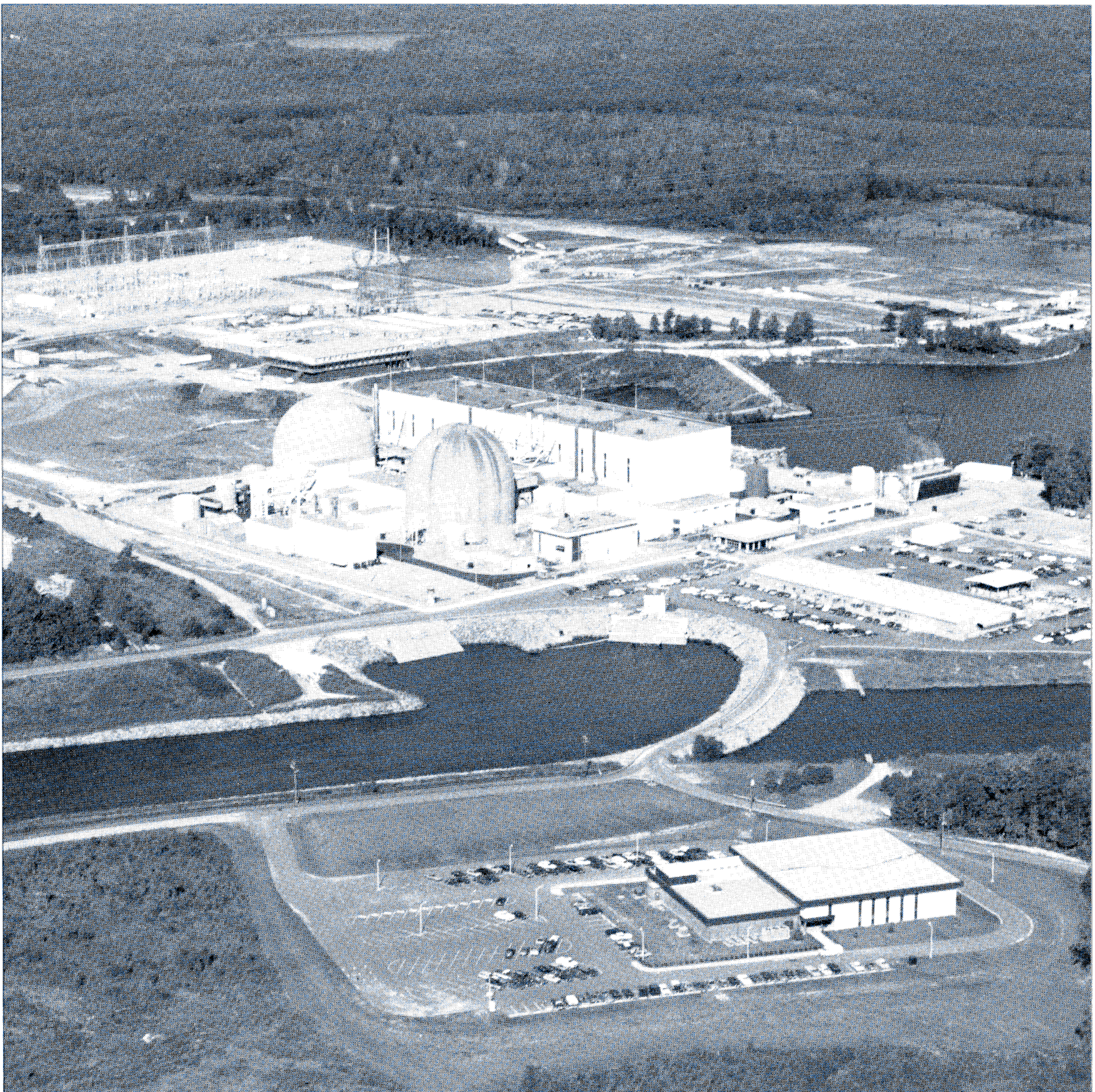




Machine-Condition Monitoring Using Vibration Analysis

A Case Study from a Nuclear Power-Plant



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A Case Study from a Nuclear Power-Plant

by *D.N.Brown*
Brüel & Kjær

The cover photograph shows an aerial view of Virginia Power's North Anna Power Station, located in central Virginia U.S.A. The plant is nuclear powered (pressurized water reactors) with a net generating capacity of 1786 MW, serving approximately 4 million people.

All photographs used in this Application Note were taken by Thomas Kelsey and are supplied by courtesy of the North Anna Power Station.

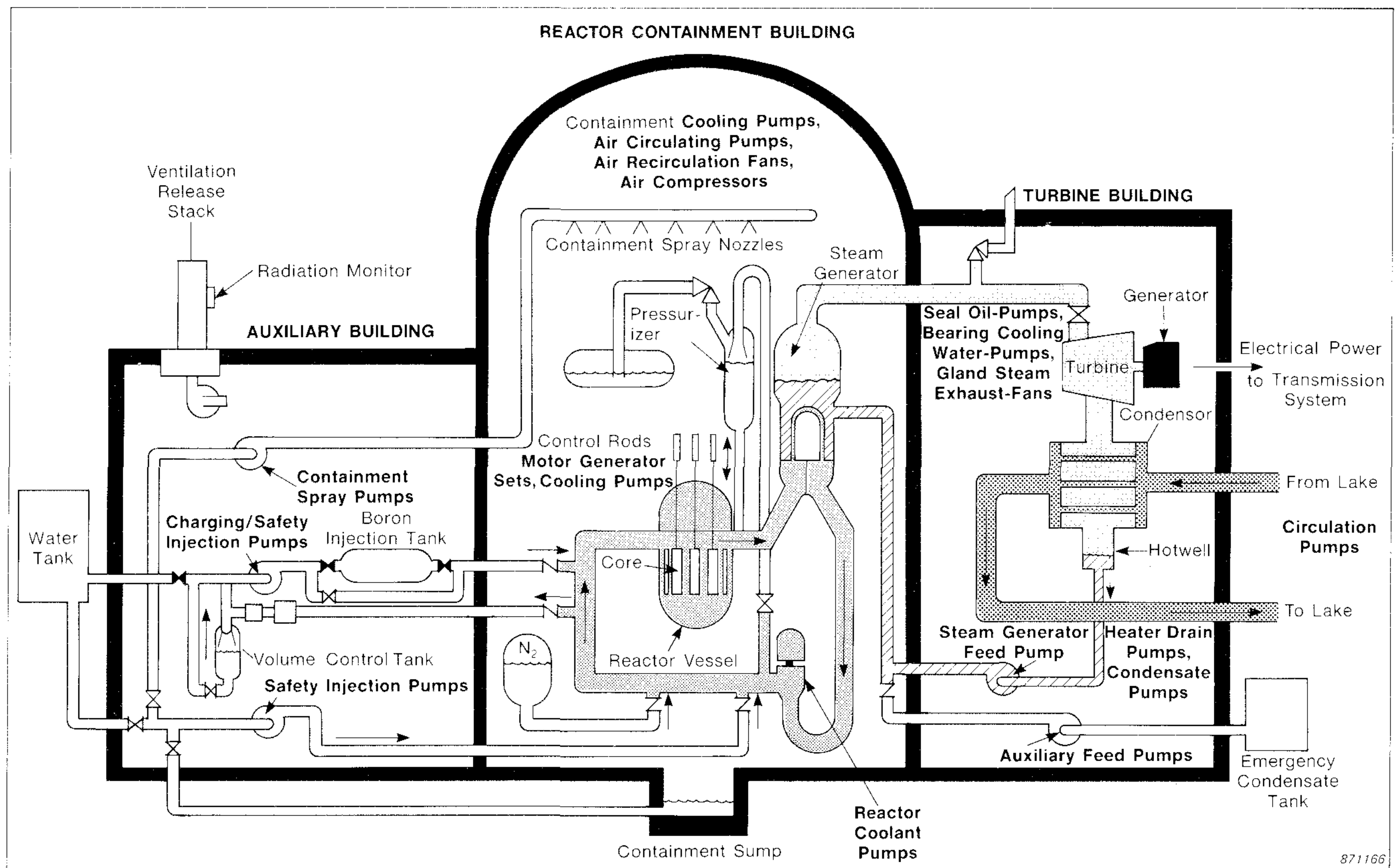


Fig. 1. Layout of one of the two nuclear power-generating units at the North Anna Power Station. Machines indicated in **bold** are covered by the vibration monitoring system

Introduction

Failures in rotating machinery can be a prime contributor to the forced outage of a power plant or its reduction in load. The cost of a reactor outage, together with stringent safety considerations, makes it essential that the condition of all machinery vital to the plant operation is maintained and that unexpected breakdowns are eliminated.

By utilising a *predictive maintenance* programme such as *vibration monitoring*, the condition of vital rotating-machinery can be effectively determined. These monitoring systems can give very early warnings of impending failures, they can determine the cause of the fault and can be used to schedule repair. Such a system can therefore prevent catastrophic failure; reduce forced outage; give maximum utilisation of available assets; increase the life of the plant and reduce maintenance costs.

This Application Note describes a programme for the vibration monitoring of vital rotating-machinery at Virginia Power's nuclear-powered North Anna Power Station. Numerous machinery faults have been detected by the monitoring system, a number of examples of which are documented here. Many of these faults could have resulted in reactor outage or at least a reduction of output if they had unwittingly been left to develop.

The North Anna Power Station

The North Anna Power Station comprises two independent Pressurized Water Reactor (PWR) units, each driving a 970 MW steam turbine. Unit #1 went into commercial operation in June 1978, and Unit #2 in December 1980.

Fig. 1 shows the layout of one of the plant's reactor and power generating units, and indicates the most critical

of the rotating machinery monitored (a complete list of the monitored equipment is given on the back page). The reactor, steam generator and the large pumps that move the water between them are all housed in a separate containment building. This is a 200 ft. high, dome-shaped construction made from steel-lined, reinforced concrete. Steam is transferred via extensive piping to the adjoining turbine building which houses the turbine, generator and condensate cooling/pumping system. The auxiliary building contains part of the emergency reactor-cooling systems and auxiliary pumping/cooling systems.

The Machine-Monitoring System

The Brüel & Kjær machine-monitoring system used by North Anna Power Station is shown in Fig.2. It is based on the principle of measuring and analyzing the vibration signals from chosen machinery on a two level system, as follows:

Level 1 – Weekly Spot-Check

Once a week, a quick spot-check on machine condition is obtained using a Type 2516 Integrating Vibration Meter. The Type 2516 is a hand-held, battery powered, vibration meter for measuring Vibration Severity and overall vibration levels. It gives a single number representing machine condition, and can indicate if any major change in machine condition has occurred since the last measurements.

This weekly check gives a good overview of the general condition of the machinery and highlights machines that require more sophisticated vibration analysis to diagnose specific problems.

Level 2 – Monthly Machine-Condition Analysis

Either once a month or when the

weekly check indicates a problem, an advanced vibration-analysis system is used to obtain a thorough analysis of machine condition by studying the frequency content of the vibration signals. This gives the earliest possible warning of a failure and allows diagnosis of the cause of the fault. Two systems are in use for making this machine-condition analysis:

1. A laboratory-based computer-aided system, shown in Fig.3. The machine vibration data is first recorded on tape using the Tape Recorder Type 7007. In the laboratory the data can be later analyzed using the Type 2033 High Resolution Signal Analyzer under control of a desk-top computer running Machine Monitoring Software WT 9114. This system performs spectrum comparison, 3-D plotting, trend analysis and fault diagnosis. This system is usually used for the monthly analysis.
2. A portable system usually used for trouble-shooting problems, shown in Fig.4. In this system, a Type 2515 portable Vibration Analyzer

is used to give an on-the-spot analysis of machine condition. The Type 2515 is a portable battery-powered FFT Analyzer that can detect faults by using spectrum comparison, and diagnose the cause of the fault by narrowband analysis, zoom, cepstrum and other built-in functions. It can be interfaced to a host computer for mass storage of data, post processing etc.

Detecting and Diagnosing Faults

Machine faults will cause a change in the shape of the vibration's frequency spectrum. The presence of such a fault can therefore be detected by comparing two frequency spectra recorded from the same machine at different times. The cause of the fault can then be diagnosed by determining which frequency components have increased and matching them with machine parts. To get the best out of the system, however, two different types of frequency spectra are used for fault detection and diagnosis.

