DTU Library

Acoustic emission surveillance methods

Nielsen, A.

Publication date:
1972

Document Version
Publisher's PDF, also known as Version of record

Danish Atomic Energy Commission

Research Establishment Risø

Acoustic Emission Surveillance Methods

by Arved Nielsen

December 1972

Sales distributors: **Jul. Gjellerup, 87, Sølvgade, DK-1307 Copenhagen K, Denmark**

Available on exchange from: **Library, Danish Atomic Energy Commission, Risø, DK-4000 Roskilde, Denmark**

We regret that some of the pages in the microfiche copy of this report may not be up to the proper legibility standards, even though the best possible copy was used for preparing the master fiche.

U.D.C. 620.179.16

December 1972 Risø Report No. 277

Acoustic Emission Surveillance Methods

by
Arved Nielsen

Danish Atomic Energy Commission
Research Establishment Risø
Metallurgy Department

Abstract

This report was prepared for the Commission of European Communities - Nuclear Energy Agency (NEA - CREST) working group on Material and Mechanical Problems Related to the Safety Aspects of Steel Components in Nuclear Plants. It continues the report Risø-M-1429 under the same title.

The present report is based on information received recently from fruitful collaboration within the Working Group, from the literature, and from personal experience and communications. The purpose is to present the status of the acoustic emission technique with respect to its application during proof testing, recurrent testing and service, of steel pressure vessels for nuclear plants.

During proof testing it is evident that the location of acoustic emission sources can be carried out very reliably. The problem of warning against catastrophic failure cannot at present be given a clear answer, although an experienced operator can make an approach to the problem and very promising investigations are in progress.

During recurrent inspection it should be possible to gain further information on the state of the steel structure by applying the acoustic emission technique if the structure is accessible.

Not much experience has been gained of acoustic emission surveillance during service in terms of Signature Analysis, but very promising investigations are in progress to solve the various problems, by using the acoustic emission technique in the hostile environment of a nuclear reactor.

ISBN 87 550 0181 5

CONTENTS

1. INTRODUCTION

A report on Acoustic Emission Surveillance Methods (Risø-M-1429) was prepared in September 1971 for the Commission of European Communities - Nuclear Energy Agency (NEA - CREST) working group on Material and Mechanical Problems Related to the Safety Aspects of Steel Components in Nuclear Plants. This permanent working group was set up in 1970, under CREST sponsorship and under the Commission's auspices to act as technical secretariat.

The scope and purpose of the group is basically:

(a) To promote a feed-in of problems encountered by safety assessors concerning materials and mechanical questions for steel components in nuclear plants.

(b) To promote an exchange of views on the priority issues to be considered in safety analysis and in applied research in this field.

(c) To promote detailed exchange of information on the relevant research programmes.

The report treats one of the various specialized topics dealt with by this working group, and its purpose was to present the members with a general survey of the applicability of AE techniques to the safety service. Great care was taken to present only statements and conclusions which could be safely based on evidence found in the literature. A rather extensive literature exists, but many contradictions are found. Consequently the conclusions of the report were rather general and the report assumed an introductory nature.

It was the general opinion within the group that more detailed and clear-cut answers to actual problems were desirable, together with indications of the research areas necessary for the development of the AE technique as a reliable tool for controlling the integrity of steel structures. The present report aims to answer these points, but it must be mentioned that this has not been possible without slightly involving the author's personal opinions.

For clarification it is appropriate to distinguish between the application of AE techniques during proof inspection, during recurrent inspection, and during service. Further, an important question to be answered is how much information can be obtained on the nature, size, and significance of defects revealed by AE.

Since September 1971 additional valuable information on AE has appeared in the literature and has also become available through a fruitful collaboration with members of the working group from which this report has benefittedconsiderably, and for which I am very grateful.

2. AE TECHNIQUES APPLIED DURING PROOF INSPECTION

Proof inspection by means of AE may have several objectives:

(1) Assurance of the integrity of the steel structure.

(2) Control of the probability that a catastrophic failure will not occur during the testing.

(3) Location of suspect areas to be considered for further attention.

(4) Collection of observations on AE conditions which can be stored for future treatment when more knowledge has been gained, and which can also be used for comparison with future observations.

Other minor aims could be listed, but in the following chapters they have been included under the four headings above.

The first objective, assurance of the integrity, is of course the primary reason for the proof test. However, pressure testing is not in itself fully convincing; it could under certain circumstances even cause unrecognised damage to the structure. If the AE technique could improve the assurance, it would be a distinct advantage.

The second objective, control of the occurrence of failure during testing, is clearly a desirable one since defects can often be repaired if their presence is known, but a failed structure is generally lost.

Unfortunately, with regard to the two above-mentioned objectives, the benefits of the AE technique cannot be fully realised at present. The limited knowledge and experience now available do, however, allow a partial realization of these objectives.

As to the third objective, location of suspect areas, it has recently been demonstrated that the AE technique is very suitable. Location can be carried out reliably and accurately.

The fourth purpose, storing of AE information, is of course easily carried out with AE transducers, amplifiers, and a tape recorder for the necessary number of channels. Anyone who has confidence in an increased application of the AE technique for control of structures ought to consider such information storage.

These simple statements should be kept in mind when the subject is treated in detail in the following chapters. Although they have been listed according to their desirability, it is more convenient to treat them in the reverse order in the discussion.

