DEVELOPMENT OF AN INCIPIENT FAILURE DETECTION TECHNIQUE FOR MECHANICAL SEALS

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ABSTRACT

The technique for detecting or predicting mechanical seal failure will guarantee that plants and turbomachinery can be reliably operated and that maintenance expense can be reduced. A technique is discussed for monitoring a mechanical seal through high frequency acoustic emission (AE), which permits an estimation of the state of a mechanical seal and acquisition of information by which a failure is predicted or detected. The characteristics of AE from the mechanical seal and a favorable method for monitoring the state of the mechanical seal are discussed. The test results of years of research obtained by experiments conducted on equipment in petroleum refinery plants and laboratories, with regard to the relation between AE and leakage or seal face damage will be also reported.

INTRODUCTION

A research project carried out by a petroleum refinery has revealed that mechanical seal failures have caused about 80 percent of pump troubles and that a large amount of both labor and money is required to control this problem. Mechanical seal failure, which usually results in an excessive amount of leakage, can lead to disasters such as fires and environmental pollution or could bring a plant's operation to an emergency stop. Usually, mechanical seals are frequently checked and are replaced in order to prevent failures. It is important to develop techniques for detecting or predicting such a failure so that plants and turbomachinery can be reliably and safely operated and maintenance expense reduced.

Techniques for predicting failures of ball bearings or other components of a pump have been developed and put to practical use, whereas techniques for predicting mechanical seal failures have not yet been developed. While failures in bearings and other pump components are a result of discontinuous destruction, it is difficult to detect failures in mechanical seals, because as a mechanical seal is operated, it undergoes gradual and continuous wear. This wear results in damage to the seal face. In addition, excessive leakage doesn't always depend on the damaging of a seal face. The conditions under which mechanical seals are used vary from seal to seal, and it is rarely possible to specify the cause of a failure. As a result, the general relationship between failures and their causes has never been verified.

About a decade ago, the Exxon Chemical Company., U.S.A., made a pioneering attempt to predict mechanical seal failures by acoustic emission (AE) monitoring, a part of the Incipient Failure Detection (IFD) System [1]. An attempt similar to the previous example was made from 1981 through 1984, as part of a project sponsored by the Ministry of International Trade and Industry of Japan. After the end of the project, voluntary research was successfully carried out by the authors. At present, no method has been developed other than the AE method for monitoring a failure in the mechanical seal. This is the only method that can be used without negatively affecting the operation of the mechanical seal and, can be easily and widely applied. However, there are many technical problems to be solved before the AE method can be regarded as a reliable method for predicting failures in mechanical seals. The achievements attained so far are introduced and suggestions are offered on how to solve these difficult problems.

The first problem in applying the AE method is whether it is possible to distinguish between an AE generated by mechanical seals and those generated by bearings, motors, fluid, and anything else located near a mechanical seal. The experiments conducted to measure and analyze AEs use artificially generated waveforms, and confirm that this problem can be solved. The second problem is determining what information can be obtained from a measured AE and whether or not the information thus obtained can detect or predict failures in mechanical seals. As a result of experiments conducted over a long time period on test apparatuses in a laboratory and on process pumps in operation in petroleum refineries, some knowledge by which this difficult problem can be solved has been obtained.

These experiments have been conducted on mechanical seals for use in process pumps for refining petroleum and processing petroleum chemically. The method obtained by the experiments described above can be applied to mechanical seals which are used in other equipment. In addition, the method can be applied for other purposes. For example, this method can be applied to the development of both the quality of mechanical seals and the criterion for examining product quality.

TEST PROCEDURES FOR BASIC STUDIES

A block diagram of the measuring and analyzing instruments used to make detailed examinations of AE wave forms generated by mechanical seals is shown in Figure 1. The frequency response characteristics of instruments are shown in Figure 2. Sensors having high frequency response characteristics in a broad band and pre-amplifiers which attenuate in the low frequency range were specially made for the experiment. AE signals recorded in a floppy disk were reproduced by a minicomputer and various analyses were carried out. For analyzing spectra, compensations for the frequency response characteristics of the sensors and the pre-amplifiers were made.

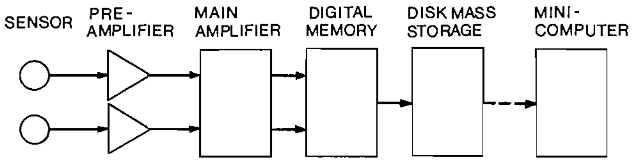

Figure 1. Block Diagram of AE Waveform Analyzing Instruments.

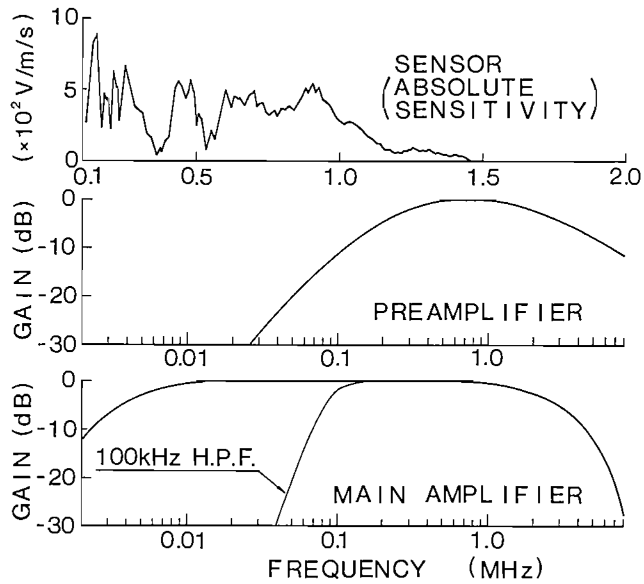

Figure 2. Frequency Response Characteristics of AE Measuring Instruments.

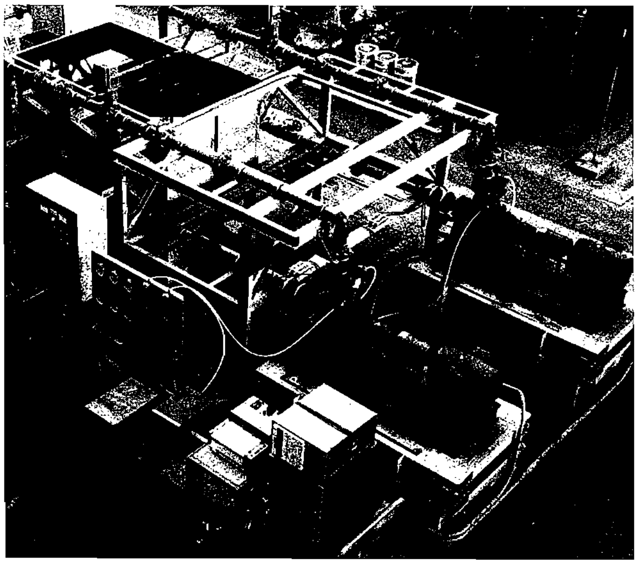

Figure 3. Test Apparatus.