For fault detection a constant percentage bandwidth spectrum is

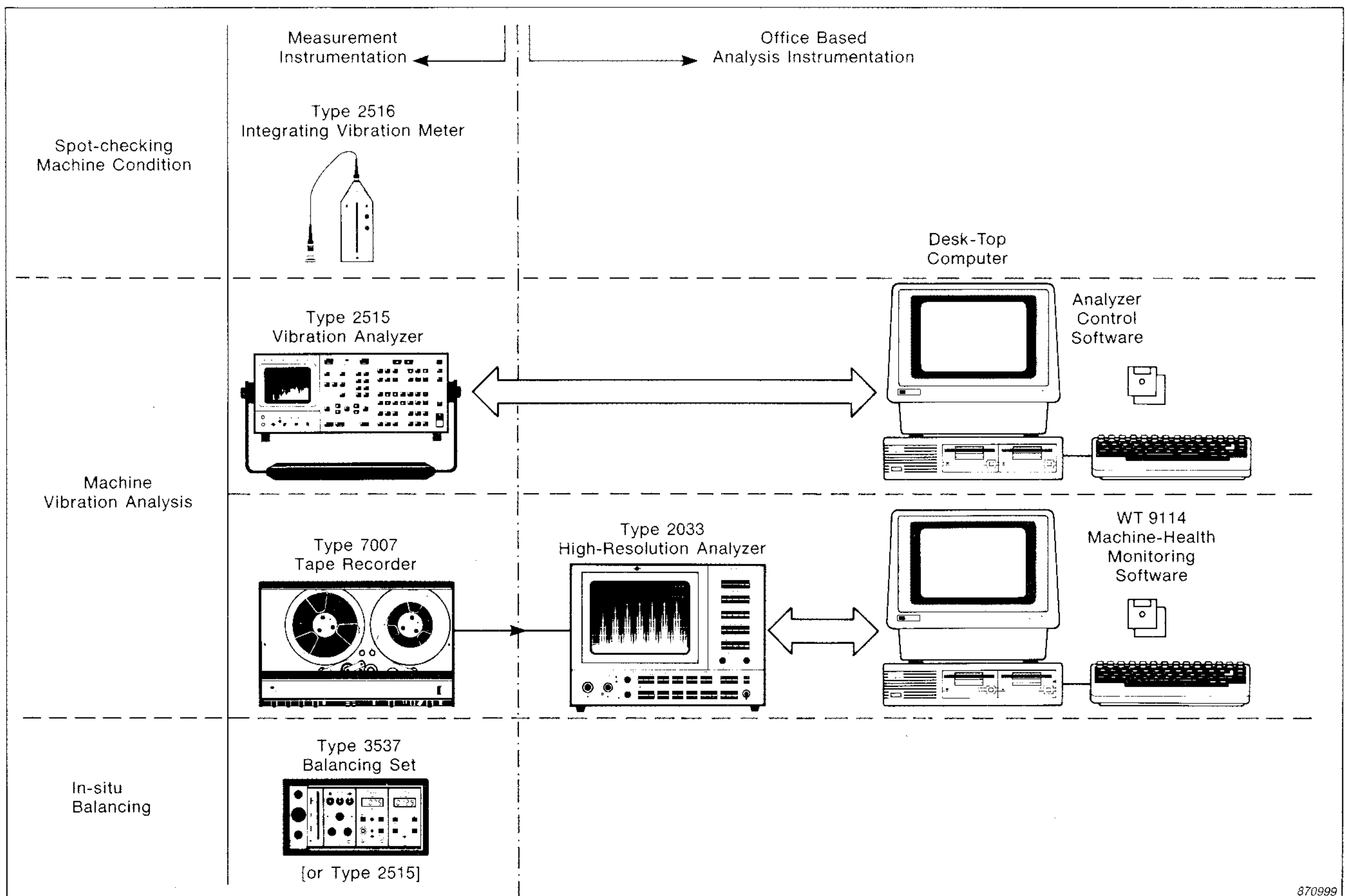


Fig. 2. Schematic layout of the vibration monitoring equipment used

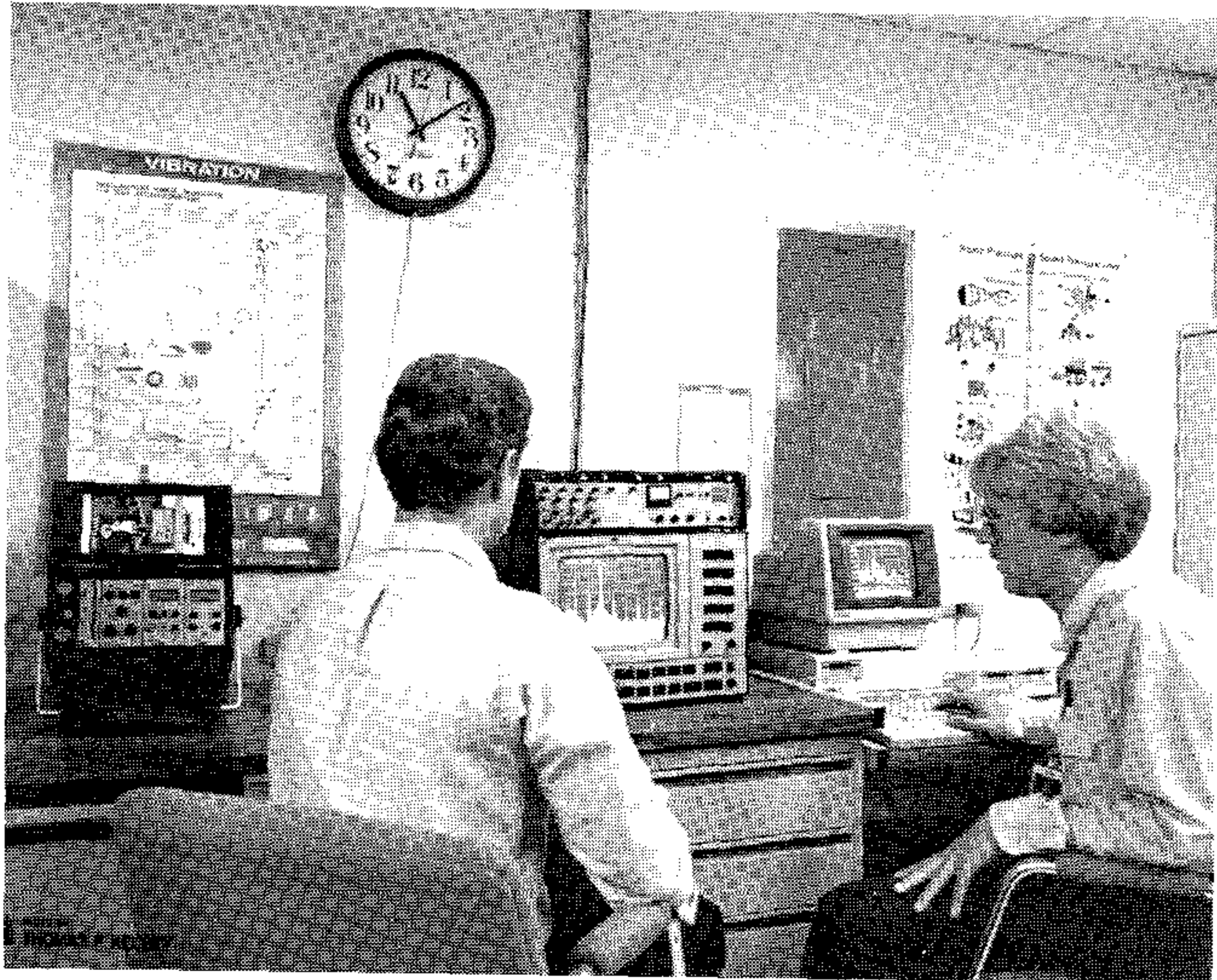


Fig. 3. The laboratory based system which is used for a detailed analysis of the monitored machines once per month

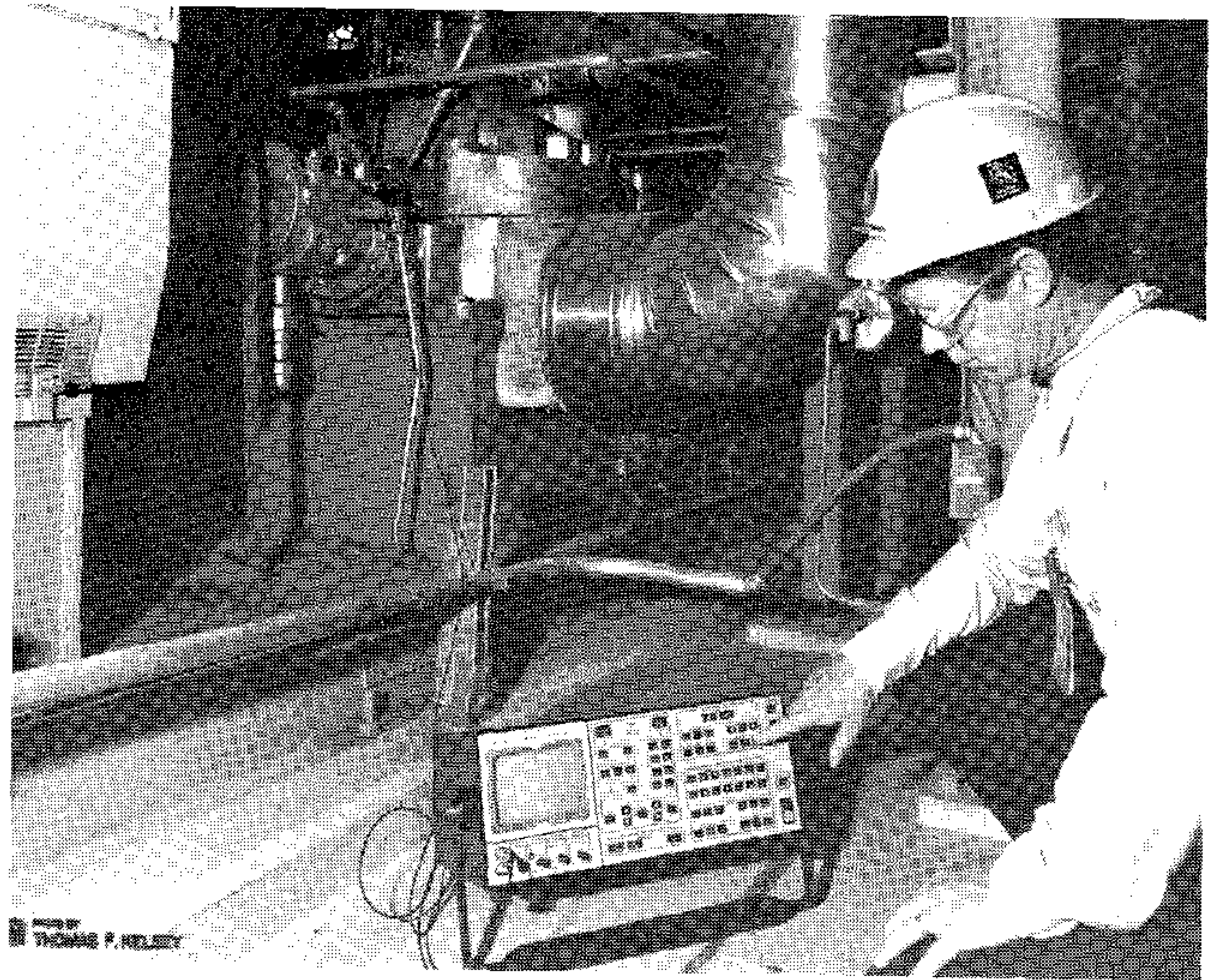


Fig. 4. The portable Type 2515 used for trouble-shooting problems. Shown here analyzing vibration from a heater drain pump

used. This gives quick data reduction, allowing a 3-decade frequency range to be used with sufficient resolution to detect all faults. Examples of this type of spectra are shown in Figs. 10, 11, 12 and 14.