2.1. AE Information Storage

It is comparatively easy and relatively inexpensive to fit AE transducers to a steel structure in suitable places and to record the output on magnetic tape. Different transducer types are available commercially, as is the necessary electronic equipment. Preamplifiers of good quality, i.e. high signal to noise ratio, are often sufficient. Multi-channel tape recorders capable of recording frequencies higher than 100 kHz are expensive to buy, but are easily available as they are used for many other purposes.

It may be possible to reduce the expense by converting the detected signal such that the input to the tape recorder is at a considerably lower frequency than 100 kHz.

For analysis of the stored information it is desirable to have full control of the transmission of the AE signal from the vessel to the transducer. For comparison of different recordings it is necessary to be able to reproduce the transmission conditions. This is at present a serious problem.

A well-known technique for testing of the sensitivity of AE transducers fixed on the structure is to record signals injected into the structure at a suitable location by an artificial source. This source is often another AE transducer clamped to the structure. By feeding electric signals to this transducer acoustic signals are injected into the structure. The sensitivity of the receiving transducers is controlled by adjusting the gain of the preamplifiers.

This method of sensitivity control lacks reliability since the transmission of artificial signals from the transducer to the structure is not itself well controlled. Another source of error is that injected signals from an AE transducer do not resemble real AE signals.

To improve the reproducibility of AE detection it is consequently necessary to study the transmission of the acoustic signals from the structure to the electric signals which are recorded. Other fields of study should include the applicability of artificial signals, the transmission conditions for such signals, and the possible introduction of artificial signals resembling the actual AE signals.

As mentioned by N. Kirby[1] research within this area is being carried out at the South West Research Institute, Texas: AE signals are injected into a 10-foot diameter vessel by means of a bar in which a fatigue crack is progressing under cyclic load.

From a very extensive research project in progress at Battelle, Frankfurt, Dr. J. Eisenblätter[7] has reported another type of signal injector suitable for transducer experiments: Fingers are cut in a steel plate, and are then loaded one by one to produce acoustic emission. It is assumed that under identical loading conditions the fingers give identical AE signals.

At the recent AE meeting in London, R. Hill[2] reported on the effects of the adhesive joint between the AE transducers and the steel structure. As explained previously[3] AE transducers operate at their natural frequency when detecting AE signals. Hill observed that the natural frequency of the AE transducer and consequently the frequency response of the system is highly dependent on the fixing of the transducer to the structure. Even at repeated mountings of one transducer with the same adhesive considerable differences in response are found. Hill concludes that it is preferable to use a mechanical fixture and a liquid coupling medium to reduce the influence on the frequency response of the transducer. However, it is well known that liquid coupling is less efficient in transmitting frequencies within the range of 100 kHz.

In this context it ought to be mentioned that different types of transducers are used in practice. Two commercial firms in the U.S.A. distinguished within the AE field, prefer longitudinal wave detection and transversal wave detection respectively. The detecting element is generally a piece of PZT ceramic which is strongly piezoelectric. It is unfortunate that irrespective of which wave form the piece is cut for, it will always be able to oscillate in other modes also, causing the frequency response to be complex.

It is difficult to treat these subjects theoretically, particularly as it is known from the ultrasonic field that even if a simple sine wave is injected into a steel structure, it will inevitably be transformed into an extremely complex mixture of frequencies of transversal, longitudinal, and surface waves, all of which have different travelling speeds.

However, it would not be difficult to design experiments for comparison of transducer types for different purposes provided a satisfactory selection of artificial signal injectors were available. Consequently the development of such injectors seems to be a key problem.

Eisenblätter[7] has reported on the experimental comparison of transducers cut to detect transversal or longitudinal oscillations respectively and mounted on a steel plate with different bonding agents. The operation at higher temperatures and high frequencies has been investigated. Different piezoelectric materials have been compared and their properties with respect to AE detection described. Transducers with damped natural frequency or operating at linear frequency response have also been investigated[3]. Although this is a very promising contribution, no general conclusions have so far been drawn.

It is possible that new types of AE transducers may appear in the future. During the recent AE meeting in London G. J. Curtis[2] reported on the application of a capacity AE transducer. Generally such transducers suffer from a very low sensitivity. Curtis had introduced an electret as dielectric and improved the sensitivity considerably. It is characteristic of capacity transducers that they can operate at considerably higher frequencies than the piezoelectric transducers generally used. It would indeed be interesting to extend the experimental comparison of AE transducers to include capacitive types.

Finally, it is known that a reflected light beam may be used for the detection of surface oscillations[4]. It is theoretically possible to detect AE by laser interferometry[5], but no experimental data have been found in the literature. It seems extremely attractive to be able to detect AE from a structure by just looking at it from a distance, but the effort necessary to develop laser methods is perhaps not justified in view of the present lack of knowledge on the nature and origins of AE.

In summarizing this section the following statements may be made:

The recording and storing of AE signals from a steel structure is a well-known and easy-to-apply technique.

The reproducibility of the technique is a problem which needs to be solved if different recordings are to be compared.

If reliable artificial sources of reproducible AE signals could be developed, it would undoubtedly be profitable to compare different transducer types and their means of attachment to the structure, in order that the reproducibility of the AE technique might be improved.

2.2. Location of Defects

The location of AE sources is now possible with a high degree of accuracy. Several different organizations now offer a surveillance service which includes the location of defects during proof testing.

As mentioned by N. Kirby[1], the location of existing cracks of small size (e.g. 2.5 mm) may be readily performed, and this size compares advantageously with the critical crack length of 25 - 100 mm, which is generally calculated for nuclear pressure vessels by fracture mechanics methods.