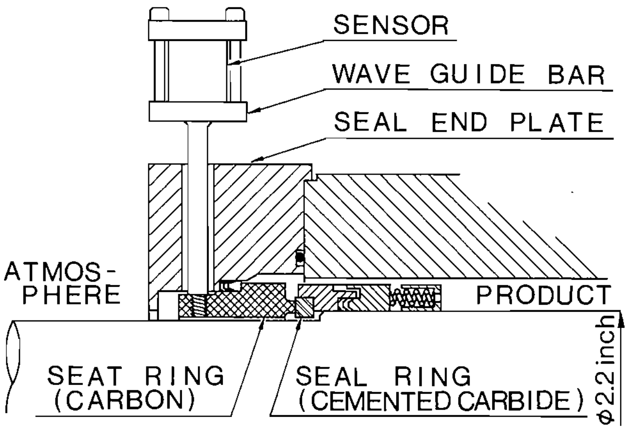

Figure 4. Mounting of a Sensor on a Mechanical Seal.

The experiment was conducted by a test apparatus (Figure 3) equipped with a standard process pump having a mechanical seal which is 2.2 in in nominal diameter and 0.15 in in seal face width. As shown in Figure 4, one sensor was mounted on a seat ring using a waveguide bar, and the other sensor was mounted on the pump casing.

AEs were measured according to the folowing conditions:

Normal	normal spring load (34 lb), normal flushing
Heavy load	double spring load, no flushing
Dry	double spring load, no sealing liquid
Pump impeller	with/without
Pump speed	3,000 rpm
Sealing liquid	15-30 psi pressured water at ordinary temperature

CHARACTERISTICS OF AE WAVEFORMS GENERATED BY MECHANICAL SEALS

Typical AE waveforms and their spectra shown in (Figures 5-9) were measured under the following conditions:

- the test apparatus was stopped,
- operating under the NORMAL conditions,
- operating under the HEAVY LOAD conditions,
- operating under the DRY conditions.

AE was measured at the seat ring and a pump without an impeller was used in this experiment.

Under the STOP condition (Figure 5), the AE signal consisted of mainly white noise generated from measuring instruments. The level of the AE was negligible. Under the NORMAL condition, (Figure 6), only a continuous type of AE was observed. Under the HEAVY LOAD condition, a continuous type of AE (Figure 7) and a burst type of AE superimposed over the continuous type of AE (Figure 8) were observed. In such a manner that both AEs were superimposed, the AE generated contained a continuous type of AE and a burst type of AE which changed its phase frequently. During this period, sometimes the two types of AEs appeared alternately and sometimes each of the AEs appeared continuously. Under the DRY condition (Figure 9), a burst type of AE which was superimposed over the continuous type of AE was observed frequently. The spectrum range of the AE is wide, namely, from a low frequency up to one MHz. A tangible change was found in high frequency over 400 KHz. It should be noted that the AE waveform generated under the HEAVY LOAD condition (Figure 8) was very similar to that generated under the DRY condition, (Figure 9). This fact indicates that AE was caused by solid contacts between sliding faces.

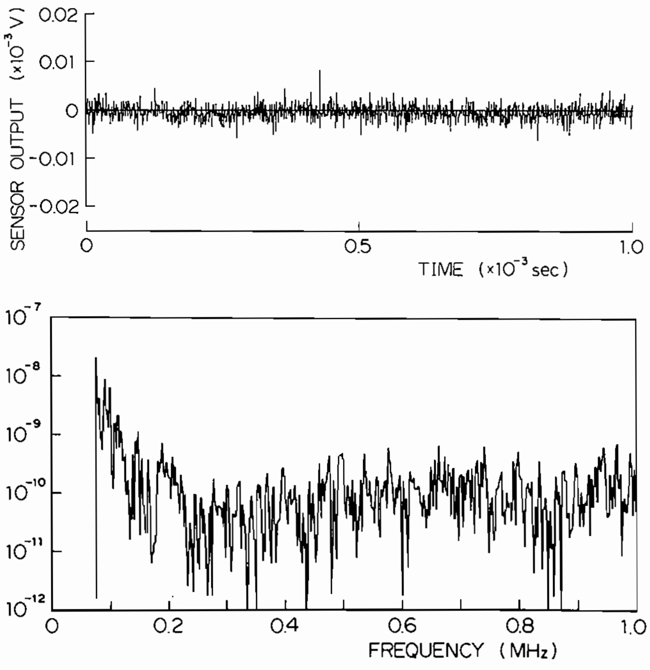

Figure 5. Typical AE Waveform and its Spectra under the STOP Condition.

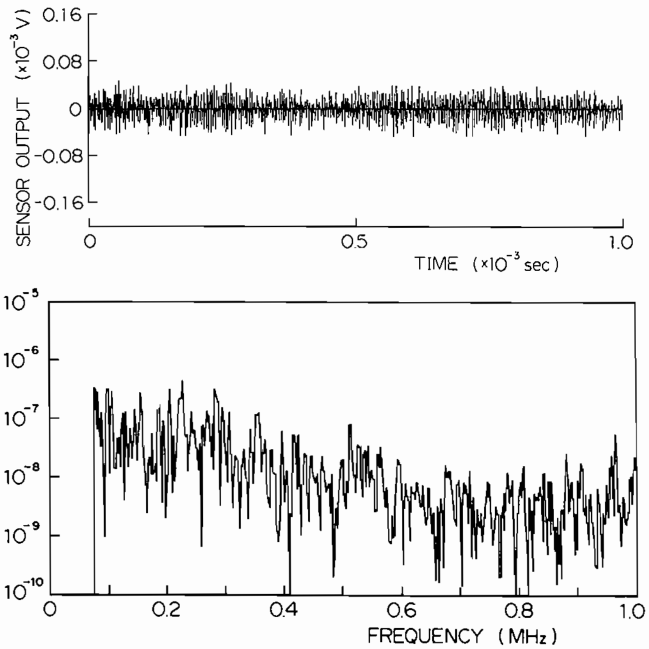

Figure 6. Typical AE Waveform and its Spectra under the NORMAL Conditon.

