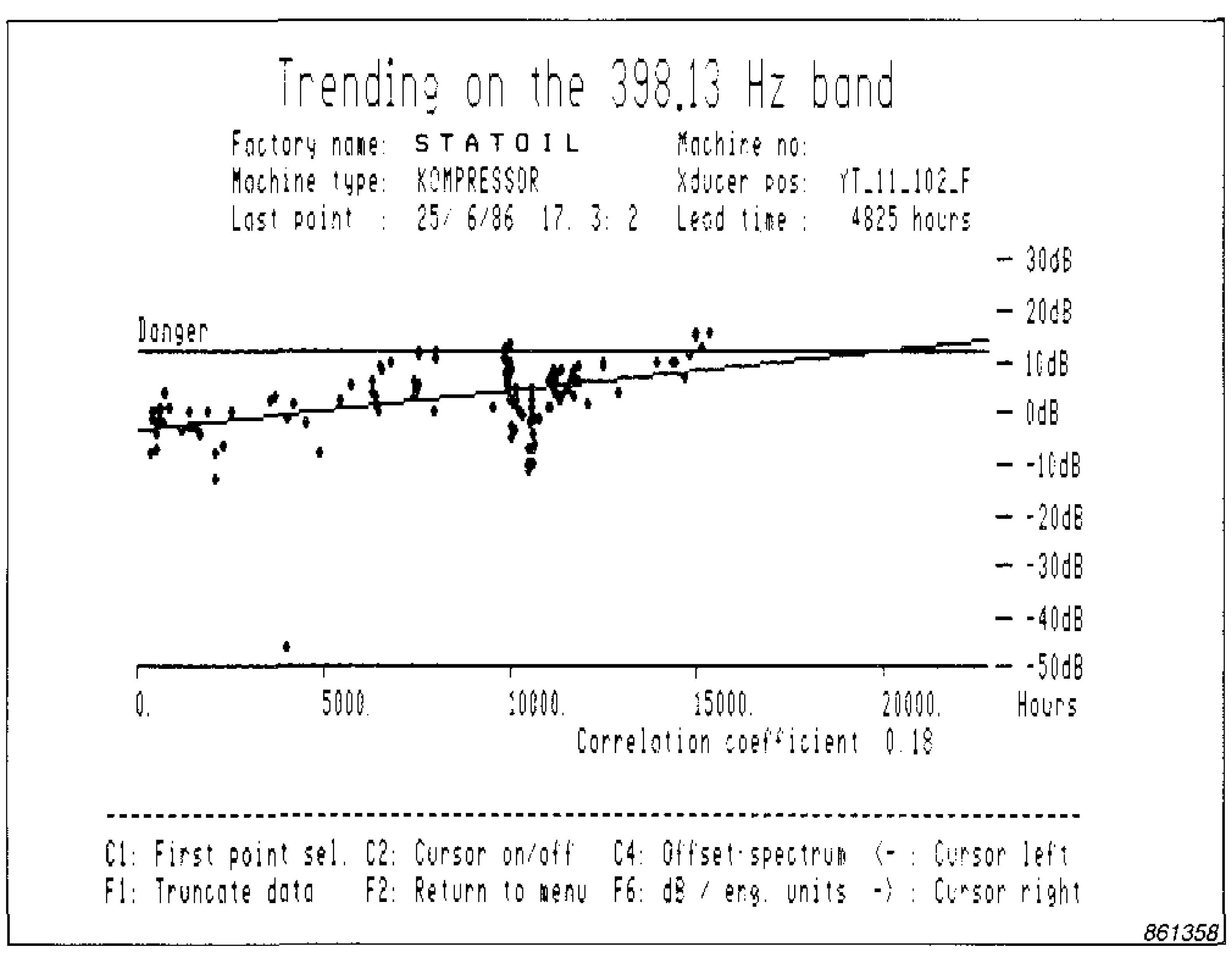


Fig. 19. Trend curve at the lobe frequency (398 Hz) from the screw compressor

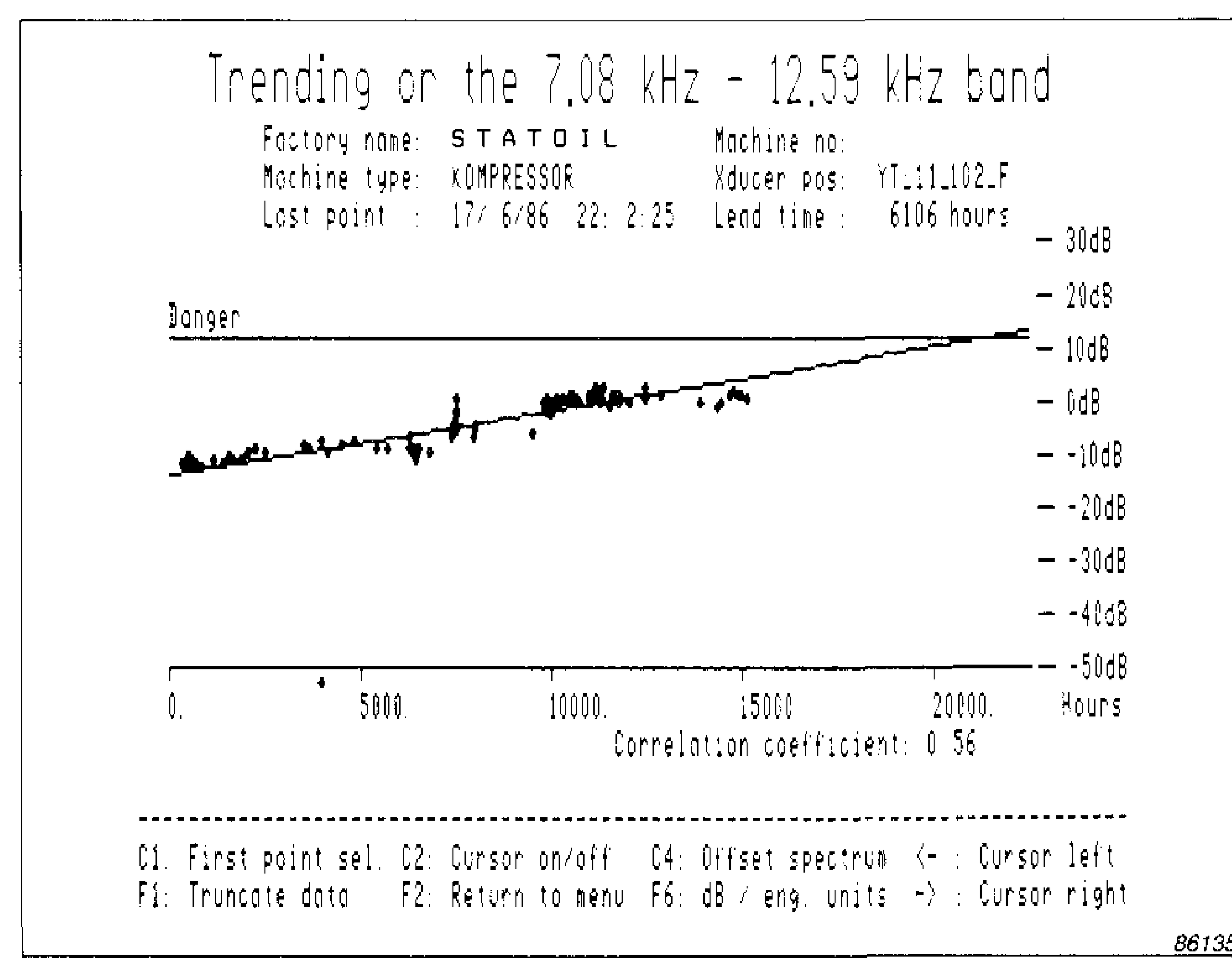


Fig. 20. Trend curve from the screw compressor showing a gradual increase in the 7 – 13 kHz range

In the following weeks, the monitoring system indicated that the situation had stabilized and continued to remain so, without major changes in the spectrum.