The reference quoted by Kirby is Dwight L. Parry who is perhaps the most experienced scientist within this area of the AE field. A more detailed description of defect location has been given by Parry and Dan L. Robinson[6] from their results obtained from AE surveillance during proof testing of both vessels and tubing.

Recently I had the opportunity of closely watching Parry and his co-workers use the AE technique during the proof testing of a very large pressure vessel for the petrol industry. The instrumentation used is described together with a short comment in the Appendix. It is a characteristic feature of the technique that a very high reliability in the location of AE sources may be attained. The AE information gained as the testing proceeds is stored in a memory and, when appropriate, fed into a digital computer. The computer is programmed to deliver information on the probability that every different part of the vessel includes a source of AE, i.e. a display of the vessel surface is covered with a network of numbers, each number indicating the probability. Further information on the statistical background for the probability calculation is given, and if the reliability should not be considered satisfactory, the program is corrected or more AE information collected for a repeated analysis. Surplus information, as a basis for probability calculation, is initially provided by using 4 channels for the analytical process instead of 3, which from a geometrical viewpoint would be sufficient for a triangulation process.

Generally 16 - 24 channels are used on a steel structure and initially 4 are chosen for the location process; this choice is changed during the test if the AE events draw attention to particular areas which may then be more efficiently covered by regrouping the channels.

Since all the information from the AE transducers is stored by a tape recorder, repeated analysis is possible at any time by replaying of the tape, and this is inevitably done with different groupings of channels. It is even possible to subtract the information from which the location of the most prominent AE sources are derived, allowing the less significant sources to be pointed out with a higher probability by the computer.

It is also possible by discriminator settings to sort out signals of a particular appearance, e.g. signals believed to be of non-metallurgical origin or from their location considered unimportant.

The location is generally carried out with an accuracy within 2 - 5 cm.

The superficial description given here of some of the properties of the system used by Parry should serve to make it clear that the reliability in the location of AE sources can be increased to a very high level by a competent operator performing careful analysis.

In the paragraphs above the location technique has only been mentioned in terms of AE source location. A reasonable question is then: What about defect location?

From practical experience gained during pressure vessel testing it is known that defects are generally found by further non-destructive examination of the locations pointed out by the AE technique. Kirby[1)] refers to a vessel similar to reactor pressure vessels in which 31 sources were located, and of these, 23 were confirmed as defects. Further evidence of the relationship between AE sources and the presence of defects has been presented by Parry[6)].

When I had the opportunity of seeing the AE technique used by Parry it was evident that the majority of locations pointed out corresponded to areas in the structure where from a technological viewpoint and experience, de fects are most likely to occur (i.e. welded connections which were only accessible with difficulty, ignition burns, etc.). When the analysis of the AE data is pursued further, defects are, according to Parry, not often found at locations of the less significant AE sources.

This correlation between AE sources and defects is rather convincing, but prompts the question: Can large defects pass unobserved by the AE technique?

It is not easy to answer this question in a straightforward way. So far many vessels have been tested, and no cases of unobserved, significant defects have been reported. This is of course not fully convincing, but if by "large defect" one understands "crack", then it is worth noting that the usual way of running experiments on the practical application of the AE technique is to cut a slit in an experimental structure and to watch the AE activity during loading. This type of experiment has been carried out on numerous occasions throughout the world, and there is no evidence in the literature of failure to detect AE, provided the equipment was operating properly.

Another point, however, is that a large crack does not necessarily produce an increase in AE during loading, but this problem is treated in the next section. The question here is whether or not defects are detected during proof testing, and it seems reasonable to assume that during proper AE surveillance of a pressure vessel there is a very low probability that a significant defect will pass unobserved.

In summarizing this section the following may be concluded:

Location of AE sources in steel structures under proof testing may be readily carried out with a high degree of both reliability and accuracy.

Generally defects are found by other non-destructive methods at the locations of AE sources, and there is a high probability that large crack--like defects will be revealed by the AE technique.

2.3. Control of the Failure Probability During Testing

The purpose of AE projects is basically to establish a warning system against catastrophic failures. This aim has so far not been achieved.

Very often AE investigations include testing to failure, and numerous curves representing the relationship between AE and stress have been published. Generally the AE signals are converted within the electronic equipment into functions which are suitable for pen recording, e.g. the signal rate referred to in the Appendix as acoustic energy release signature.

It has often been reported in the literature that the AE rate increases continuously until failure occurs, but the level of AE rate at which failure will occur is at present indefinable. Steels differ very much in their AE behaviour as shown by Eisenblätter[8]. At the recent London conference, I. L. Mogford[2] presented a series of signal rate curves from different steels which also showed entirely different behaviour. Brittle steels tend to produce more AE signals than soft steels, and it is generally brittle materials which exhibit a rising AE rate before failure, but even soft steels fail when the stress concentrations at crack tips are too high.

It seems very tempting to relate AE to fracture mechanics. This has been done, and as mentioned by Kirby[1] extensive investigations within these areas are carried out throughout the world. Eisenblätter[7] has derived a simple mathematical equation presenting the relationship between AE signal rate, I, and the Stress Intensity Parameter, K. The derivation is based on the assumption that the total count of AE is proportional to the plastic zone size or to a possible slow crack extension. Tensile testing has been done to support this theory.