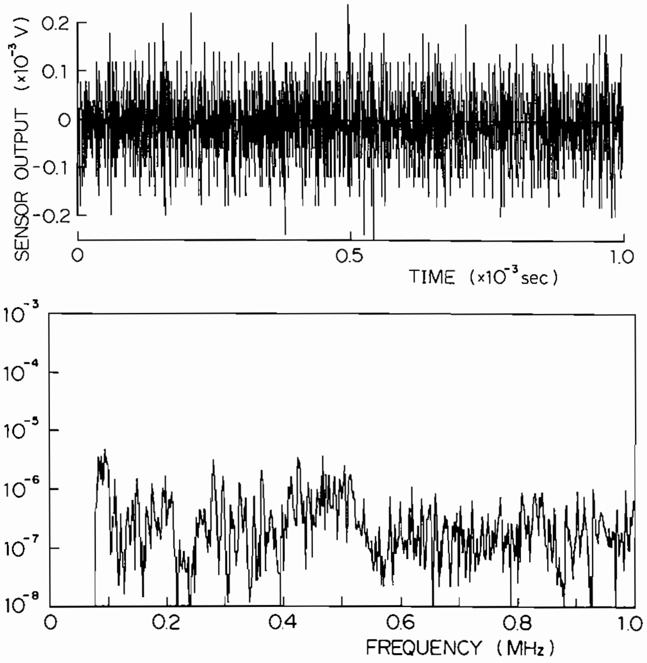

Figure 7. Typical AE Waveform and its Spectra under the HEAVY LOAD Condition.

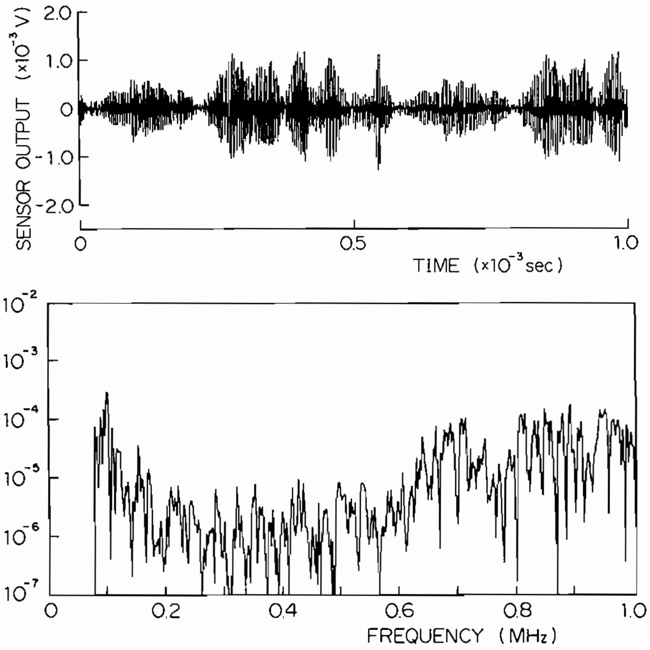

Figure 8. Typical AE Waveform and its Spectra under the HEAVY LOAD Condition.

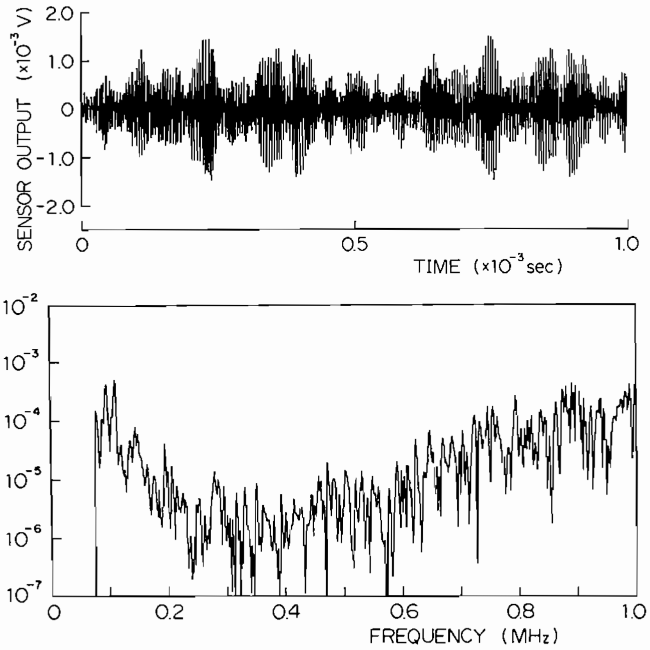

Figure 9. Typical AE Waveform and its Spectra under the DRY Condition.

An amplitude distribution diagram, in which the relation between the threshold and the counts of a waveform is determined, is presented in Figure 10. In the diagram, the abscissa indicates the threshold and the ordinate indicates the counts which the amplitude of AE wave exceeded the threshold per unit time period. Additional data obtained under the same condition is shown in the diagram. Differences between AE waveforms observed under the previously described conditions are clearly shown. The diagram clarifies that the variation of AE waveform under the HEAVY LOAD condition is greater than that under the NORMAL condition and sometimes such variation becomes the same as that under the DRY condition. The diagram implies that the amplitude of the AEs permit an estimation of the state of mechanical seals.

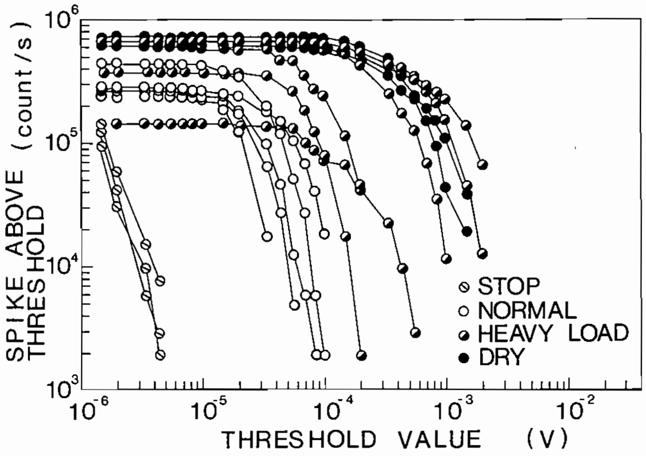

Figure 10. Amplitude Distribution Diagram of AE Waveforms.

INFLUENCE OF NOISE AND SENSOR POSITION ON AE MEASUREMENT

From a practical point of view of an AE measurement, AE generated by fluids, mechanical components, and anything else must be considered. In addition, it is impossible in practical use to link a waveguide bar to a seat ring in order to assure the reliability of the mechanical seal.

In order to investigate any influence of noise and the position of the sensor on AE measurement, the output from sensors mounted on both a seat ring and on a volute casing were simultaneously measured for comparison.