For **fault diagnosis** the *FFT Transform* is used to produce a *narrowband* spectrum. This gives a far more detailed frequency analysis of the vibration signal. Examples of this type of spectra are shown in Figs. 8, 9, 16 and 17.

Trend Analysis

Once a fault has been detected and its cause diagnosed, it is necessary to determine when the fault will become critical so that maintenance can be scheduled well ahead of breakdown. This is done by plotting the historical

development of the vibration level at a particular frequency or frequency range, and estimating how long it will take before a predefined danger limit is reached. Examples of this trend analysis can be seen in Figs. 13 and 15.

Rotor Balancing

When the need to rebalance a rotor arises, either the Type 2515 Vibration Analyzer or a Type 3537 Portable Tracking Balancing Set are used. The Type 3537 (see Fig. 6) is a dedicated balancing set which has a narrowband tracking filter to balance machines running at unstable speeds. Both the Types 2515 and 3537 measure vibration level due to unbalance and phase angle relative to a marker. This information is keyed into a pocket calculator using Balancing Calculation Software WW 9021 which calculates the

mass and its position required to balance the rotor.

Monitoring in Containment

During reactor outages, the engineers are able to enter the containment building with the Type 2515 Vibration Analyzer. They monitor the cooling fans which cool the control-rod drive-mechanism and the various pumps and other machinery present. Monitoring in the containment building, however, poses a number of problems due to the dangers of radiation exposure to operators and contamination of any instrumentation used. The Type 2515 is, however, ideally suited for use in such an environment, as:

1. It is portable and battery operated, and thus requires no awkward external power supplies;

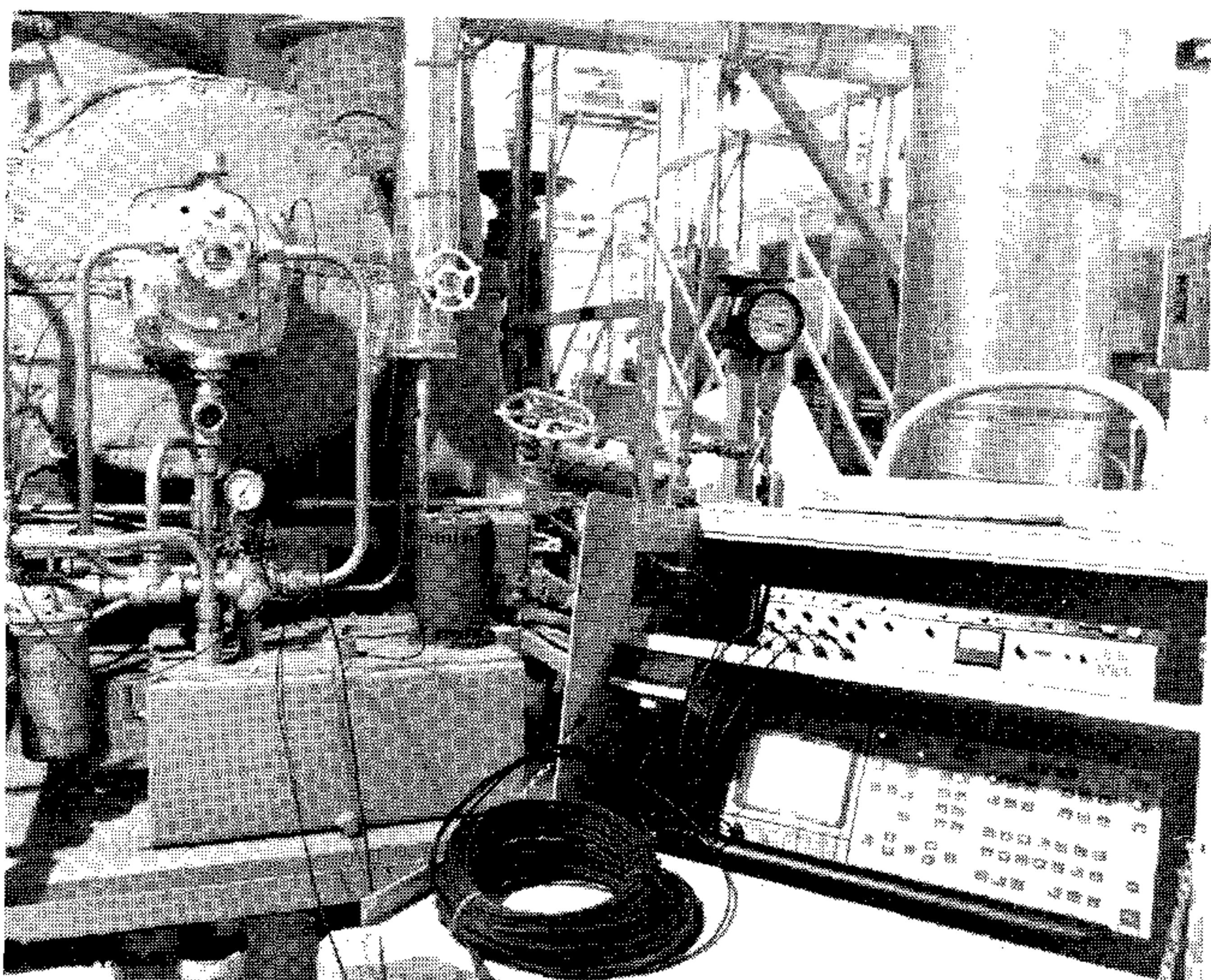


Fig. 5. Taping vibration from a steam generator feed water pump. The 2515 is also in use for on-the-spot trouble-shooting



Fig. 6. Using the Type 3537 Portable Tracking Balancing Set to balance a gland steam fan

2. It is very quick to use, which is important as time is limited due to radiation exposure;
3. It gives both a check on machine condition and diagnoses any faults on-the-spot;
4. Being waterproof it can easily be scrubbed down to remove contaminated particles; although the engineers usually enclose the instrument in, and operate it through, a clear-plastic bag. This bag can then be quickly discarded on leaving the containment building;
5. It can get to awkward areas, which is very useful as operation in the containment building is very often in confined spaces;
6. It contains no internal fans so there is no danger of sucking in contaminated dust.

The Machine-Monitoring Programme

The monitoring programme covers a total of 98 machines (a list of which is given on the back page), chosen using the following classification:

1. Machines critical to production – not duplicated, e.g. Turbine/generator;
2. Machines critical to production – duplicated, e.g. Steam generator feed-water pumps, circulating pumps;
3. Machines non-critical to production yet important for other factors (e.g. safety), e.g. Back-up diesels, quench spray pumps;
4. Problem machines.

Measuring the Vibration

The vibration pickup is made via accelerometers which can be attached to machines at strategic points. Accelerometer bases have been permanently fixed onto the monitored machines to allow for easy fixing and repeatable measurements. The output of the accelerometers can be directly connected to the Vibration Meter Type 2516, Vibration Analyzer Type 2515, Tape Recorder Type 7007 or Balancing Set Type 3537.

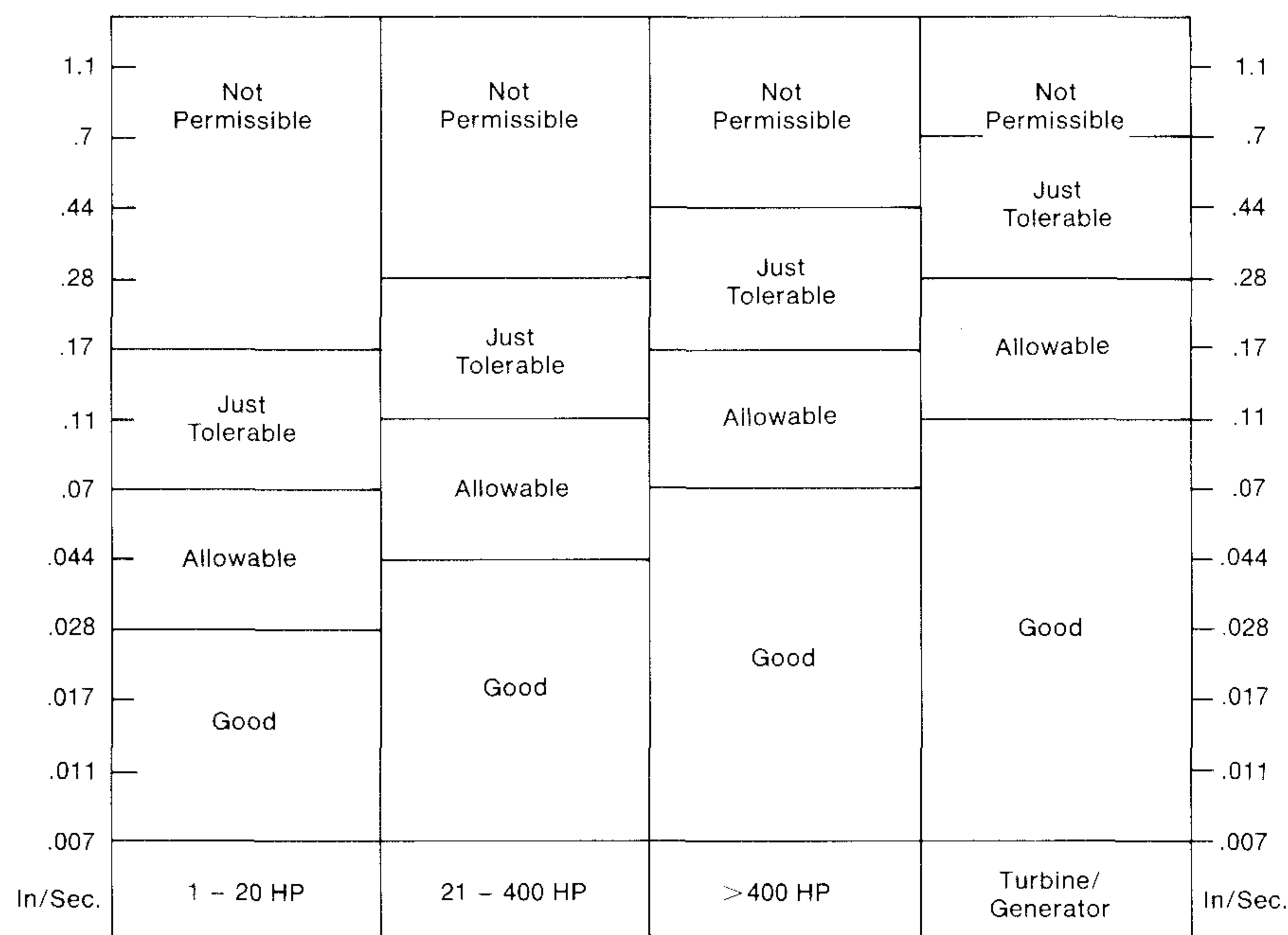
Measurement route assignment and control of data collection is organised with the aid of comprehensive record keeping using a personal computer.

The Weekly Check

Once per week the vibration meter is used to obtain overall vibration levels from each of the 98 monitored machines. The measurement procedure takes approximately 2,5 hours to complete. Measurements are restricted to one per machine, measuring at the bearing which had the highest vibration level last time that particular machine was analyzed.

Vibration Severity

To determine how critical a particular vibration level is, and to obtain an indication of the machine condition,



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Fig. 7. Example of the Vibration Severity chart used for assessing machine condition

the engineers make use of the Vibration Severity standards. These are drawn up for vibration measurements made in the 10 Hz to 1 kHz frequency range according to international standards (ISO 2372/3 & 3945), and they indicate the overall quality of a machine. Fig.7 shows an example of a vibration severity chart, and it can be seen that relative increases and not absolute vibration levels are of most importance. An increase of $\times 2,5$ (8 dB) indicates a change in the condition classification, and an increase of $\times 10$ (20 dB) indicates that vibration levels have reached the "danger" zone.

The Monthly Analysis

Once per month, vibration data from all measuring positions on all 98 machines are recorded using the Tape Recorder. It takes approximately 3 days to complete these measurements.

Having recorded all the data it is played back into the laboratory-based

monitoring system for analysis. Newly recorded frequency spectra are compared with previously stored reference spectra. Vibration increases at particular frequencies are noted, and the severity of the increase is determined by using the same criteria as for the Vibration Severity. Any faults detected in this way are then analyzed to determine their cause. The trend of the vibration increase is then calculated to determine when the level will become critical.