Generally one considers the integrity of a steel structure in terms of a critical crack length calculation in which the key factor is the Stress Intensity Parameter, K, at the tip of a crack-like defect. The critical K is a material property which is estimated experimentally. When the actual K in a structure exceeds the critical K of the steel, failure occurs. This situation implies the presence of defects in the vicinity of which the actual K is raised by the loading conditions or by the deterioration of the defects.

Based on this approach it would clearly be an enormous advantage to be able to estimate the actual K from AE measurements on a steel structure.

During the testing procedure to estimate the critical K of a steel it might perhaps be worth-while to report the corresponding AE activity and then try to use this information to estimate the actual K in the structure where defects of unknown size are assumed to be present.

It is encouraging that so much effort is being concentrated, throughout the world, on the possible relationship between fracture mechanics and acoustic emission. However, no generally applicable quantitative relation has so far been established, and even in specific cases no methods have been proposed for the practical application of such relationships.

It is perhaps difficult to see how quantitative relationships can be established as long as the reproducibility of AE transducer operation remains a problem. This then emphasizes the key problem of improving the reproducibility of AE detection.

Many AE investigators have been disappointed by the experience that the AE rate decreased before failure. This is mainly observed when tough steels are considered. In these steels large plastic zone formation often precedes failure, and this does not always cause AE. A similar behaviour is often seen during tensile testing experiments. A good example of this is shown in the figure[8].

Eisenblätter has further, by detailed analysis, shown that the high AE rate at the yield stress is probably due to Lüders' band formation. The AE rate which accompanies general yield is then insignificant compared with the enormous rate at the yield stress.

If this behaviour is reproduced from a multitude of stress concentrations at defects in an experimental vessel, it will inevitably present the disappointing problem of a decreasing AE rate as failure approaches.

Consequently information on the presence of defects of critical size in a steel structure might well be revealed at an early stage of the testing procedure and not when the failure is approaching. Parry has reported that during AE surveillance his attention is caught by sudden decreases as well as by sudden increases in AE rates. Then the AE sources can be located and subjected to other non-destructive testing procedures in order to estimate the size and type of the possible defects present. This information can then be used as a basis for a decision on the necessary precautions to be taken. It is obvious that the phenomena mentioned in this section need to be properly explained if confidence is to be raised as to the ability of the AE technique to control the failure risk during proof testing.

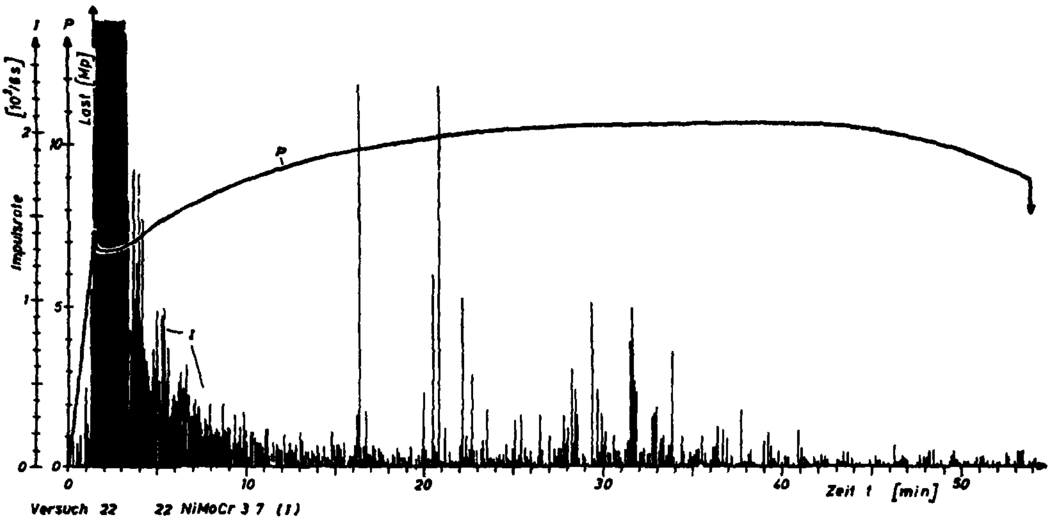


Bild 21: Impulsrate I der Schallemission und Last P in Abhängigkeit von der Zeit beim Zugversuch an 22 NiMoCr 3 7 (I). Abzuggeschwindigkeit 0,05 cm/min.

(Dr. J. Eisenblätter)

Acoustic emission pulse rate, I, and load, P, as functions of time, on tensile testing of 22 NiMoCr 37 (I). Loading velocity 0.05 cm/min.

In this context it might be mentioned that fracture mechanics in its present form is not the best of tools with which to handle large plastic zones, and much disagreement exists as to how this ought to be done. It would perhaps be profitable to use the AE technique as a tool for investigating the deformation behaviour of steels and not only in order to link AE information to conventional fracture mechanics.

To draw a clear conclusion from this chapter is not easy. Even though considerable effort is most promisingly being devoted to the exploration of the relationships between AE and fracture mechanics, it is at present not possible to state by which criterion the failure probability should be estimated during AE surveillance.

However, if an experienced operator is able to recognize unusual AE behaviour, e.g. an acoustic energy release signature different from that generally recorded, then the test can be suspended, AE sources located, defect size and type estimated by other non-destructive methods, and on the basis of fracture mechanics decisions can then be taken as to the continuation of the testing. This approach is a significant improvement on straightforward pressure testing.

2.4. Assurance of the Performance of the Steel Structure

Every test carried out successfully will of course raise the confidence in a structure. AE surveillance is no exception, the question is only whether it is sufficiently profitable to use this method.