An AE measurement was carried out on a pump without an impeller under NORMAL and HEAVY LOAD conditions. Resulting AE waveforms and their spectra are shown

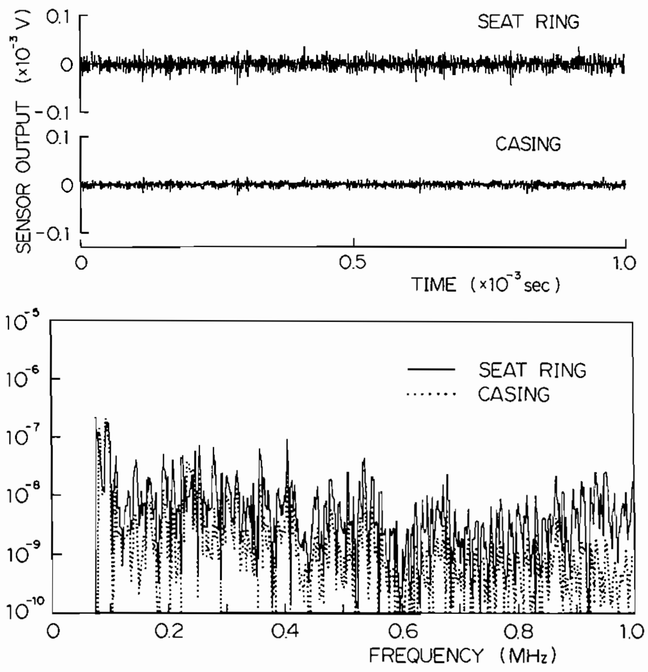

Figure 11. Influence of Noise and Sensor Position (without Impeller) under the NORMAL Condition.

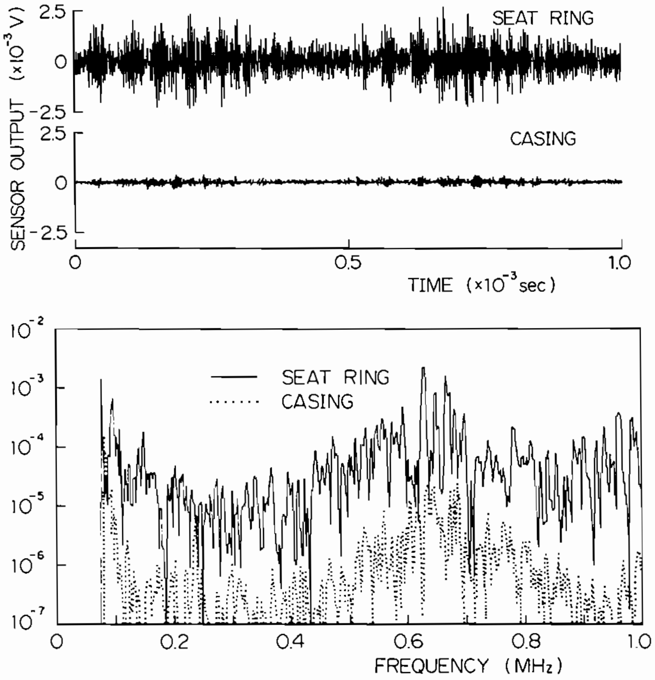

Figure 12. Influence of Noise and Sensor Position (without Impeller) under the HEAVY LOAD Condition.

in Figures 11 and 12. The AE value measured on the casing was attenuated by 10dB to 20dB, compared with that measured on the seat ring in both conditions; however, the waveform characteristics were not lost. The AEs were not influenced by the AE generated from ball bearings and other components of the pump, because the frequency range of the AE generated from ball bearings and other components of the pump is as low as 100 KHz.

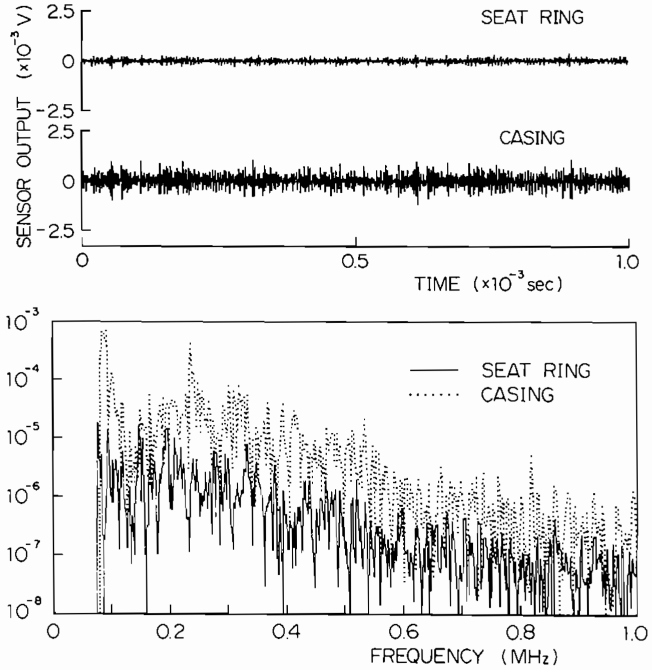

Figure 13. Influence of Noise and Sensor Position (with impeller) under the NORMAL Condition.

An AE measurement was carried out on a pump with an impeller under NORMAL and HEAVY LOAD conditions. Resulting AE waveforms and their spectra are shown in Figures 13 and 14. During the experiment, the pump was operated under the excessive flow rate region, so that cavitation noise generated from a discharge valve was observed. Under the NORMAL condition (Figure 13), the amplitude of the waveform measured on the casing was greater than that measured on the seat ring. The AE generated by the mechanical seal was masked by the cavitation noise. As shown in Figure 13, the main component of the spectrum of the cavitation noise had a low frequency of less than 500 KHz. Under the HEAVY LOAD condition (Figure 14), the influence of the cavitation noise was observed in the low frequency range. However, as the peak in the neighborhood of 800 KHz shows, the characteristics of the AE generated from the mechanical seal were confirmed by the sensor mounted on the casing.

The test results described above indicate that the AE of a mechanical seal can be detected in the casing of a pump and distinguished from AEs generated by cavitation noise having a relatively high frequency range, by inspecting a frequency range higher than 500 KHz.

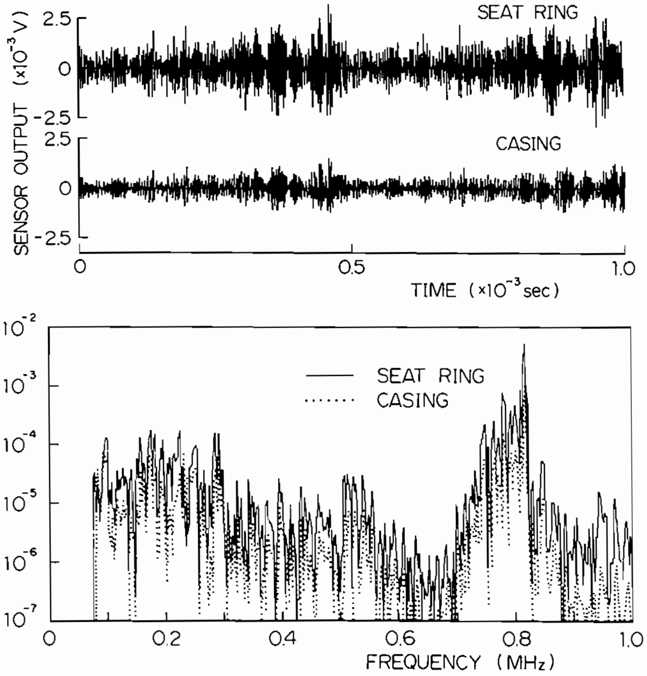

Figure 14. Influence of Noise and Sensor Position (with impeller) under the HEAVY LOAD Condition.