Reporting Procedure

Following the monthly analysis, a report is sent out informing of the results of the monitoring programme. In the event of a suspect machine being found, a maintenance guidelines report is issued, followed by a work order. On completion of the repair, the findings of the maintenance team are reported back to the Predictive Analysis Department for assessment.

Case Stories

The following gives some examples of faults detected and diagnosed by the machine-monitoring system.

Reactor Coolant Pumps

These are vertical, centrifugal pumps driven by 7000 hp motors for circulating cooling water through the reactor.

Due to the importance of these pumps and their location in the containment building where access is restricted, they are permanently monitored by an alternate (non-B&K) system, with a display of the overall vibration levels in the reactor control room. To frequency analyze the vibration signals, however, the engineers use the Type 7007 Tape Recorder to record the vibration signals from a signal output on the control room display for later analysis in the laboratory.

These pumps are removed one at a time for inspection and repair during

refueling outages. At one such inspection it was noticed that some of the motor rotor-bars were cracked. Subsequent to this a detailed vibration analysis of the remaining pumps was made to determine if this fault was widespread. This analysis revealed that all six pumps from the two reactor units (there are three pumps per unit) exhibited rotor-bar cracking. The faults showed up as a peak in the spectrum at a frequency corresponding to the rotation frequency \times the no. of bars (1185 RPM \times 133 bars), see Fig. 8.

The engineers were then able to keep a close check on the condition of the pumps, and inform maintenance about which of the pumps should be repaired next. Having detected this cracking, the monitoring equipment was promptly taken to Virginia Pow-

er's second nuclear power plant where the same problem was found.

It is interesting to note that, due to the low level of vibration caused by these cracks, the vibration data from the permanent transducers monitoring overall levels showed no sign of a change in pump condition. This phenomenon is again illustrated in Fig. 9, which clearly shows the advantages of using frequency analysis (and hence spectrum comparison) to detect faults. All the relevant frequency components can be clearly identified, and the smallest increase in their vibration level will be registered during a spectrum comparison. However, the vibration level of these components would have to rise above the level of the dominating peak before the overall level was affected.

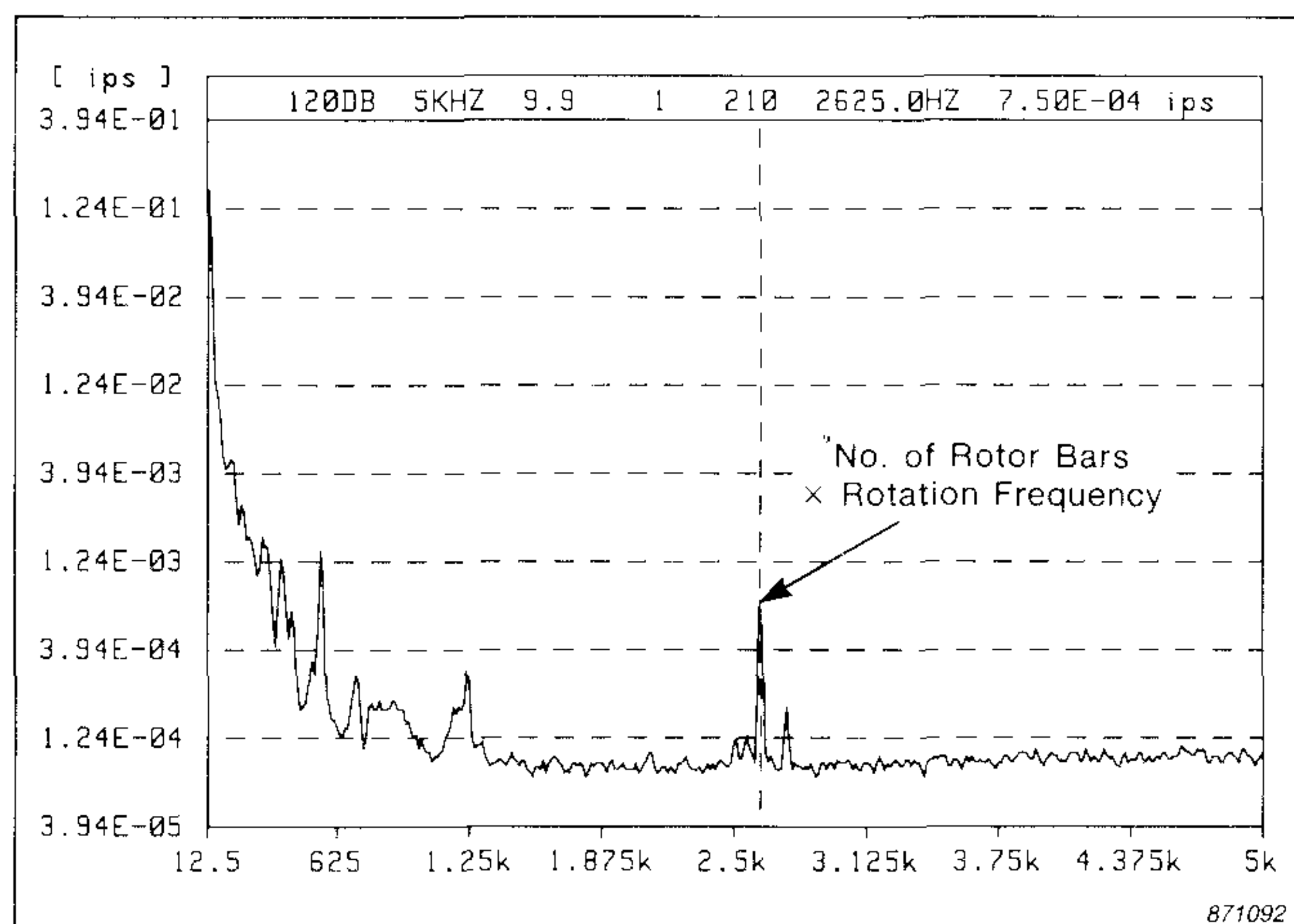


Fig. 8. Narrowband diagnostic spectrum from a reactor coolant pump showing a prominent peak at 2625 Hz

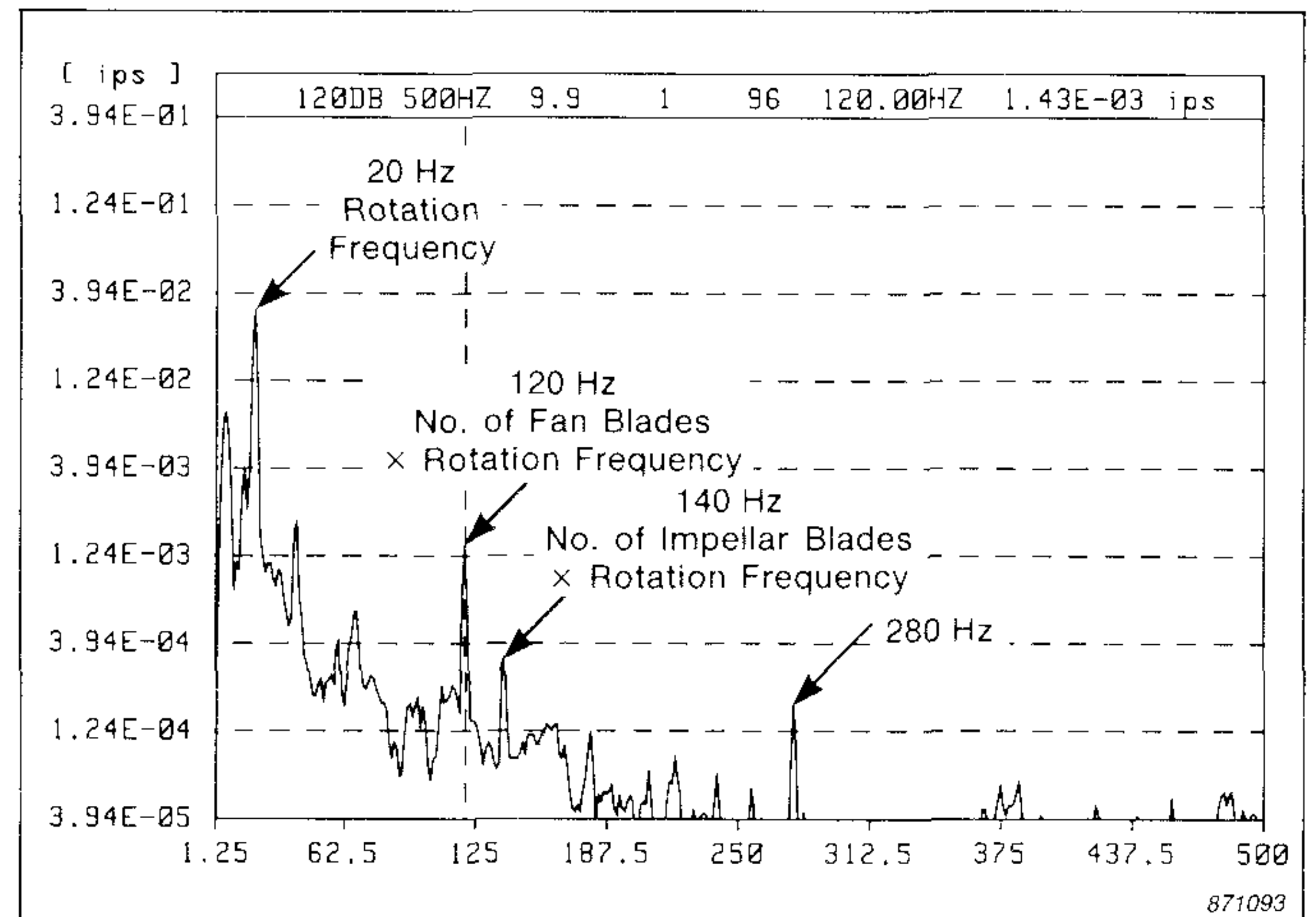


Fig. 9. Narrowband diagnostic spectrum from a reactor coolant pump clearly showing that the 20 Hz rotation frequency dominates the spectrum

Control-Rod Drive Motor-Generator Sets

These motor-generator sets supply power for the reactor control-rod drive mechanism. The generator, driven by 150 hp motors, is of the synchronous type generating 438 kVA. To maintain a constant load on the generator, a large (1500 lb) flywheel is positioned between the motor and generator.

During a routine weekly check with the hand-held vibration meter, high vibration levels were measured on the generator. Subsequently, vibration data was tape recorded for further analysis in the laboratory.

Fig. 10 shows a spectrum comparison taken from measurements made at the generator in-board bearing. The figure shows large vibration increases in the high frequency range, a characteristic of rolling-element bearing damage. The bearing was clearly in a relatively advanced state of damage.

It was feared that the load caused by the heavy flywheel could result in the damaged bearing failing catastrophically, possibly causing excessive damage to the generator (replacement cost is approx. \$50 000). This could then have resulted in a plant shut down.

Maintenance was therefore quickly scheduled and the damaged bearing replaced. The motor-generator set was back on-line within 24 hours.

Steam-Generator Feed-Water Pumps

These are horizontal, single-stage, centrifugal pumps supplying feed water to the steam generator. The pumps are driven by two direct-coupled motors driving in tandem. Due to the large steam demand whilst the plant is at full load, two of the three pumps must be in operation, the third in standby. In the unlikely event that one of the operating pumps should

fail, the standby pump must start and be able to function at full capacity in a matter of seconds to prevent a plant load reduction or a reactor trip due to low steam-generator levels.

On one of the pumps, excessive axial vibrations were measured on the out-board motor at a frequency corresponding to twice the rotational speed

(120 Hz). A spectrum comparison of vibration measured at this point, see Fig.11, shows a marked increase at 120 Hz. From this data and past experience it was assumed that the pump and its two motors were misaligned.

The motor was subsequently stripped and inspected, and damage to the shoulders of the sleeve bearings

was found; the shoulders of the shaft had evidently been pushed into the bearing by the misalignment. It was estimated that the fault was so severe that it would have caused a failure within one week had the monitoring system not been in use.