The load test itself raises confidence, but it is well known that pressure vessels have failed after pressure testing and at lower pressures. Additional non-destructive testing is consequently desirable, and ultrasonic testing, X-raying, magnetic particle testing, etc. are very efficient ways to obtain information on the type and size of possible defects. The question remains, however, as to whether all the defects present are found. This depends to a large extent on the time and care taken by the operator.

The AE technique, on the other hand, has the distinct advantage, as made clear in section 2.2, that it covers the entire structure; every location is obviously accessible during AE surveillance.

As pointed out in the previous section, the AE technique is at present only suitable as a supplement to existing non-destructive testing methods, but it increases the reliability of these methods considerably.

The AE technique is the only one applicable for the detection of widespread crack growth still going on during load testing of the structure. Other non-destructive methods may be used before and after load testing to the same purpose but with very little reliability. From AE surveillance during the loading of a structure it is not possible to distinguish between actual crack growth and other metallurgical processes caused by the presence of a defect. But on the basis of the so-called Kaiser effect[3)] the AE should, upon reloading under identical conditions, be at a low level. Thus, if any significant AE does occur upon reloading at a later time, it must be due to some deterioration, but if reloading is done immediately under identical conditions, AE must be due to crack growth. Both incremental growth and deterioration of the defect brought about by the growth are detected by the AE surveillance.

By the simple modification of a pressure test to include repeated pressurization a considerable increase in the information gained from the AE surveillance can be obtained, i.e. crack growth can be reliably revealed, and the very significant problem of possible crack growth caused by loading conditions during service can be tackled.

The re-pressurization pressure does not necessarily have to be as high as the proof pressure; a value between this latter pressure and the operating pressure may be chosen. Nor does the intermediate pressure have to be zero.

Based on the advantages mentioned above, in particular that the application of the AE technique increases confidence in the structure tested, it may be argued that in future all nuclear steel pressure vessels ought to be submitted to this kind of surveillance. This is particularly true when the attitude of the public towards nuclear pressure vessels is kept in mind.

Regarding AE surveillance during proof testing D. L. Parry states that, six nuclear pressure vessels, nine chemical pressure vessels, two storage vessels, two storage tanks, gas transmission lines, and further piping have been tested to date by means of his acoustic technology. Other organizations have applied acoustic analysis to rocket casings and other structures.

It is particularly desirable that the present proof test procedures be modified in order to obtain the largest possible benefit from the AE surveillance. Precautions to reduce mechanical noise from pressurizing equipment, supports, and attachments are also desirable.

These remarks might serve as a conclusion to be drawn from this section, but there are two further points which ought to be dealt with in this context: Firstly the importance of AE surveillance as applied during overstressing in order to stress-relieve structures and secondly the information about defects which is obtainable by means of the AE technique.

2.4.1. AE Surveillance During Overstressing

Large pressure vessels are usually stress-relieved after welding by a heat treatment at about 650 °C. However, the new steels with high yield points that have been developed are less suitable in this respect since the steel must be microstructurally insensitive to this treatment. Fortunately stress-relieving can be accomplished by other means, and overstressing is one of the most profitable since its beneficial effects on the structure include not only the relief of residual stresses. On the other hand overstressing does not produce annealing of heat-affected zones, but if the heat treatment were to be done at a temperature sufficient for the annealing of the heat-affected zones of the welds, then the stresses could be relieved by overstressing.

The use of the overstressing technique has been reviewed by R.W. Nichols[9] and shall be only briefly mentioned here. The effectiveness of overstressing in reducing residual stresses by local yielding is dependent upon how closely the overall stress approaches the general yield stress of the structure, and this can cause problems.

A structure may be designed such that a level of overstressing can be permitted which is sufficient to cause satisfactory stress relief. Nevertheless, a certain risk of permanent damage exists if defects of a certain size deteriorate rather than profit from the overstressing, i.e. cracks may grow to critical lengths. The risk that this passes unobserved is greatly reduced by AE surveillance during overstressing, and thus one of the most significant disadvantages of the overstressing technique is reduced. It is understood that structures suitable for overstressing must contain only minor defects. This feature is checked automatically by AE surveillance during overstressing.

The ageing phenomena which take place in the locally yielded zones after overstressing are not generally considered to be significant, but if they are, this may be controlled by load testing under AE surveillance conditions after a lapse of time sufficient for the ageing processes to have taken place.

In conclusion, AE surveillance is a way to reduce some of the disadvantages of the overstressing technique.

2.4.2 Information Gained on Defects by the AE Technique

This point has in fact been covered in the preceding sections, particularly 2.3., but it is so often raised that it ought to be given an explicit formulation.

Information on the location of defects is very precisely given by the AE location technique (section 2. 2), but exact information on the type and size of a defect is at present not easy to obtain. The problem may be tackled, however, by using both statistical and experimental approaches.

Since AE surveillance is being increasingly used during the testing of large pressure vessels, it is inevitable that statistical experience is being gained as to the relationship between AE behaviour and defect morphology. As mentioned in section 2. 2, Parry has demonstrated that by refined analysis of AE information regions are located in which only insignificant defects or no defects at all are found by subsequent ultrasonic testing. Coarse defects are of course found by initial analysis. Thus it is possible to classify defects by an AE location technique.