MEASURING METHOD AND TEST PROCEDURES FOR MONITORING MECHANICAL SEAL

It is too difficult to apply the method for measuring and analyzing AE waveforms to monitor a large number of mechanical seals in real-time, in view of the effect and cost. As described above, failures in bearings and components occur due to a discontinuous destruction, so that their failures can be detected by comparing the AE waveform of normal conditions with that of failures. It is, however, impossible to immediately detect a mechanical seal failure with an AE waveform, because when a mechanical seal is operated, it undergoes gradual and continuous wear which results in damage to the seal face. In addition, excessive leakage doesn't always depend on the damaging of a seal face. Thus, there is a need to develop a continuous monitoring method by which the state of mechanical seals can be efficiently and appropriately monitored to detect or to predict failures.

A typical block diagram of a measuring system which is used in laboratory experiments and at job sites is shown in Figure 15. An AE signal output from a plurality of AE sensors is sequentially selected by muitiplexers, and then, the signal gain is adjusted and converted into root-mean-square (RMS) values recorded using a personal computer. AE instruments used in this experiment are of the same type as those used in the previously described fundamental experiment, except that 100 KHz high-pass filters are added to the main amplifier (Figure 2) and explosion-proof instruments are taken for use at jobsites. The outline of the measuring procedure is shown by the flow chart in Figure 16. AE data sent to an AE sensor is processed in about five seconds by the following operations: selection of AE sensor by the multiplexer, adjustment of the gain of the main amplifier, and input of 100 data samples to the AE sensor. Sequential input of AE data to the AE sensors is repeated for 15 minutes to calculate maximum, minimum, mean values, and standard deviations of each sensor and to file these values with a storage device.

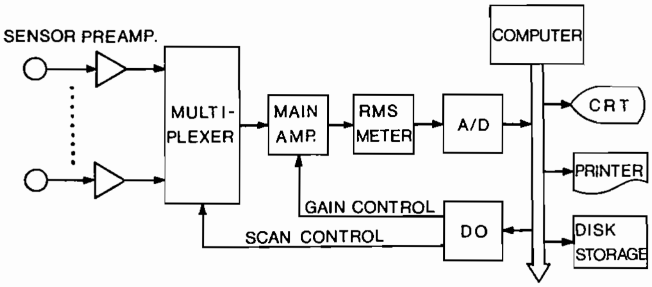

Figure 15. Block Diagram of the AE Monitoring System.

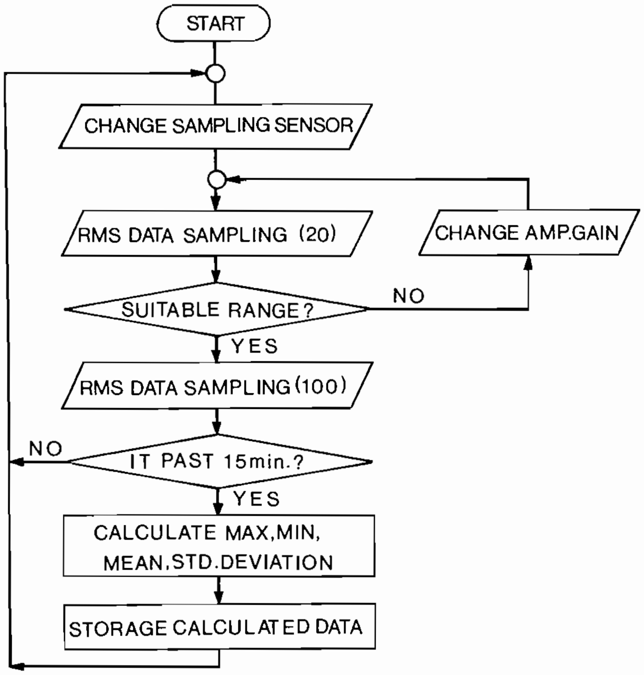

Figure 16. Flow Chart of Measuring Procedure.

An example of data displayed by CRT is shown in Figure 17, where the abscissa indicates time and the ordinate indicates RMS values. The maximum, minimum, and mean values are shown by curves. The standard deviations are shown by lines extending vertically upward and downward from the average value, and have a value of 1 σ in both halves.

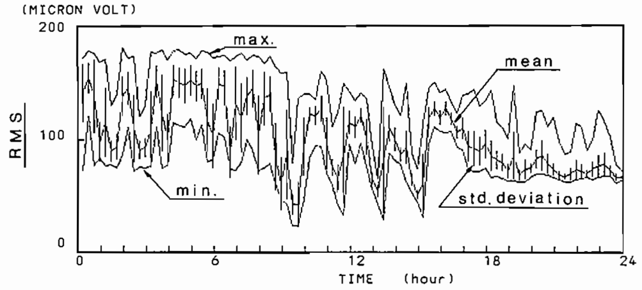

Figure 17. Data Display Example by CRT.

Continuous monitoring experiments were conducted on a test apparatus (Figure 18) and pumps in operation in petroleum refinery plants (Figure 19). AE sensors were mounted on seal end covers in the experiments. The surface configuration of mechanical seals and amount of carbon were periodically measured. Some of the mechanical seals were checked for leakage by automatic measuring devices and some were checked by visual observation.

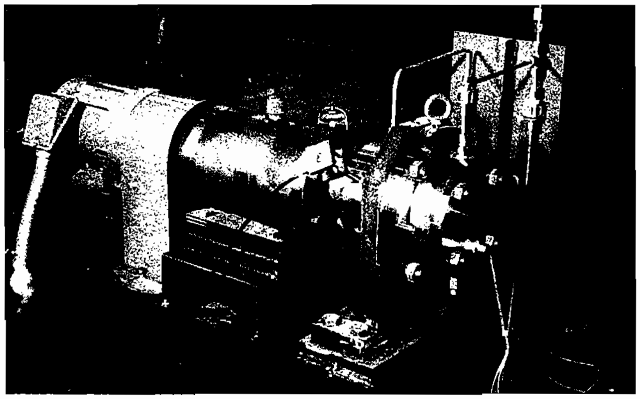

Figure 18. Measurement on Experiment Apparatus.