The production line was, in fact, run for more than 10 months after the first alarm, before the whole production line was overhauled in a planned manner. At this shut-down the screw compressor was examined and some wear found to the compressor's screws.

Case 3 – Extruder

There are 7 extruders at the plant, each being driven by an electric motor through a gearbox with 5 shafts, including the two screw shafts in the extruder itself (Fig. 21 shows the complex arrangement of gears). The extruders are not monitored by the permanent monitoring system, but are covered by the periodic measurement and analysis programme.

The manufacturer of the extruders recommends that the extruders be stripped after 25000 running hours for repair of the gear wheels and rolling element bearings. However, since the introduction of vibration monitoring using spectrum comparison, the condition of the extruder gears and bearings could be followed closely and the maximum possible life obtained. This has allowed a rationalization of the maintenance interval, which has in some cases been doubled to 50000 hours,

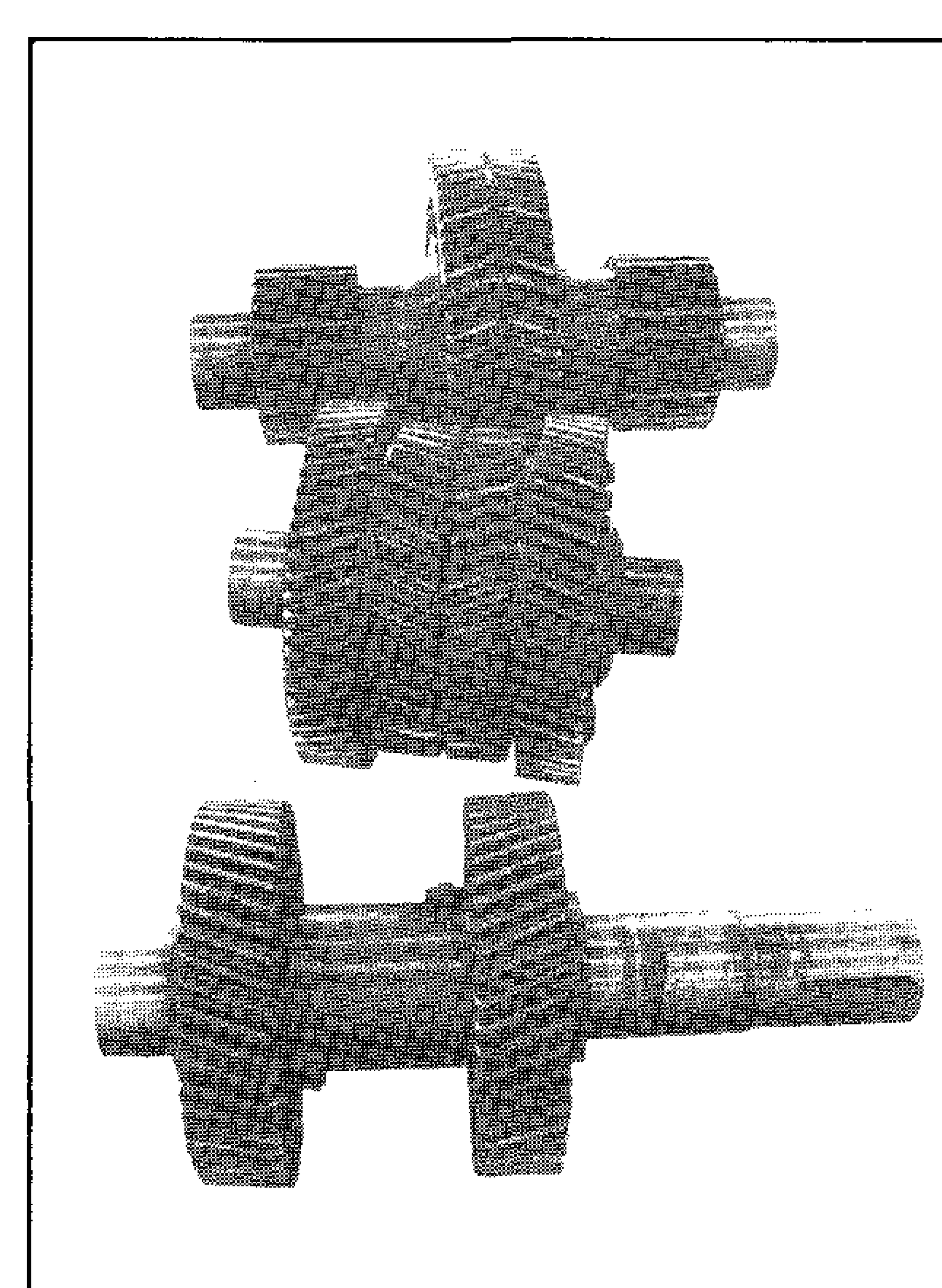


Fig. 21. The extruder gears

and is likely to be increased further as more experience with the vibration signatures from these machines is collected.

Needle Bearing Damage

It appears that extruders which have minor damage to the small needle bearings carrying the screws (faults which are normally very difficult to detect), exhibit an increase in the very low frequency range, see Fig. 22. These frequency components are lower than the shaft running speeds, and are dominated by sub-harmonics of the rotational speed of the screws and the output shaft from the gearbox, that is 1/2, and 1/3 etc. of these shaft speeds. This is an effect often encountered in connection with looseness in a machine, suggesting that the needle bearing damage is associated with excessive looseness of the screw shaft.

Gear Teeth Damage

Gear faults such as misalignement, unevenness and local tooth damage are normally reflected as sidebands around the toothmesh frequency. The frequency spacing of these sidebands is equal to the shaft speed. Fig. 23 shows a zoomed spectrum from the extruder gearbox, centered around the toothmesh frequency at 696,25 Hz. The sideband spacing of 11,3 Hz, which is clearly visible, is equal to the intermediate shaft speed. When the gearbox was stripped for maintenance, the gear wheel on the adjoining shaft was seen to have small local damage on part of the tooth circumference.

The vibration measurements on these machines have until now been made off-line. However, in view of the encouraging results with the off-line monitoring, it is now being considered to extend the on-line permanent monitoring system to cover these extruders as well.