When the reproducibility of AE detection has been improved, it may become possible, through experimental investigations, to establish a useful relationship between AE and the Stress Intensity Parameter, K. This parameter can give a good indication of size or significance and by means of a fracture mechanics approach may be used for estimating failure probabilities. When sufficient knowledge has been gained about the relationship between AE and metallurgical processes and when fracture mechanics has been developed sufficiently to cover the situation of plastic deformation, it may become possible to obtain exact information on defect type and size by means of the AE technique.

These considerations might also be applicable to fatigue loading, since incremental crack growth is perhaps more readily discerned than plastic deformation by the AE technique.

3. AE TECHNIQUES APPLIED DURING RECURRENT INSPECTION

During recurrent inspection the reasons for applying AE surveillance are exactly the same as those mentioned in the previous chapters, always assuming that the recurrent inspection includes pressure testing.

Some additional comments may be presented with respect to the possible utilization of the information gained from the initial tests and with respect to the accessibility of the steel structure in question.

3.1. Comparison of AE Information Gained from Initial and Recurrent Pressure Tests

The Kaiser effect implies that AE should be low during a repeat pressure test. However, it is doubtful whether this holds true after a certain period of time has elapsed since the previous test. Materials often deteriorate by ageing, particularly when plastic deformation has taken place, and in addition to this nuclear structures are exposed to neutron irradiation. For these reasons it is probable that AE would be detected during recurrent inspection even though any defects present may not have changed appearance. No significant information has been found in the literature on the effects of material deterioration during service on AE behaviour. Without this information recurrent inspection of slow, continuous growth of defects, e.g. corrosion or fatigue crack growth, seems very difficult.

If AE detection were reproducible, then the monitoring of test pieces could perhaps be used as a means of following material deterioration during operation. On the basis of this sort of information it might be of importance to compare AE recordings from initial and recurrent tests.

It must be concluded that a comparison of AE recordings from initial and recurrent tests is at present unlikely to give significant additional information. But experience will of course be gained if the technique is utilized, and it will in any case be interesting to compare the relationship between the AE rates from different sources and to compare the locations of AE sources.

3.2 Accessibility of the Steel Structure During Recurrent Testing

A nuclear pressure vessel might well be inaccessible during recurrent testing. This is a serious problem, and careful planning is therefore necessary at the initial stage.

Eisenblätter[8] has reported successful operation of AE transducers and preamplifiers after 9 months of exposure on a reactor pressure vessel (Gundremmingen).

It seems possible to keep AE transducers and preamplifiers operating under BWR and PWR conditions, and consequently accessibility should not be a problem in this connection. However, if the structure is inaccessible to other non-destructive testing methods (e.g. ultrasonic testing), some of the advantages of AE surveillance may be lost. The location of AE sources and the recording of AE rate are valuable, but when decisions are to be taken, it would be a serious drawback if supplementary non-destructive testing is impossible.

It is to be concluded that if the structure is not accessible, then although AE surveillance during recurrent testing may be possible, it might not be very profitable.

4. AE TECHNIQUES APPLIED DURING SERVICE

As mentioned in[3] a few indications have been found in the literature of continuous AE surveillance of reactor pressure vessels in the U.S.A., but more thorough information is not available. The technique which is used may be considered in terms of mechanical signature analysis, i.e. the pattern of the recorded behaviour when the structure is operating properly is taken as a reference signature. Deviations from this signature during subsequent operating conditions indicates a changed and perhaps poorly functioning structure.

In considering mechanical signature analysis as it is applied to the AE behaviour of the nuclear pressure vessel it may be stated[3] that if a change is observed in the AE detected during continuous surveillance, then a change in conditions must have occurred. This change could be unexpected and due to rearrangement of the stress distribution in the structure which might be a critical situation. The change in conditions might also be due to crack growth by fatique or stress corrosion or to deterioration of material properties by ageing or irradiation. Thus an unexpected change in the AE behaviour should be viewed suspiciously and should encourage further investigation as to its causes.

An example of signature analysis is given by C.C. Price and J.R. Karvinen[14] from the reactor EBR-II. However, this does not cover AE, but vibration noise at frequencies lower than 10 kHz detected by accelerometers.

Experience covering AE has so far not been recorded, and it needs to be gained before the applicability and significance of this type of analysis can be estimated, but when it does appear, it might well contribute considerably to the safety of reactor pressure vessel operation.

However, serious problems have to be faced when the AE technique is applied under the rough ambient conditions inherent in nuclear pressure vessel service. The problems are high temperature, neutron irradiation, and particularly high noise levels and the presence of strong transient signals from sources other than acoustic emission sources. Tremendous efforts have been made recently and are still being made to solve these problems.

4.1. AE Surveillance at High Temperatures and During Neutron Irradiation

J.B. Vetrano, W.D. Jolly, and P.H. Hutton[10) have reported on investigations made at Battelle Pacific Northwest Laboratories. A wave guide has been developed through which AE is picked up by a transducer at a distance of a few centimetres from the reactor vessel. The wave guide is preferably coupled mechanically to the vessel, and the preamplifier is built into the transducer housing. Successful experiments with similar wave guides have been reported by Dunegan[11)].

Long wave guides seem to have only a limited influence on the transmitted AE signal and by these means the problem of the hostile reactor environment can be overcome. In addition to this, however, Eisenblätter[7)] has gained promising experience by mounting transducers directly on a reactor vessel during service.