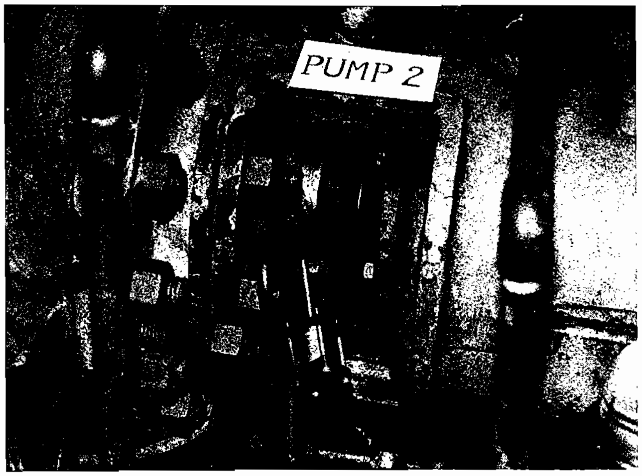

Figure 19. Measurement on Process Pump in Petroleum Refinery Plant.

DETECTION OF WEAR AND DAMAGE OF MECHANICAL SEAL BY MONITORING AE

Typical AE trends which were obtained at jobsites and the surface configurations which correspond to the AE trends are shown in Figure 20. As shown in Figures 20 and 21, when an AE level is very high or AE continues fluctuating sharply for a long time, mechanical seals are worn and damaged to such an extent that they form blisters or cracks. When an AE level is low as shown in Figure 22 and Figure 23, the degree of damage to mechanical seals is small. When AE remains stable (Figure 23), the surface state of a mechanical seal is satisfactory. These results indicate a relationship between AE trend and the sliding condition of a mechanical seal; that is, when AE level is high, the mechanical seal is operated under almost dry sliding and severe wear conditions. When

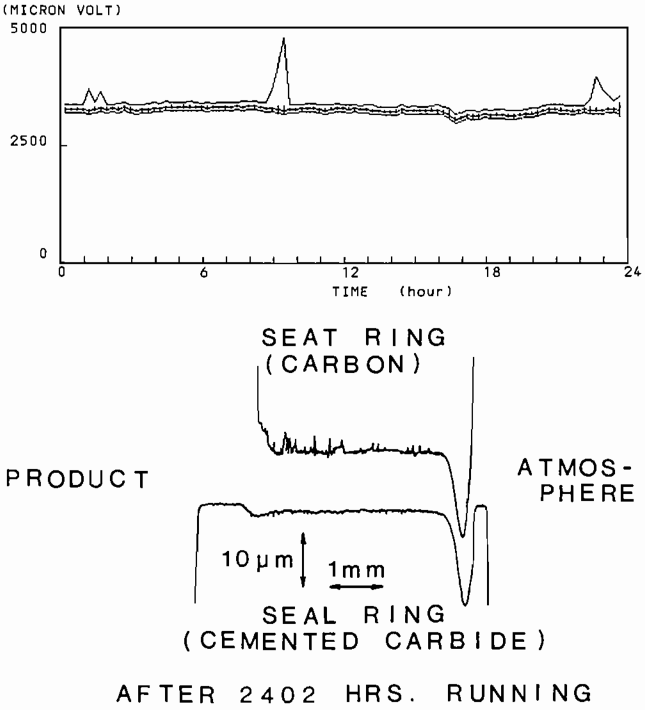

Figure 20. Typical AE Trend and Surface Configuration of Mechanical Seal on a Process Pump Operated with LPG.

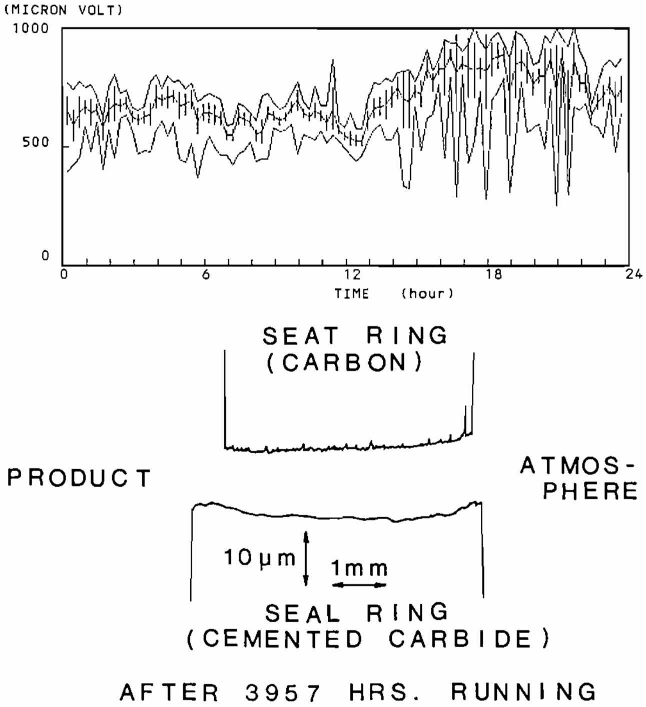

Figure 21. Typical AE Trend and Surface Configuration of Mechanical Seal on a Process Pump Operated with LPG.

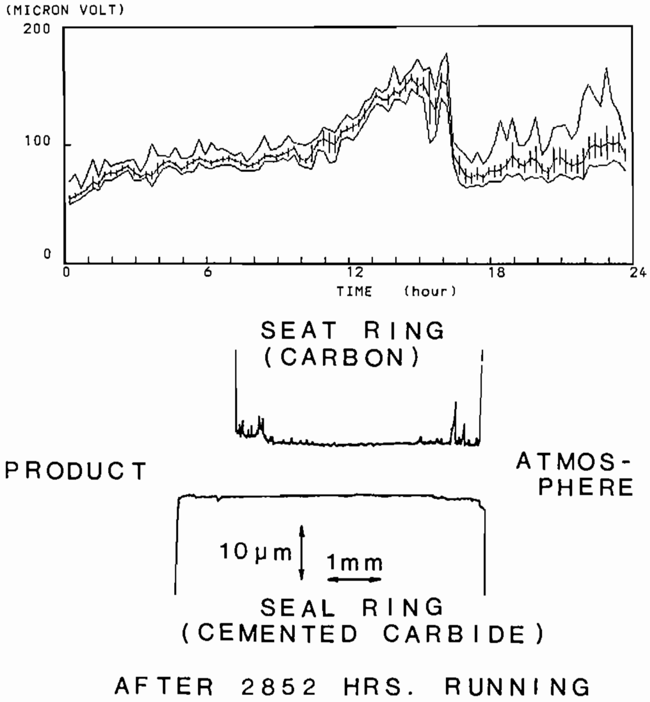

Figure 22. Typical AE Trend and Surface Configuration of Mechanical Seal on a Process Pump Operated with LPG.