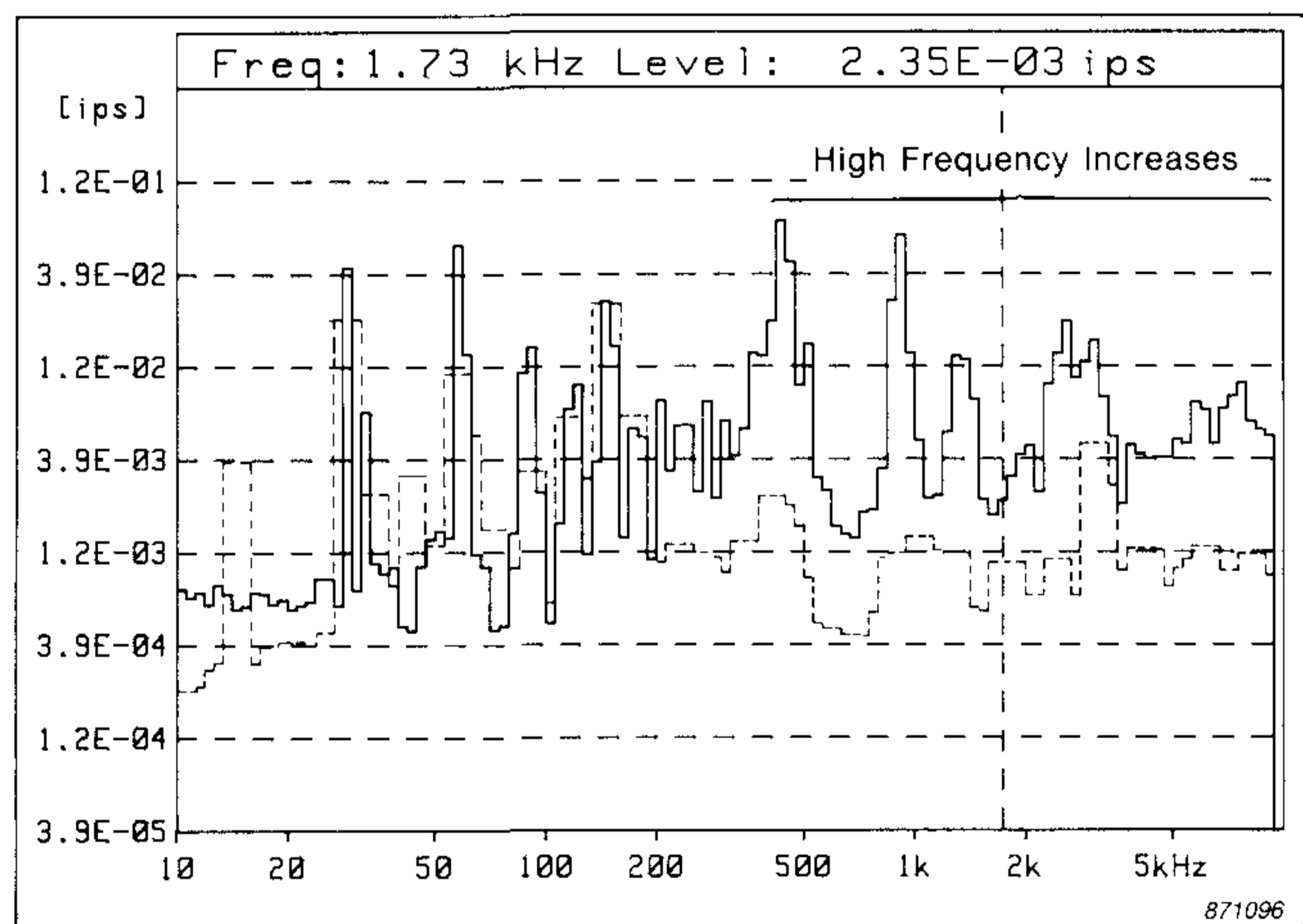


Fig. 10. Spectrum comparison from a rod-drive M-G set showing a large increase in the whole upper frequency range

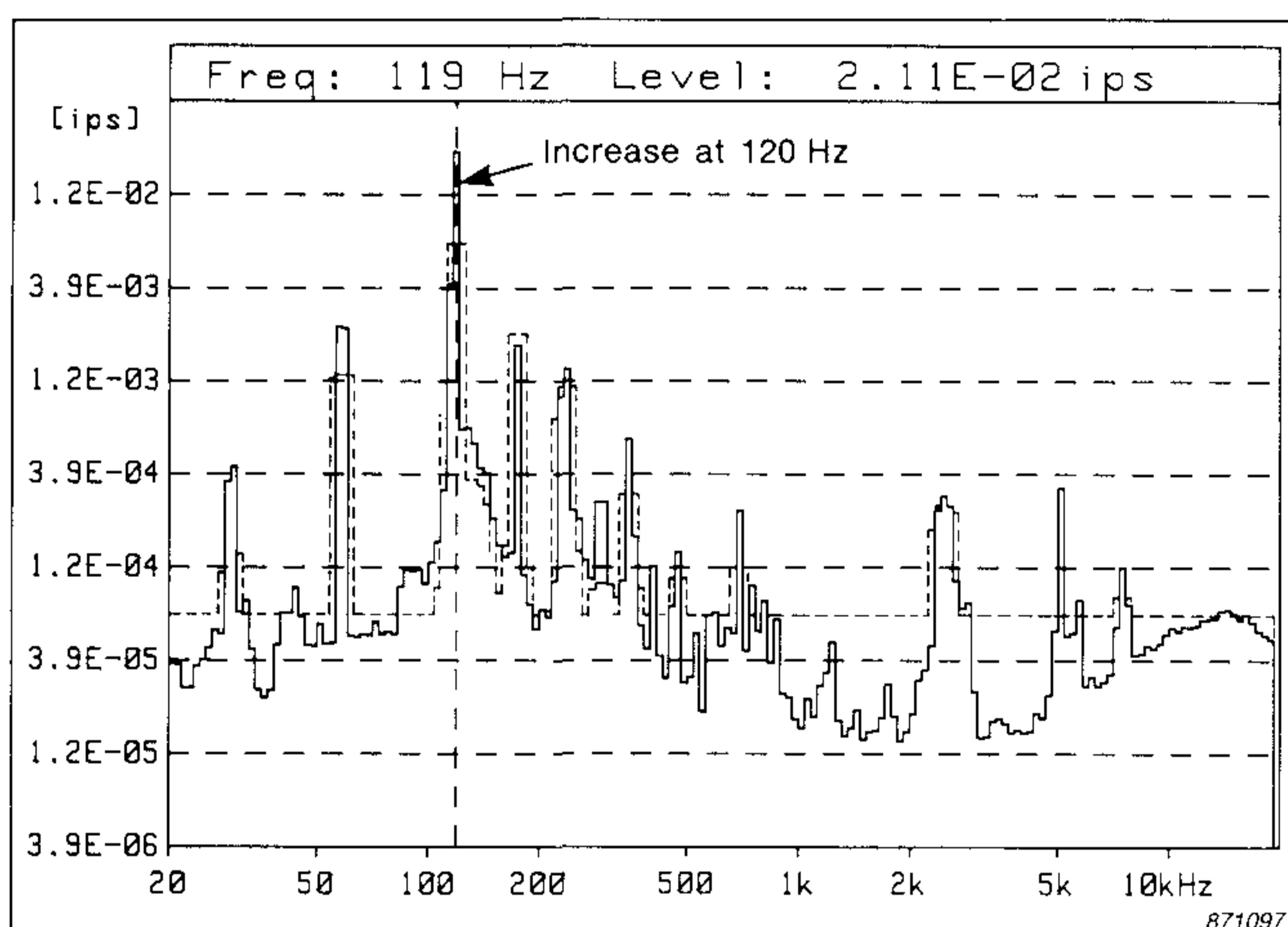


Fig. 11. Spectrum comparison from a steam generator feed water pump showing an increase at 120 Hz

Low-Pressure Heater-Drain Pumps

These are 500 hp horizontal pumps for pumping preheated low-pressure turbine condensate into the main condensate stream.

High vibration levels were measured on the in-board sleeve bearing of one of these pumps. Fig.12 shows a spectrum comparison indicating a significant increase at 120 Hz, which corresponds to twice the rotational frequency. To stop and inspect the

pump, however, would have meant reducing the plant load which was considered very inconvenient at that time. It was, in fact, deemed necessary for the pump to remain in service for at least one week.

The Type 2515 was therefore used to monitor the bearing on a daily basis. Fig.13 shows a trend of vibration levels at 120 Hz. The vibration was seen to level off and even decrease a little.

Spare parts were made available and repair scheduled for a weekend when the power demand was not so high. The pump was stripped and the damaged bearing replaced. When the pump was restarted, the Type 2515 was again used to check the vibration levels, and the last measurement in Fig.13 shows that the vibration had returned to normal.

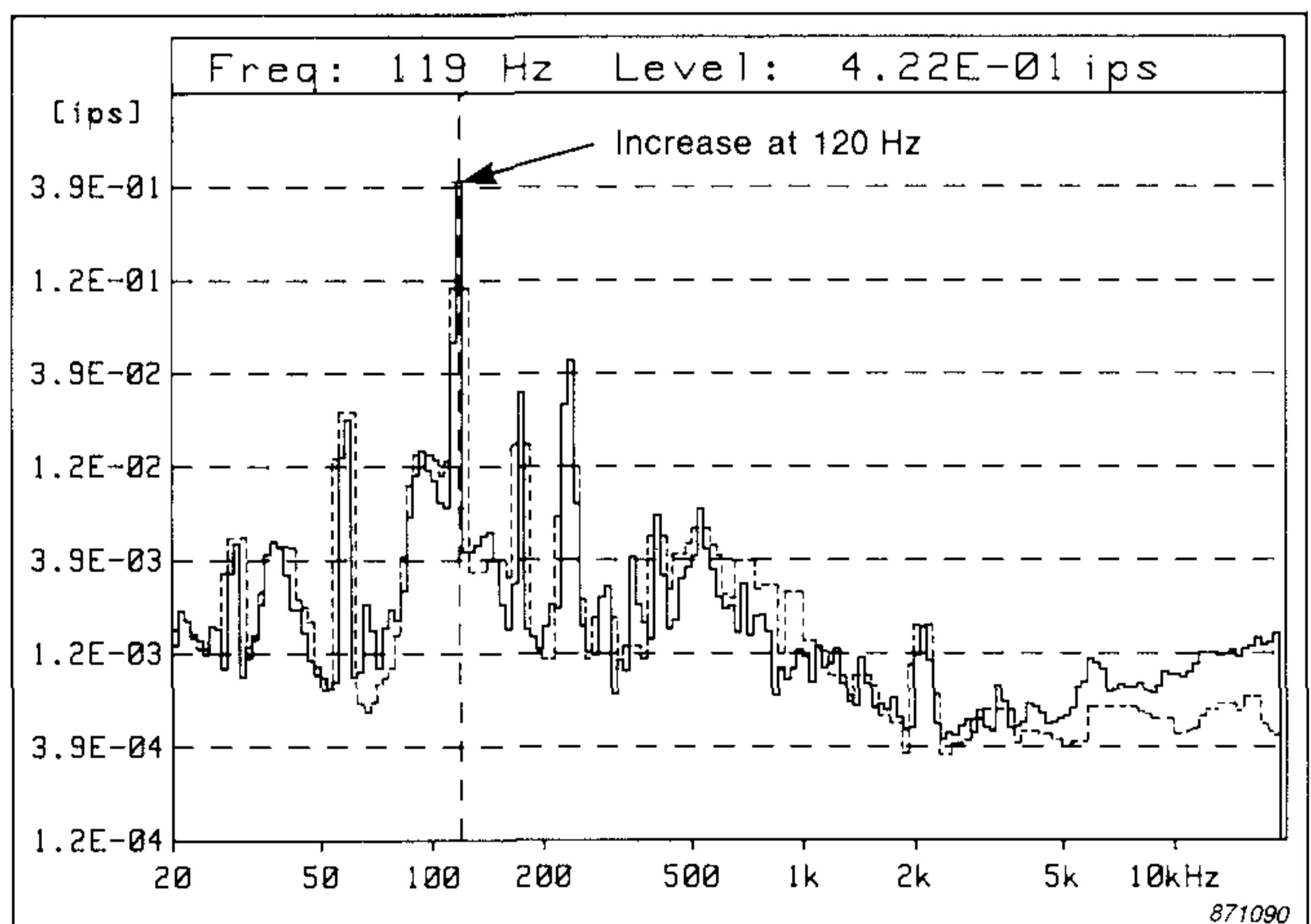


Fig. 12. Spectrum comparison from a low pressure heater drain pump showing a significant increase at 120 Hz