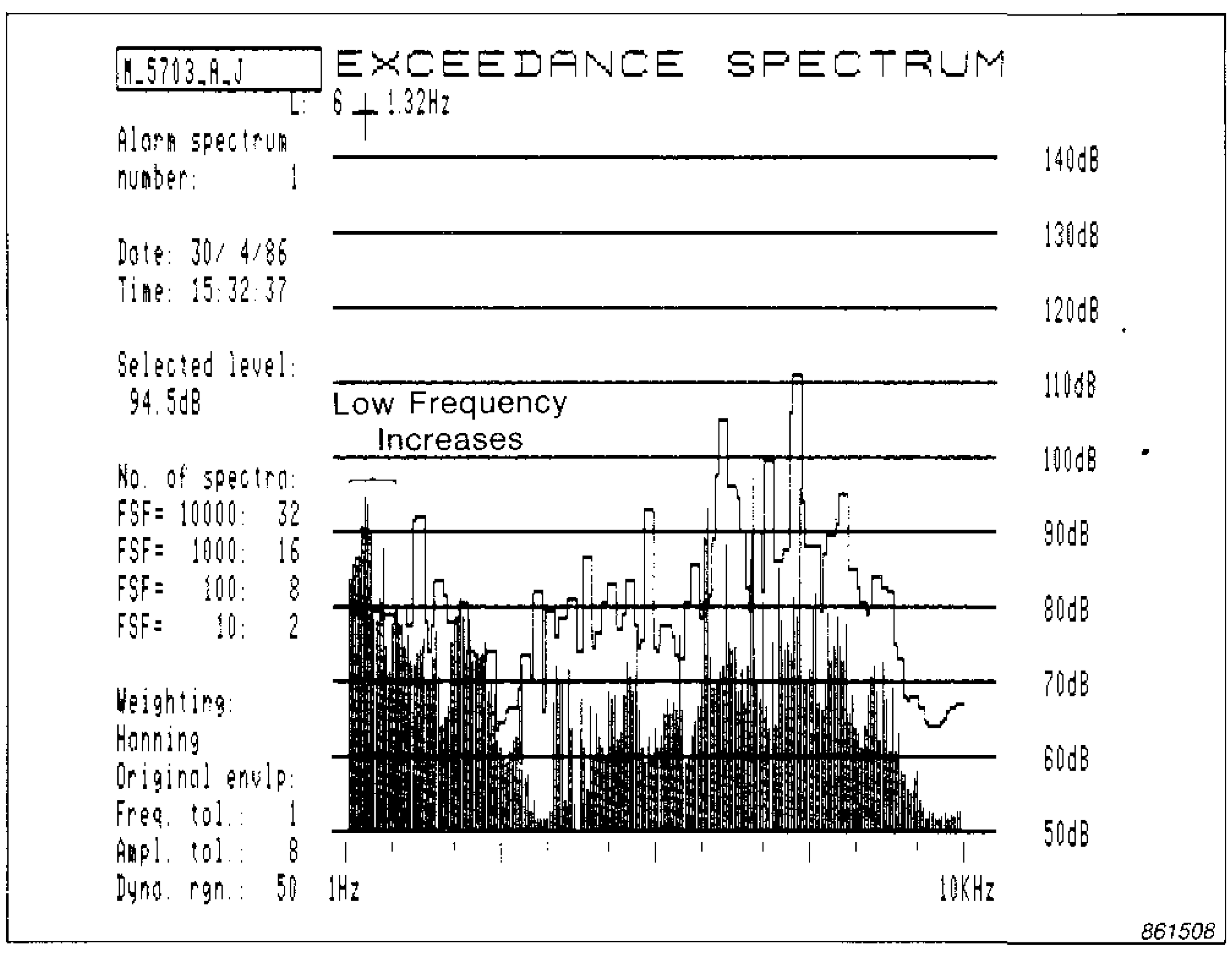


Fig. 22. Spectrum from the extruder showing increases at the very low frequencies