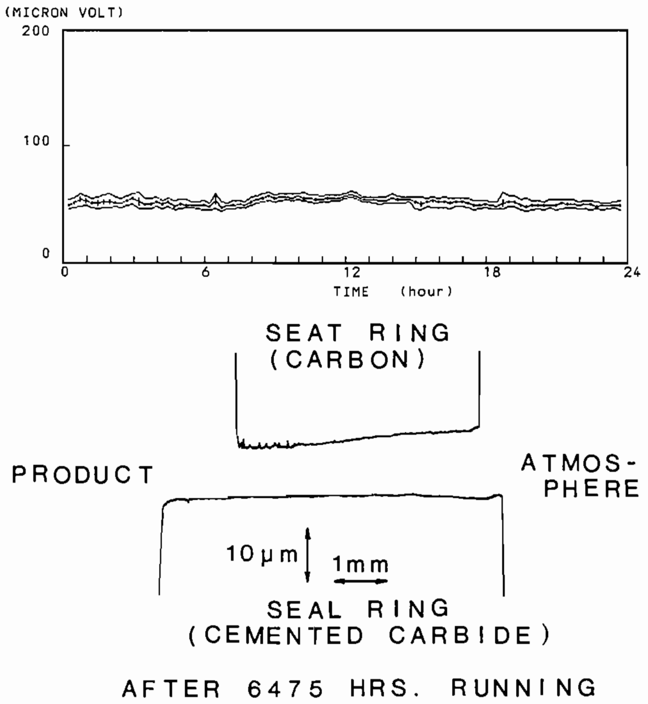

Figure 23. Typical AE Trend and Surface Configuration of Mechanical Seal on a Process Pump Operated with Kerosene.

AE level is low, a lubricating film is formed on the sliding surface. It also indicates that standard deviation, i.e., AE fluctuation, is sharp and the that sliding condition is unstable. Over a long time period, three kinds of AE trends were observed; that is, an AE trend which continued in the same state except when the mechanical seal was driven, an AE trend which continued in the same state some time after a mechanical seal was driven, and an AE trend which varied over a certain period.

The relationship between wear amount and AE obtained in test apparatus on which the same types of mechanical seals whose nominal diameters are 1.8, 2.2, and 2.6 in are mounted is shown in Figure 24. In Figure 24, the abscissa indicates the cumulative values of AE mean values and the ordinate indicates the reduced length of the sliding surface of a seat ring made from carbon. It is apparent that the wear amount of a seat ring is proportional to the cumulative values of the AE mean values, which means that an estimation of the wear speed and wear amount of a mechanical seal is possible by monitoring AE.

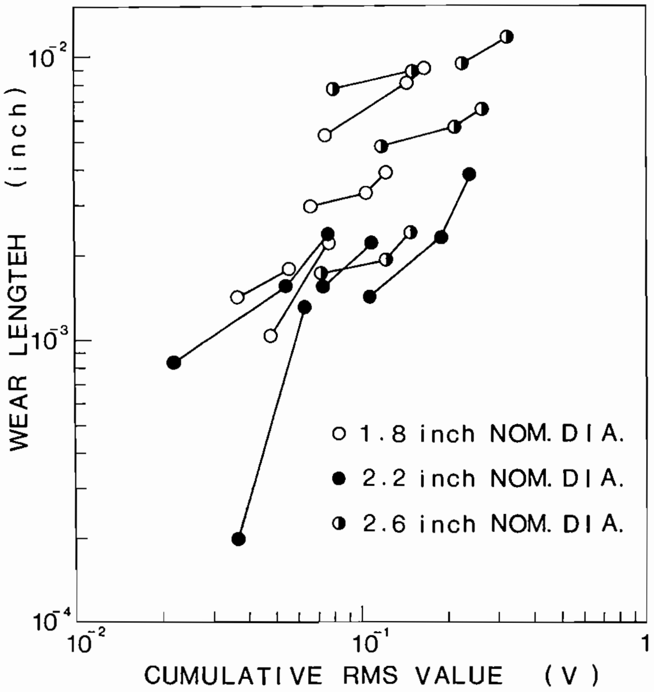

Figure 24. Relationship Between Wear Amount of Seat Ring and Cumulative RMS value.

These results indicate that monitoring AE enables detection of wear which occurs during long time periods or a failure which occurs suddenly on a mechanical seal surface. This suggests that the AE monitoring method can control mechanical seals more effectively and safely than the conventional method, on the basis of statistical data taken from records based on the time period over which individual mechanical seals function.

DETECTION OF ABNORMAL LEAKAGE BY MONITORING AE

The most important objective in monitoring a mechanical seal is to predict or detect leakage of a product at an early stage of a mechanical seal failure. The leakage of a product from the mechanical seal face occurs because of abnormal wear or cracks caused by an overload imparted to the mechanical seal face, abnormal wear on the mechanical seal face caused by slurry or deposit, obstruction of a seal ring's movement caused by accumulation of slurry and the like, or an inappropriate assembly. Since it is difficult to specify the causes of leakage, this problem has not yet been solved. In order to observe the characteristics of AE successfully, experiments were conducted not by artificially leaking liquid from a mechanical seal, but rather by monitoring the AE generated by a mechanical seal mounted on an operating pump. This is the reason for the very long duration of this experiment. According to the experiment, AE indicated the following two typical trends at or before the time leakage occurred:

- The indicated minimum and/or other RMS values of AE was at a very low level.
- The indicated mean RMS value of AE was at a high level, and the deviation indicated an even higher value.

Typical examples of the first group of AE characteristics are shown in Figures 25, 26, and 27. The results obtained on a test apparatus are shown in Figure 25. The liquid used for the experiment was water (150 psi and 210°F). As shown in Figure 25, when leakage occurred, the indicated minimum value was at a very low level. Thereafter, the mean and maximum values decreased. After the leakage stopped, the AE level increased again. The results observed in a process pump operating with LPG (220 psi and 100°F) are reflected in Figure 26. The AE level remained relatively low over a

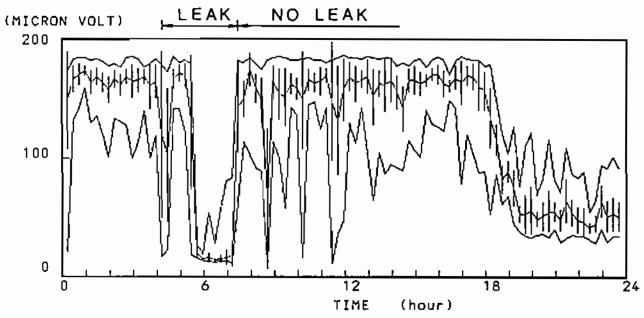

Figure 25. AE Trend When Leakage Occurred.