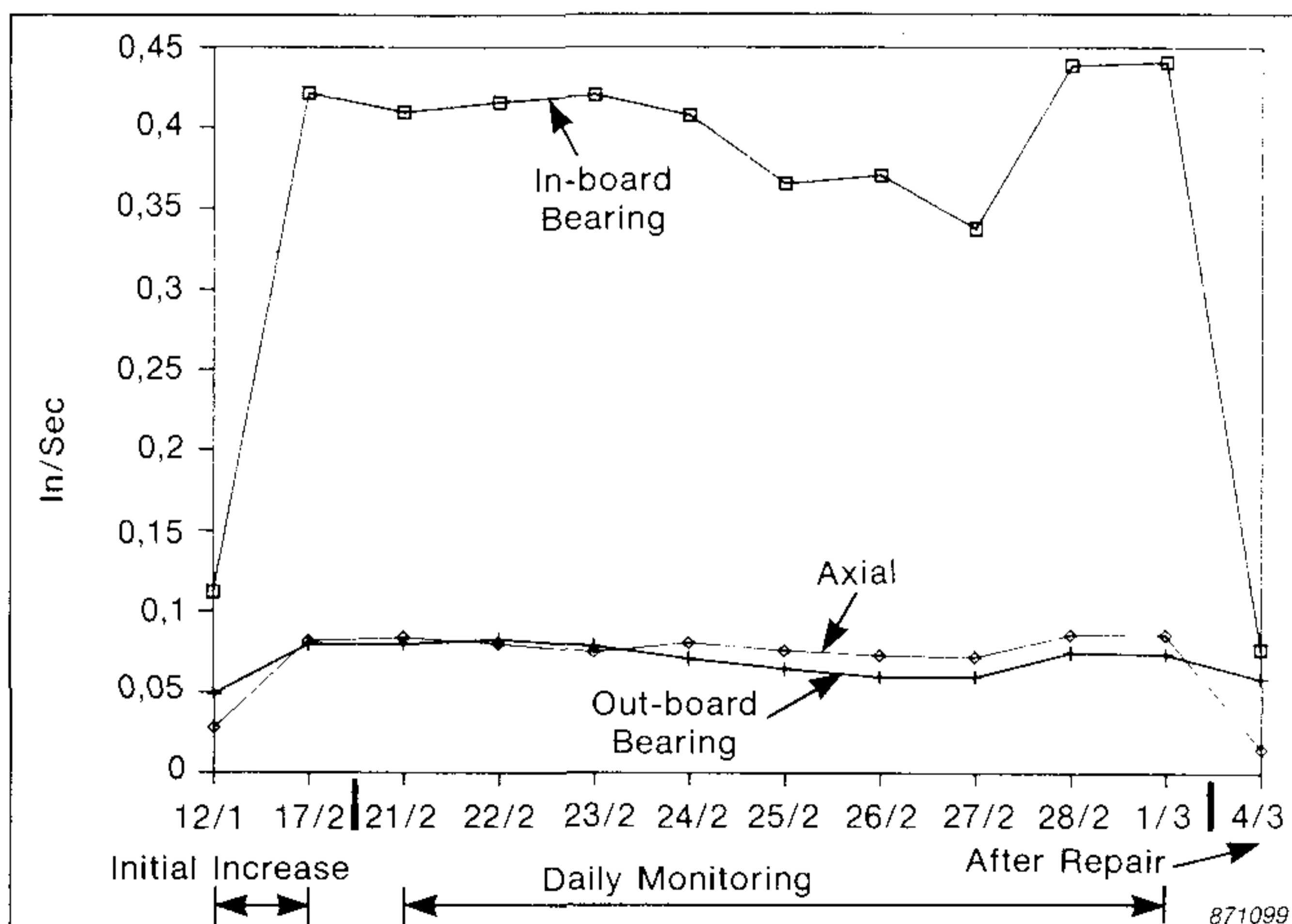


Fig. 13. Trend curve from a low pressure heater drain pump measured at 120 Hz

Main Turbine

The turbine is a 1800 RPM, 970 MW unit, consisting of one double-flow high-pressure turbine cylinder and two double-flow low-pressure cylinders. The turbine/generator set is permanently monitored by an original equipment manufacturer (OEM) system of shaft riders, giving a display of overall vibration levels in the reactor control room. However, for vibration analysis of the turbine, the B&K accelerometer-based system is also used.

In the summer of 1986, the no.1 LP turbine suffered severe blade damage and it was necessary to replace the rotor spindle. In the winter of 1987, the vibration levels of bearing no.4 (associated with the LP turbine), began to increase. Fearing a possible repeat of the previous failure, the vibration from the LP turbine's bearings was analyzed and trended daily. The results were forwarded to the Superintendent of Maintenance for review. Fig.14 shows a spectrum comparison

from the turbine indicating an increase at 30 Hz, the rotational speed. Fig.15 shows trend plots at this frequency. Bearing 4's vibration level increased significantly whilst the others remained steady (for clarity, only results from bearings 4 & 5 are shown).

Because of this daily monitoring effort, the management felt confident that the signs of imminent failure could be detected in ample time to prevent another catastrophic failure.

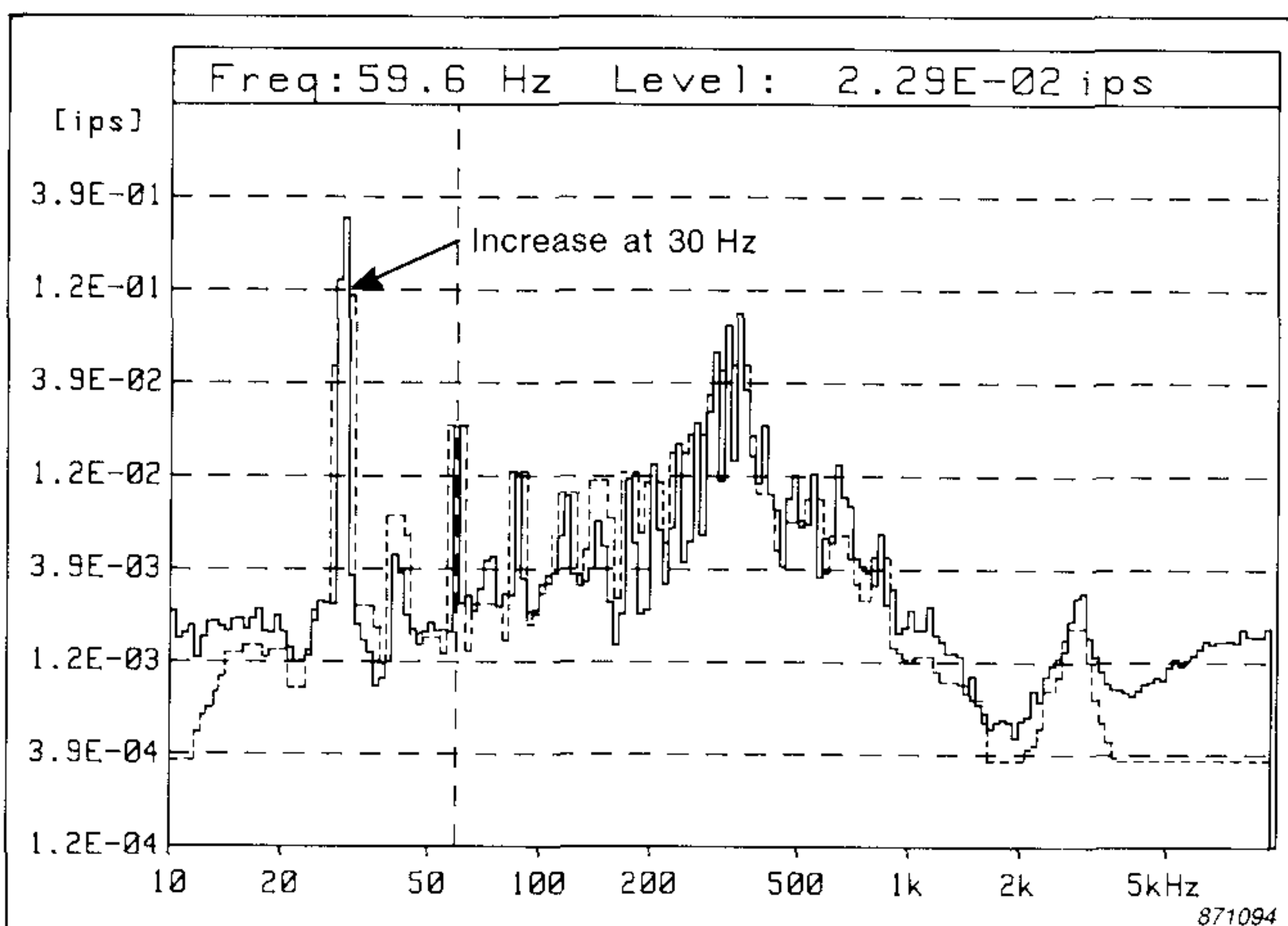


Fig. 14. Spectrum comparison from a turbine showing an increase at 30 Hz

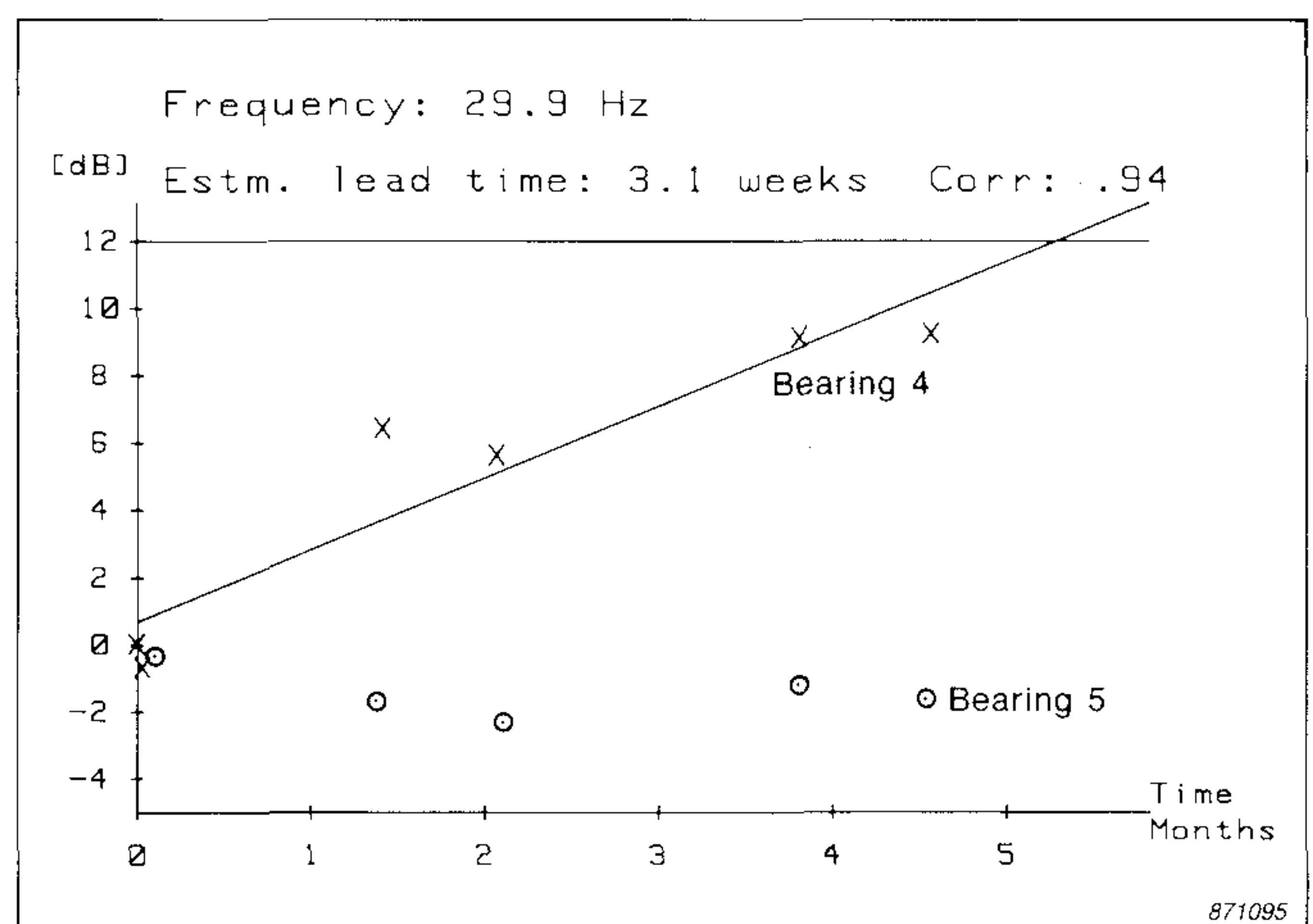


Fig. 15. Trend plot from a turbine measured at 30 Hz

Transformer Coolant Pumps

These are small (5 hp) pumps supplying cooling oil for the main step-up transformers.