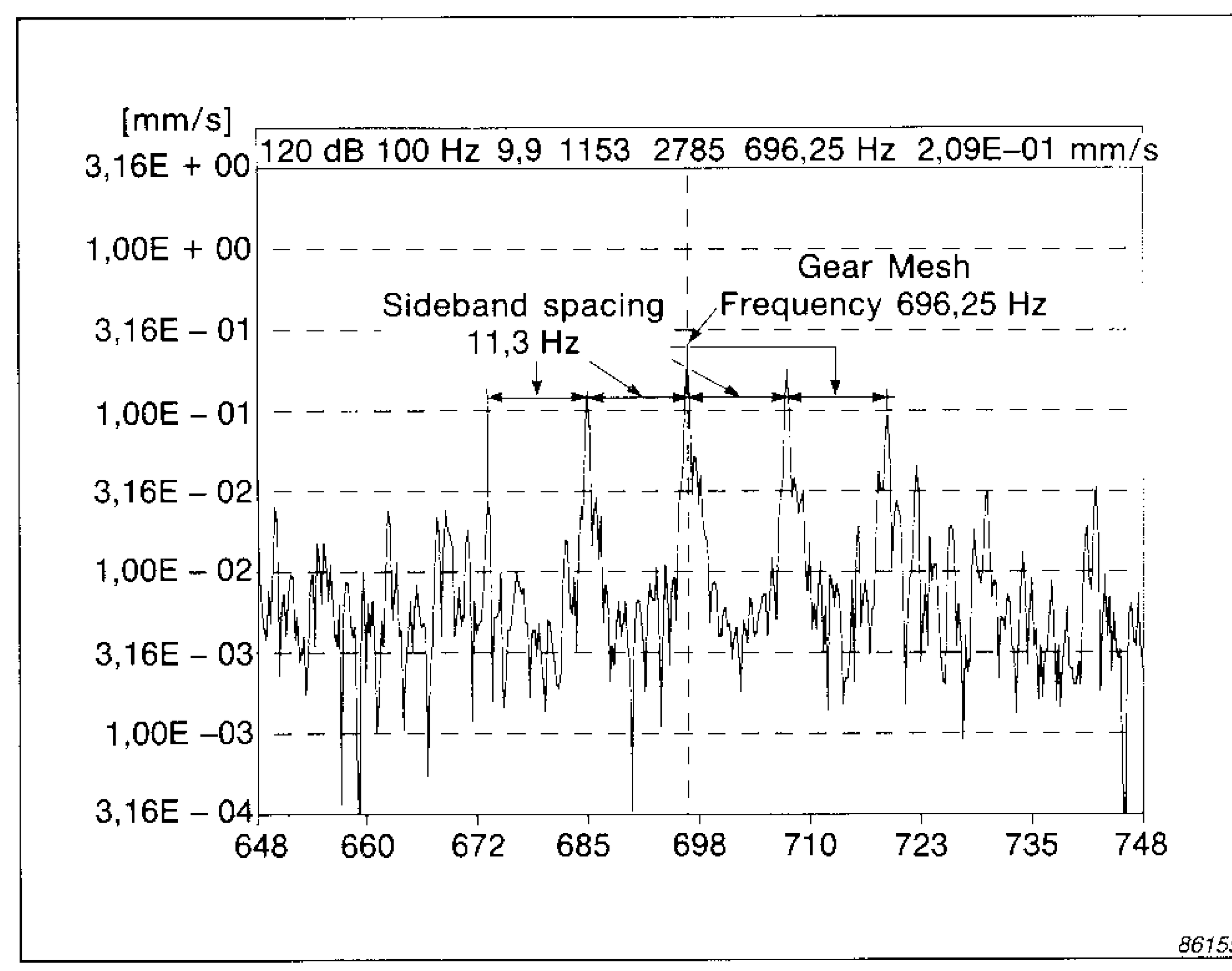


Fig. 23. Zoomed narrowband spectrum from the extruder gearbox, clearly showing the sidebands around the toothmesh frequency