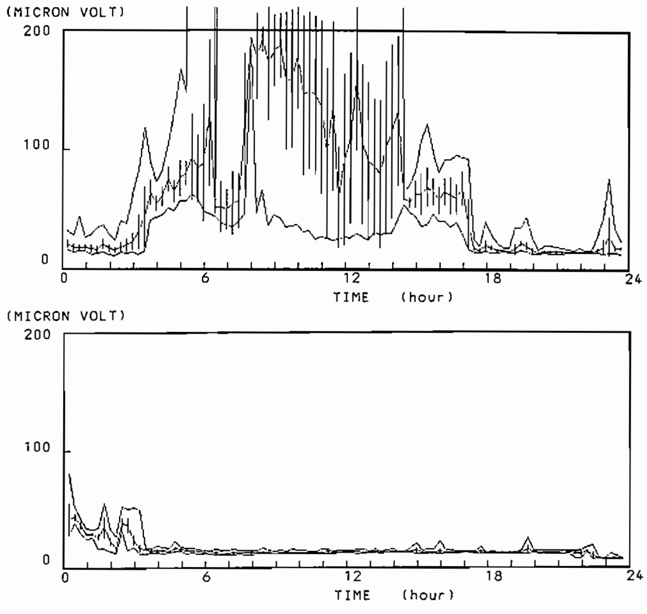

Figure 26. Low Level AE Trend During Leakage Following an Abnormal AE Trend.

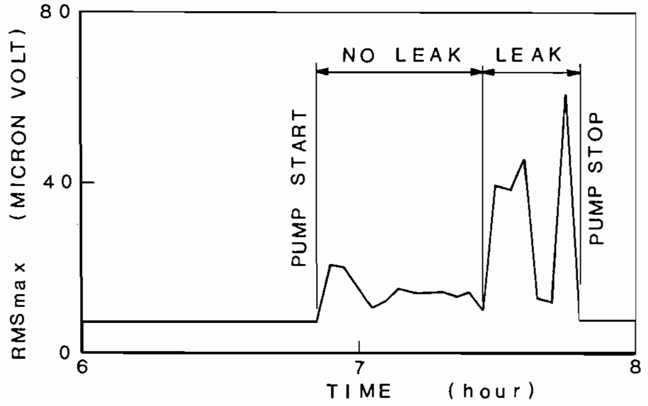

Figure 27. AE Trend When Leakage Occurred Immediately after the Pump Started.

long period of time. After a very abnormal trend appeared, as shown in the upper graph, the AE level became extremely low as shown in the lower graph, and then continuous leakage was confirmed. An AE trend of the maximum RMS value of AE during a time period immediately after a pump started operating is shown in Figure 27. The product was LPG (500 psi and 80°F). The AE level remained very low after the pump started operating. The AE level was lower at the point when large quantities of leakage occurred. No wear track was observed on approximately 1/4 of the whole periphery of a seal face. This means that the inappropriate mounting of the mechanical seal caused leakage. Thus, the leakage which occurred in mechanical seals belonging to the first group of AE trends was caused by the fact that an excess amount of liquid film was formed on the mechanical seal surfaces.

A typical example of the second group of AE characteristics is shown in Figure 28. The product was LPG (630 psi and 90°F). The AE level remained very high and stable more than 1,000 hours after a pump started to operate, as shown in the upper graph. Thereafter, when the AE level fluctuated, as shown in the lower graph, the leakage was confirmed. Leakage sometimes stopped when the AE level became stabilized as shown in the upper graph. Much damage was observed on this mechanical seal surface (Figure 4), which was replaced several thousand hours after it was mounted on a pump. Thus, in the case of the second group of AE trends, leakage was caused by extensive damage to a mechanical seal surface and, as a result of such leakage beginning, the AE became very unstable. In addition, there is a possibility of liquid bursts in large quantities in this latter group, which necessitates the taking of precautions against an explosion.

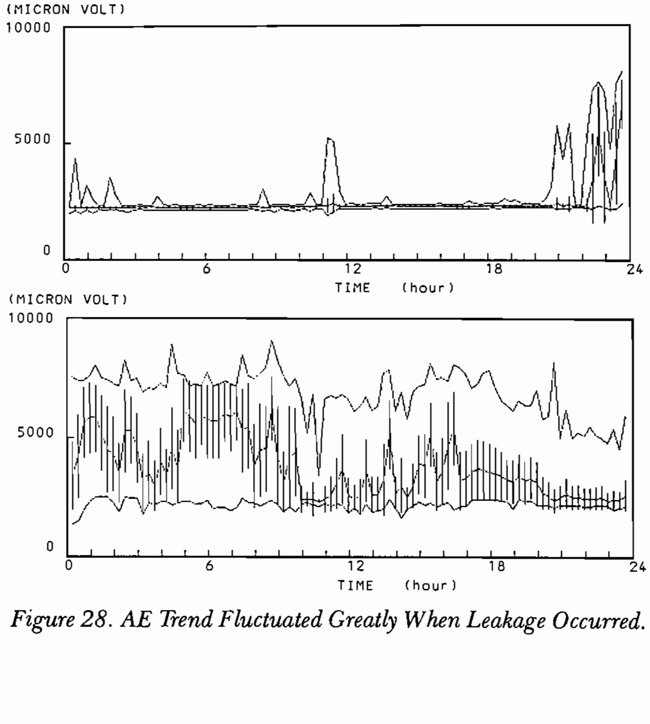

Figure 28. AE Trend Fluctuated Greatly When Leakage Occurred.

According to the data obtained up to now, the leakage amount was slight, except for the leakage that occurred immediately after a pump started operating, as described previously with reference to Figure 27, so that a pump was operated with a mechanical seal mounted thereon or a mechanical seal was replaced as soon as a failure was detected. Most of the observed leakage belongs to any one of the above-described types. No particular difference, however, was found in AE levels in liquids having a relatively high viscosity, such as kerosene, when a slight amount of leakage occurred.

CONCLUSION

The improved AE monitoring method can be applied to obtain information on the condition of a mechanical seal which is being operated and to predict or detect a possible failure in a mechanical seal. Since the frequency band of AE is generated by a mechanical seal is in the range > 1 MHz, AE can be easily detected without noise interference generated by bearings, motors, etc., close to a mechanical seal. Since AE generation is caused by the solid contact of sliding faces of the mechanical seal, AE directly correlates with the wear/damage of a mechanical seal face; thus, an estimation of wear speed or wear amount is possible. When leakage occurs, it may be due to an excess liquid film which might be formed on a mechanical seal face, or it may be due to the extensive damage which might happen to a mechanical seal face. In both cases, the result will be a reduction of the AE level or an increase of the fluctuation which will permit the prediction or detection of mechanical seal failures.

The technique followed during this research for predicting or detecting a failure of a mechanical seal is considered an efficient one, when applied practically, and has already been efficiently applied to design mechanical seals and examine product quality. There are still many problems to be solved from a practical point of view. Therefore, plans are being made to apply this technique to the following: various kinds of liquid, particularly liquid with high viscosity or slurry liquid, a mechanical seal made of various kinds of materials, a mechanical seal having various structures, the development of a more efficient and universal AE measuring method and system. Fundamental research for obtaining more accurate information is now being energetically pursued. We are convinced that more and more data about the technique for predicting or detecting a failure in a mechanical seal will be obtained.

REFERENCES

1. Bloch, H. P., "Development and Experience with Computerized Acoustic Incipient Failure Detection (IFD) Systems, ASME Paper No. 77-pet-2, (1977).