Because of frequent failures in the transformers, a decision was made to monitor these pumps. It was feared that the pump's rotor bushings were wearing, causing the impeller to grind on the casing, thus introducing metal wear-particles into the cooling oil. This contamination could seriously affect the transformer operating safety.

Fig.16 shows a narrowband spectrum taken from one of the pumps. This shows a marked 30 Hz harmonic pattern – 30 Hz being the shaft rotation frequency. Fig.17 shows a narrowband zoom spectrum, also clearly showing a 30 Hz pattern. On being presented with this data, the Superintendent of Substations decided to change all the pumps during a reactor refueling outage. This was a very costly procedure involving the draining of several thousand gallons of cooling oil from each transformer, but was a mi-

nor investment compared with the cost of a transformer failure.

On inspection of the pumps, some wear was found on the thrust bearings. However, on further study it was found that the mounting of the pumps was suspect, causing the pumps to vibrate excessively. This mounting problem would account for the prominent patterns seen in Figs.16 and 17 as looseness is usually characterised by a large number of harmonics.

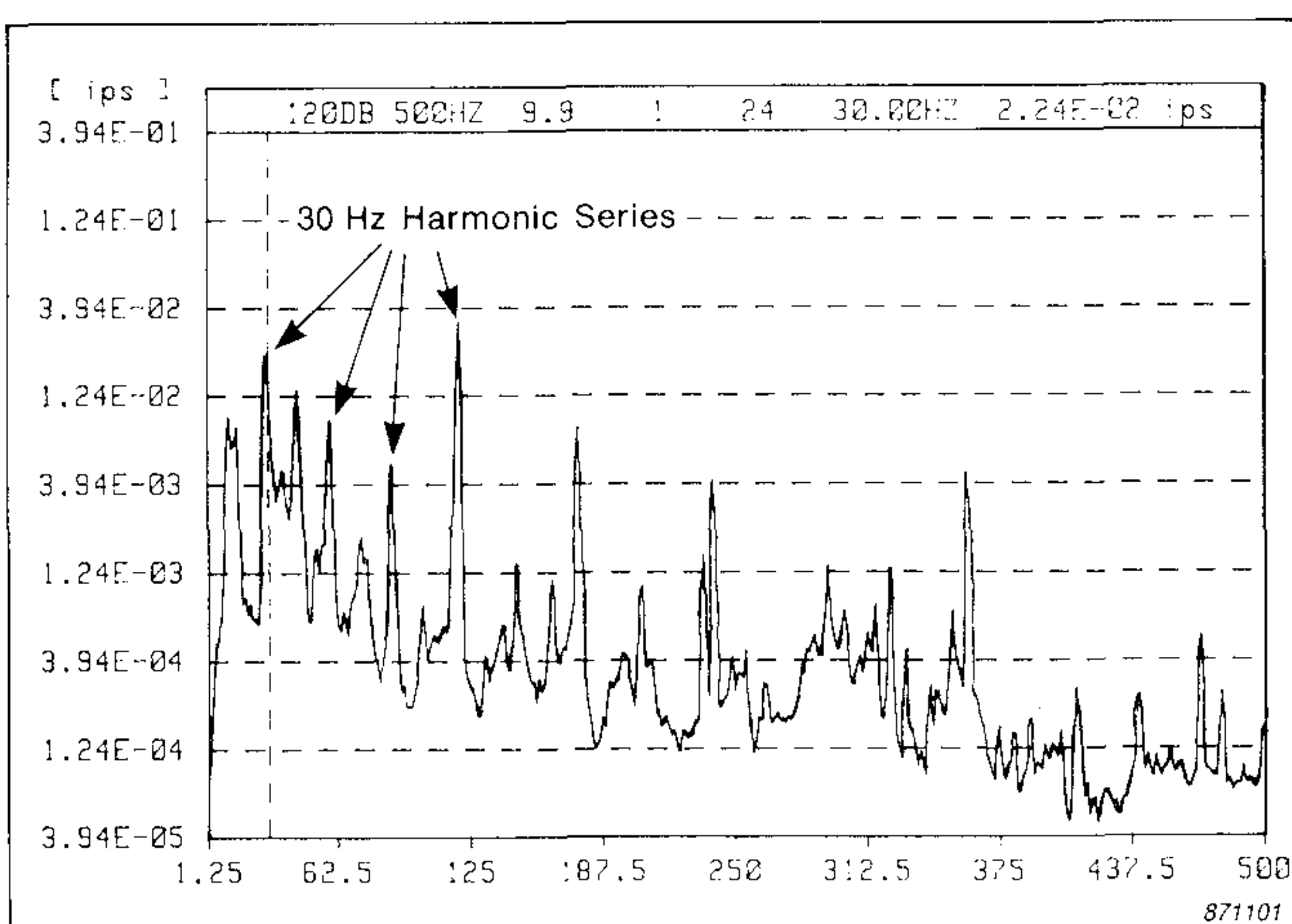


Fig. 16. Narrowband diagnostic spectrum from a transformer coolant pump showing a marked 30 Hz harmonic series

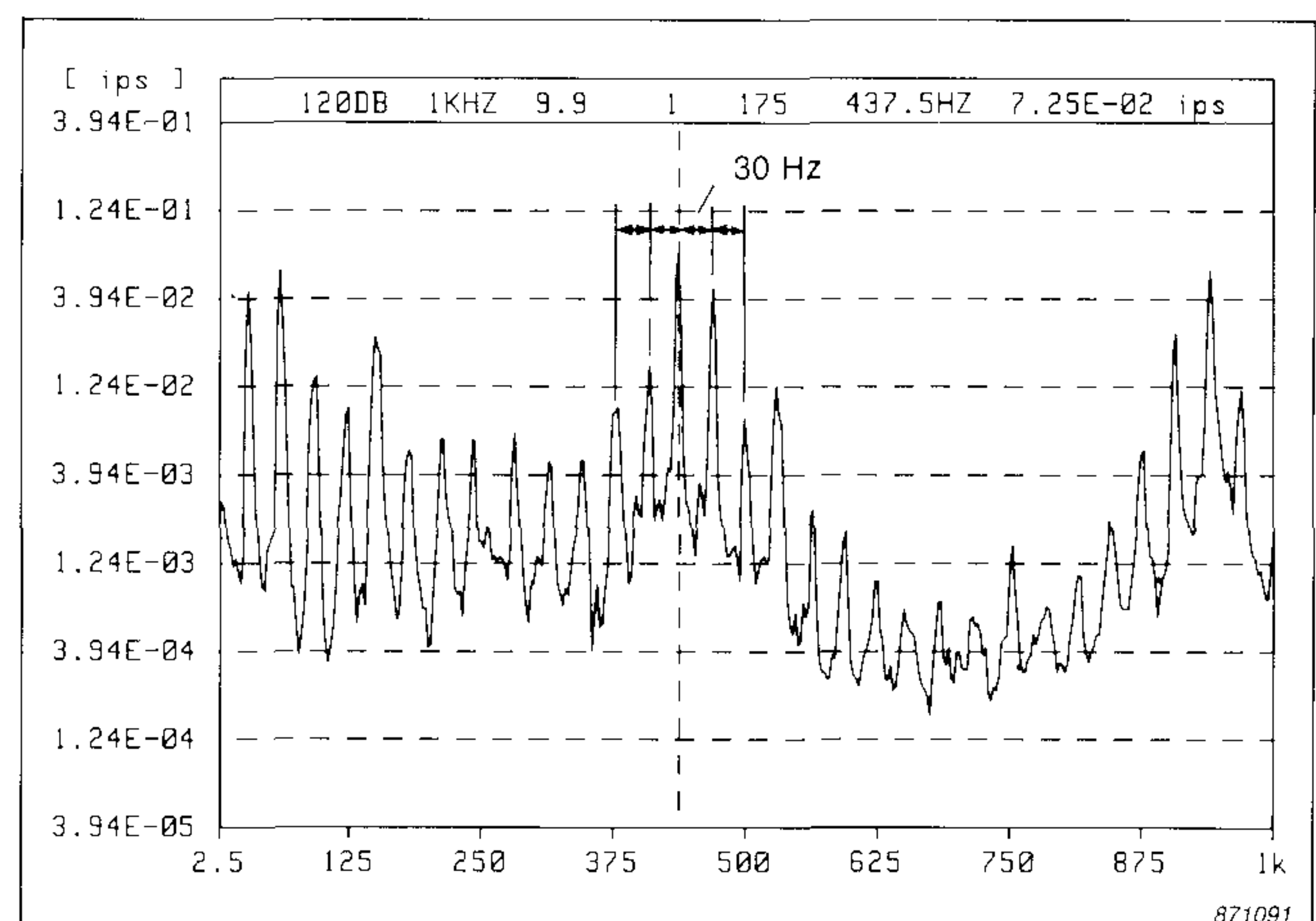


Fig. 17. Zoomed narrowband diagnostic spectrum from a transformer coolant pump

Vertical Circulating Pumps

These are extremely high volume (250 000 gallons/min) vertical pumps used to circulate lake water to the condensate well for condensing the exhaust steam from the low-pressure turbines.

Whilst securing one of the circulator pumps, an attempt to isolate the pump by closing the motor-operated discharge valve, resulted in the valve disc becoming dislodged from the stem and the valve not closing. With the pump motor de-energised, the pump began to rotate in the reverse direction due to the back-flow through the pump to the lake. Since the direction of rotation and the hydrodynamic forces had changed on this pump, it was unknown as to what damage the motor and/or pump would sustain.

Rather than shut down the plant, it was decided to monitor and trend vibration data on a twice-daily basis and report these findings to the Maintenance Superintendent. Management allowed the plant to continue operation until such time as it was convenient to shut down, confident that if any degradation of the motor or pump did occur, the daily vibration analysis would detect it early enough to prevent a major failure. No indication of any deterioration in condition was recorded and the plant was allowed to run for an additional 2 months. The motor was later inspected and discovered to have suffered no damage.

Balancing the Gland Steam Fans

These are overhung fans which provide sealing of the turbines to prevent leakage of air into or steam out of the steam turbines.

These fans have been known to use up one set of bearings a year due to unbalance problems. Traditionally, the fans were removed and rebalanced in the machine shop – it was always considered difficult to balance the fans in place due to their poor mounting. However, using the Type 3537, the engineers were able to successfully rebalance the fans and reduce the vibrations to a reasonable level.