Conclusions

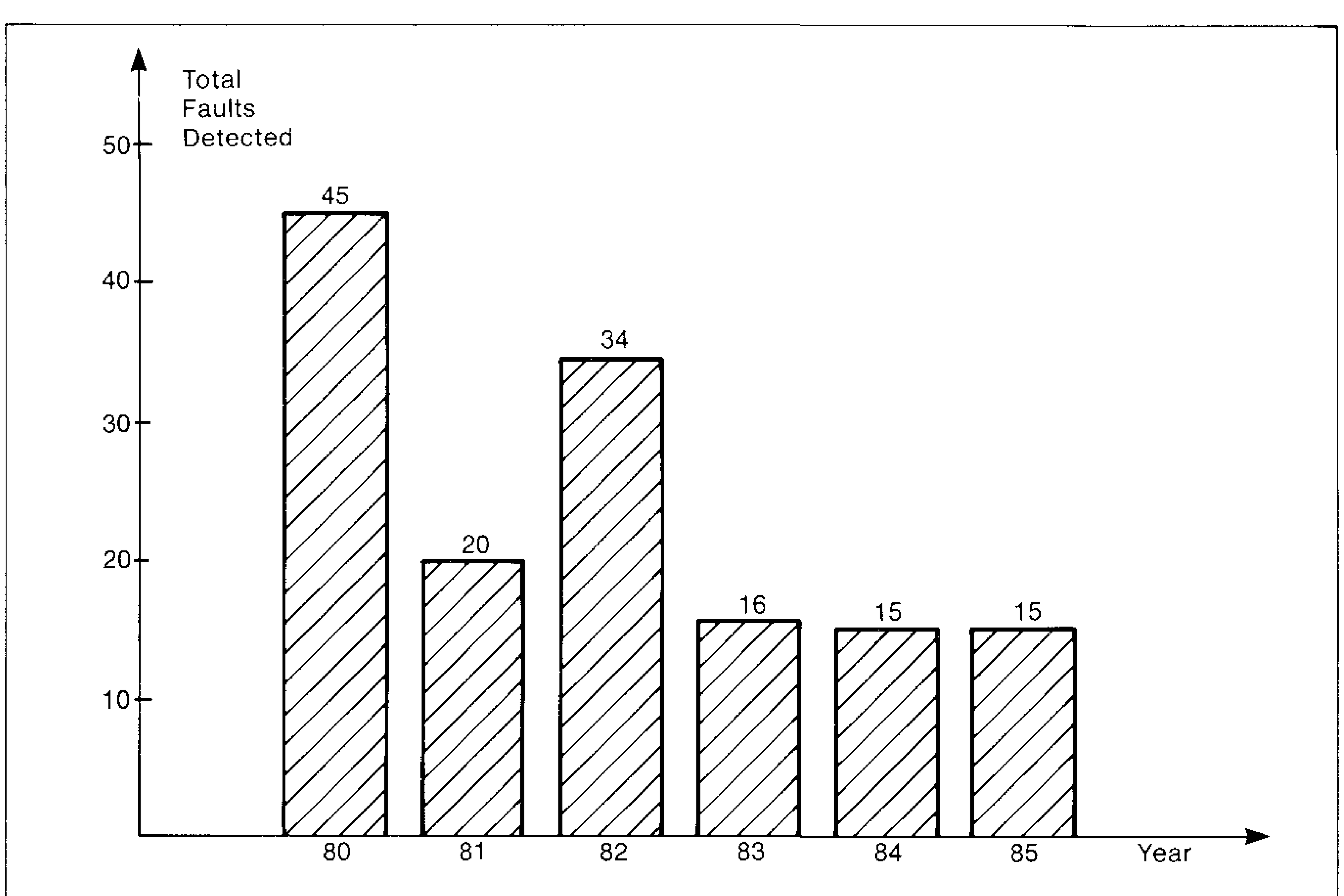


Fig. 24. Number of faults detected using vibration monitoring since the plant began full operation in 1980

The system has shown itself to be capable of detecting both quickly and slowly developing faults. It not only provides the security of knowing that sudden deterioration of machine condition will be detected in time for action to be taken, but also allows accurate detection and diagnosis of the faults to be made, well in advance of breakdown. In many cases, early indication of a worsening of condition has been given. The machine condition could then be followed very closely to continue operation for the longest possible time and to determine the best time for maintenance.

Some of the advantages of the system are outlined below:

Permanent Monitoring

Permanent monitoring gives the safety of knowing that there is a continuous watch on machine condition.

Broadband Monitoring
Permanent broadband monitoring gives warnings of sudden deterioration of machine condition, thus avoiding serious breakdown.

Spectrum Comparison
Spectrum comparison gives early detection of changes, allowing minor changes in condition to be detected and the reason for the fault to be diagnosed. **Trend Analysis** then allows these changes to be followed closely, and the machine run for maximum possible time.

Computer Based Systems
Computer based systems offer the advantage of automatic control of the monitoring system, giving ease of data handling and large data storage.

Fig. 24 shows the number of faults that have been detected using the vibration monitoring programme. It is interesting to see that the curve appears to follow the beginning of the "bath tub" failure curve – the number of faults was high at the very beginning when machinery was new and prone to teething problems, and then dropped off to a steady rate.

It is, of course, not possible to say that each and every fault detected by the monitoring system would have caused an unexpected breakdown. However, the cost of just **one** agitator breakdown would pay for the complete monitoring system. In the original proposal for the monitoring system, the maintenance management at Statoil expected a pay-back time of 18 months. The actual pay-back, at a very conservative estimate, was in fact well inside this time.

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