4.2. AE Surveillance at High Noise Conditions

The noise spectra have been estimated for several different nuclear reactor pressure vessels in the U.S.A. and Germany[10); 7)]. Minima in the noise spectra have been found within the range 0.2 - 1 MHz. At 1 MHz, however, the detection range is so low that a very large number of transducers is necessary to cover an entire vessel. Experimental work has consequently been concentrated on the low end of the frequency range. If a minimum in the noise spectrum is utilized, AE transducers tuned to this frequency are applied in connection with narrow-band filters. AE signals are then picked up at this frequency at a certain signal to noise ratio.

Other ways of filtering are possible. A prediction-error filter has been introduced[12)]. On the basis of a noise sample the predicted output of the filter is compensated. When a signal arrives at the filter, this is in error with the prediction and results in a large output from the filter.

So far in this chapter only white noise (i.e. more or less continously covering a wide frequency band) has been considered. Transient noise signals, resembling AE signals, are more difficult to filter out, but it is possible by choosing typical features by which noise and AE signals can be distinguished.

Parry has in his location system accomplished a perfect screening of AE signals from friction noise by utilizing the longer persistance of the latter signals.

Y. Nakamura[13] has utilized a gating system which allows only signals arriving at the right transducers in the expected order to be recognized as AE signals.

If a location system is within reach, this is a useful tool for screening from signals whose origin is indefinable or from signals from outside the region of interest (e.g. the pressure vessel).

Vetrano[10] has introduced a screening from turbulent noise because it is distributed over a certain region within a certain period of time. AE sources are precisely defined in space, and in the spatial distribution of signal sources turbulent signals will, over a certain period of time, disappear in the white noise.

Cavitation noise is very similar to AE signals. According to Vetrano, it should be possible to distinguish between these two types of signal by the very high and continuous rate of cavitation signals. Under stable service conditions AE signals from a defect will presumably be at a much lower and more varied rate.

A very promising project is being run at the moment in the U.S.A. under the Heavy Section Steel Technology Program[15]. In Idaho an AE test facility has been established, using the 8-m (26 feet) long EBOR (Experimental Beryllium Oxide Reactor) vessel. This vessel has been modified for testing purposes to provide acoustic signals which simulate cracks growing in the vessel as well as acoustic noise which represents various reactor noises. With this system it has been possible to generate conditions which simulate hydrostatic testing and a varity of operating conditions.

In this and some of the previous chapters have been mentioned a certain number of laboratories known for their valuable constributions to the AE research. It might in this context be mentioned that at C.C.R., Ispra, a status report on failure detection by AE techniques has been prepared by G. Volta; this report includes a list of laboratories working in the field of AE within the CEE area and outlines of their main activities.

Judging from the considerable efforts made in this field, the problems involved with continuous AE detection under the high noise conditions present during nuclear reactor service will certainly be solved in the near future.

5. CONCLUSIONS

AE Techniques Applied During Proof Inspection:

(1) Detecting, recording, and storing of AE signals from steel structures is easy to do and widely used. Even though the technique is at present far from perfect, it might in some cases be useful to apply it just to obtain a recording of the acoustic behaviour of the structure during testing.

(2) The reproducibility and accuracy of the AE technique need to be improved when recordings are compared on a quantitative basis or when quantitative analysis is done, e.g. estimation of stress concentrations in terms of K to K_{Ic} ratios or estimation of rates of different damage processes. The transmission of AE signals from structure to transducer seems to be the principal problem to solve. In addition the properties of the transducer need to be controlled particularly with respect to frequency conditions both when wide-band and when narrow-band transducers are desirable for the particular application.
To achieve a satisfactory improvement it would be a great help if controllable, reliable sources of reproducible AE signals were available. For this reason the development of such sources ought to be pursued.

(3) Location of AE sources in steel structures during proof testing may be readily carried out with a high degree of both reliability and accuracy. At the AE sources defects are generally found by other non-destructive methods, and there is a high probability that crack-like defects will be revealed by the AE location technique.

(4) The contribution of the AE technique in raising confidence in the structure tested is significant. The AE technique covers the entire steel structure at the moment of the first severe loading and points out less reliable areas.
Other non-destructive methods cover limited areas at a time and yield detailed information about the type and extent of the defects. Thus the AE technique is a valuable complement to other non-destructive methods. By modifying the proof testing procedure the AE technique might yield valuable information on crack growth conditions. In this context it is worth noting that some of the disadvantages of applying the overstressing

technique for stress relief are counteracted if AE surveillance is used simultaneously to control defects.

(5) Control of the failure probability during proof testing based on acoustic surveillance is at present hardly possible. An experienced operator is able to recognize unusual and alarming AE behaviour, and the test can be suspended and precautions considered. But, even though considerable effort is promisingly being devoted to the exploration of the relationships between AE behaviour and fracture mechanics, it is at present not possible to state by which criterion the failure probability should be estimated during AE surveillance.

(6) Information on type and size of defects is not generally obtainable by AE surveillance.
The shortcomings mentioned under (2) have to be overcome before a numerical correlation between AE behaviour and fracture mechanics can be established. If this is obtained, it might well be the AE behaviour at an early stage in the test which indicates the significance of the defects present. Information on crack growth by fatigue or stress corrosion might also be obtainable.

AE Techniques Applied During Recurrent Inspection

(7) When the structure is fully accessible the same sort of advantages may be gained from AE surveillance during recurrent testing as when it is applied during proof testing. However, no experience is at present available.
On account of the shortcomings mentioned under (2), comparison of AE recordings from initial and recurrent tests is unlikely to give significant additional information which might not be gained by other non--destructive methods.

(8) If the structure is inaccessible, then although AE surveillance during recurrent testing might be possible by using stationary transducers, it would at present be very difficult to interpret the data collected, and again no experience is available.