Backup Diesel Generators

There are two backup diesels per unit available for supplying emergency power to each reactor unit. On each

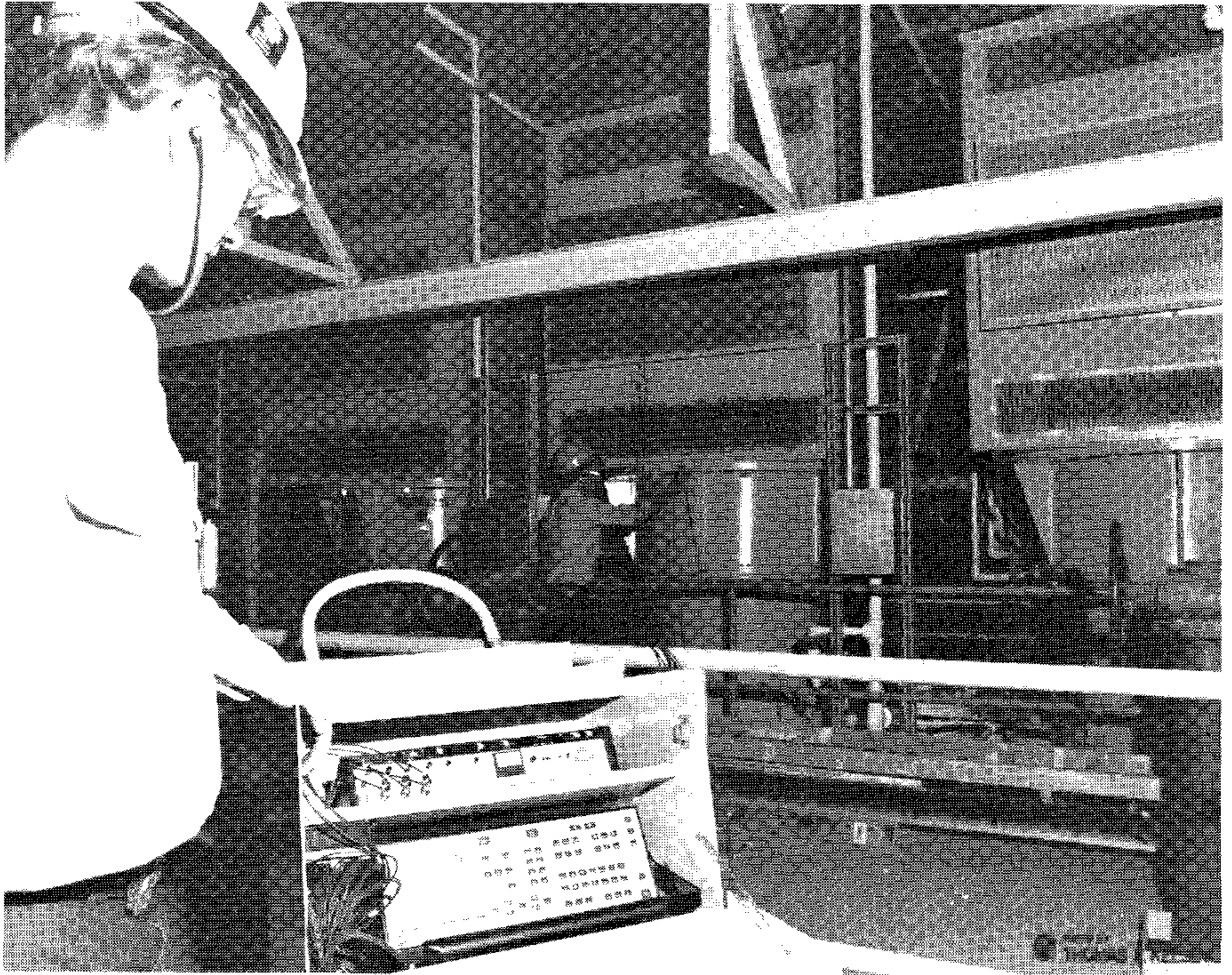


Fig. 18. Tape recording vibration from a vertical condensate pump



Fig. 19. The main turbine

diesel, the two turbochargers and major shafts and bearings are monitored during test-runs. The installation of a

permanent monitoring system to automatically keep a check on the two diesels is being considered.

Conclusions

The goals set by the North Anna Power Station when installing the monitoring system, of reduced forced outage and maximum utilisation of available assets have been well met. This Application Note has detailed a number of examples where the monitoring programme has successfully picked up and diagnosed machine faults. Not only have a number of possible catastrophic failures of critical units been avoided, but in many cases faults have been detected and monitored closely to ensure that significant damage is avoided. In this way, the unit could be operated safely until the load could be altered or until maintenance could be scheduled, thus minimizing disruption.

With the introduction of the monitoring system, the maintenance department has been able to move away from the more traditional preventive maintenance schemes. They now focus on a predictive maintenance programme, where corrective maintenance is carried out based upon the results of periodic frequency-analysis of machine vibration.

Multi-Million Dollar Savings

With the cost of reactor outage an estimated \$1 million per day, the incentives for keeping the plant running at maximum output are obviously very high. Indeed, the performance of Virginia Power's North Anna Power Station has exceeded the average for the entire U.S. industry for the fifth consecutive year. This record owes a lot to the machine-monitoring programme. In 1984, the year the monitoring programme was implemented, an estimated \$2 million were saved and in 1985 an estimated \$3,5 million. These figures are quite significant, especially when considering the state of the utility industry in general. The construction of many nuclear plants has been cancelled, and the number of new fossil plants is uncertain. The industry is faced with the task of improving the reliability of existing power plants, many of which are operating beyond their design life. The use of the monitoring programme at the North Anna Power Station has proved vibration monitoring to be a viable approach to improving the reliability of rotating equipment.

Monitoring in Fossil-Fueled Power Stations

The reactor, steam generator and the large pumps that move the water between them are all housed in the separate containment building. These are the nuclear parts of the power station – the only major parts in the nuclear station that are not in a fossil-powered station. The monitoring of the turbine, generator, numerous feed-water pumps and the large amount of ancillary equipment (compressors, fans etc.) placed outside containment, would therefore be the same in all types of steam-powered generating plants. This Application Note therefore serves as an illustration of the benefits of vibration monitoring in these plants as well as the nuclear plant at the North Anna Power Station.

Senior Engineering Technicians Mike Armstrong and Don Critchfield were transferred from the Electrical Shop inside North Anna Power Station to setup the Predictive Analysis Department in the beginning of 1984. Since that time they have been employed full time on the vibration-monitoring programme. Their ultimate goal is to tie in the monitoring programme at the North Anna Power Station with a similar programme at Virginia Power's second nuclear-power plant at Surry. Using a telecommunications link, information from one plant will be readily available at the other, and the same type of machine from the two different sites will be able to be compared.

The author wishes to express his gratitude to Mike Armstrong and Don Critchfield for all their help in gathering information for this report. Thanks are also due to Station Manager Wayne Harrell, Superintendent of Maintenance Mike Kansler, and Senior Electrical Maintenance Engineer Jim Keiser for permission to visit and report on the North Anna Power Station.

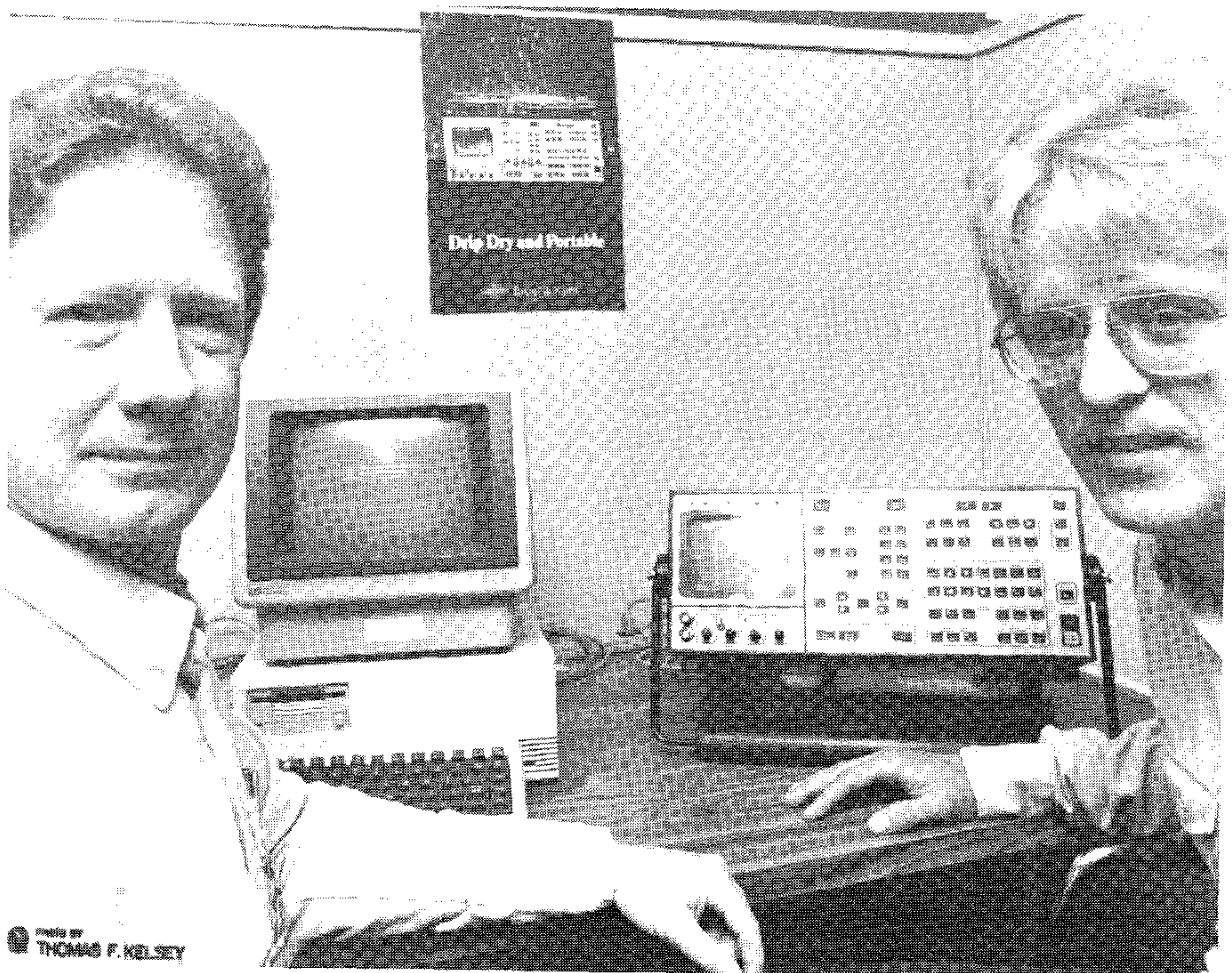


PHOTO BY THOMAS F. NELSEY

Equipment Monitored (per Unit)

Auxiliary Building/Safeguards Building

Control Rod Motor Generator Set (×2)
Iodine Filter Fans (×2)
Boron Charging Pumps (×3)
Low Head Safety Injection Pumps (×2)
Recirculation Spray Pumps (×2)
Component Cooling Pumps (×2)
Instrument Air Compressors (×3)
Terry Turbine (×1)
Half Size Auxillary Feed Pumps (×2)

Quench Spray Building

Quench Spray Pumps (×2)

Containment Building

Reactor Coolant Pumps (×3)
Residual Heat Removal Pumps (×2)
Control Rod Shroud Cooling Fans (×6)
Air Recirculating Fans (×3)
Reactor Coolant Pump Cubicle Exhaust Fans (×3)

Turbine Building

Turbine and Generator
Turbine High Pressure Oil Pump
Turbine Bearing Cooling Water Pumps (×2)
Turbine Air Side Seal Oil Pump
Turbine High Pressure Seal Oil Backup Pump
Turbine Gland Steam Air Exhaust (×2)
Generator Leads Fans (×2)
Generator H₂ Side Seal Oil Pump
Generator Oil Reservoir Vapor Extractor
Generator Bearing Vapor Extractor
Steam Generator Feed Pumps (×3)
Condensate Pumps (×3)
High Pressure Heater Drain Pumps (×3)
Low Pressure Heater Drain Pumps (×2)

Other

Main Transformer Recirculation Oil Pumps (×3)
Circulating Water Pumps (×4)
Emergency Diesel Generators (×2)
Electric Fire Pump



WORLD HEADQUARTERS: DK-2850 Nærum · Denmark · Telephone: +45 280 05 00 · Telex: 37316 bruks dk

Australia (02) 450-2066 · Austria 02235/7550*0 · Belgium 02-242-97 45 · Brazil 246 8149 · Canada (514) 695-8225 · Finland (90) 8017044 · France (1) 64 57 2010
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