AE Techniques Applied During Service

(9) Application of the AE technique during service is complicated by the rough ambient conditions (noise, temperature, irradiation), and no

experience from practical applications is available. Different methods to overcome the difficulties have successfully been tried experimentally, and considering the impressive efforts devoted to this subject, particularly in the U.S.A., it seems inevitable that the problems involved in continuous AE detection under the conditions present during nuclear reactor service will be overcome in the near future.

(10) When methods of AE surveillance during service have been successfully developed, the serious problem still remaining will be how to utilize the information gained. At the moment it seems natural to use this surveillance in terms of mechanical signature analysis.

6. REFERENCES

1) N. Kirby, Application of Acoustic Emission Surveillance Methods to Reactor Pressure Vessels. Supplementary note to Risø-M-1429. UKAEA, REML, Culcheth. Internal report.

2) R. HILL and R.W.B. Stephens (Chelsea College), Acoustic Emission from Adhesive Joints.
G.J. Curtis (Nondestructive Testing Centre, Harwell), The Characterisation of Failure Mechanisms by Means of Acoustic Emission.
I.L. Mogford (Central Electricity Research Laboratories, Leatherhead), Acoustic Emission and Fracture in Steels.
Unpublished lectures given at the meeting "Acoustic Emission", 14 March 1972, Imperial College, London.

3) A. Nielsen, Acoustic Emission Surveillance Methods. Risø-M-1429, (1971) 9 pp. Internal report.

4) R. Adler, A. Korpel, and P. Desmares, An Instrument for Making Surface Waves Visible. IEEE Trans. Sonics Ultrason. SU-15 (1968) 157-161.

5) G.A. Massey and R.R. Carter, Portable Laser Instrument for Vibration Analysis and Transducer Calibration. NASA-CR-73137 (1967) 16 pp.

6) D.L. Parry and D.L. Robinson, Incipient Failure Detection by Acoustic Emission: A Development and Status Report. IN-1398 (1970) 111 pp.

7) J. Eisenblätter, W. Heide, and R.v. Klot, Forschungsarbeiten zur kontinuerlichen Überwachung der Rissausbreitung in Druckbehältern. Untersuchungen im Labor: Sondenentwicklung und Messungen an Proben. 3. Bericht. Dezember 1969. Battelle Institut E.V., Frankfurt am Main.

8) J. Eisenblätter, W. Heide, H. Jöst, and R.v. Klot, Forschungsarbeiten zur kontinuerlichen Uberwachung der Rissausbreitung in Druckbehältern. Teil II. Weitere Untersuchungen über die bei der Rissausbreitung emittierten Schallwellen. Abschlussbericht März 1971. Battelle Institut E.V., Frankfurt am Main.

9) R.W. Nichols, Use of Overstressing Techniques to Reduce Risk of Subsequent Brittle Fracture - 1, 2. Brit. Weld. J. 15 (1968) 21-42, 75-84.

10) J.B. Vetrano, W.D. Jolly, and P.H. Hutton, Continuous Monitoring of Nuclear Reactor Pressure Vessels by Acoustic Emission Techniques. Battelle Pacific Northwest Laboratories. Lecture given at the conference Periodic Inspection of Pressure Vessels, 9-11 May 1972, London.

11) H. L. Dunegan, The Impact of Acoustic Emission on the Technical Community. Unpublished lecture given at the meeting "Acoustic Emission", 14 March 1972, Imperial College, London.

12) E. A. Robinson, Multichannel Time Series Analysis With Digital Computer Programs (Holden-Day, San Francisco, 1967) 298 pp.

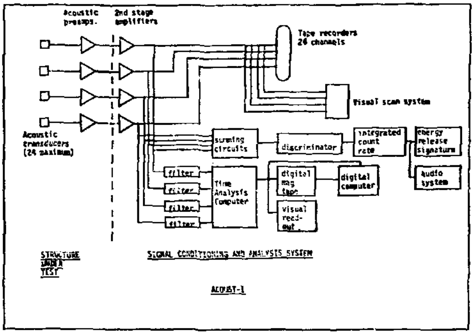
13) Y. Nakamura, Acoustic Emission Monitoring System for Detection of Cracks in a Complex Structure. Mater. Eval., 29, (1971) 8-12.

14) C. C. Price and J. R. Karvinen: "EBR-II Noise-Signature Analysis During the First Half of Fiscal Year 1971". ANL/EBR-36 (1971) 58 pp.

15) R. D. Wylie, Developments in Nondestructive Testing Techniques in Reactor Pressure Vessels, Paper No. 1, presented at the Heavy Section Steel Technology Program, 6th Annual Information Meeting, Oak Ridge, Tennessee, 25-26 April 1972.

16) G. Volta, Incipient Failure Detection by Stress Wave Emission Techniques. Status Report.
(EURATOM, CCR, Ispra, Italy, (1972). 24 pp.

APPENDIX



AE equipment for the surveillance of a large pressure vessel. For the sake of clarity only four transducers are indicated in the diagram, although in operation the number would be considerably higher.

The system can be divided into three lines with the following operational purposes:

(1) Data storage is shown at the top of the diagram. All information from all transducers is, after suitable amplification, recorded on a tape recorder (frequency range 200 kHz) for storing. It is appropriate simultaneously to connect the channels singly or in groups to an oscilloscope (Visual Scan System) to be able to survey the operation of the transducers and tape recorders.

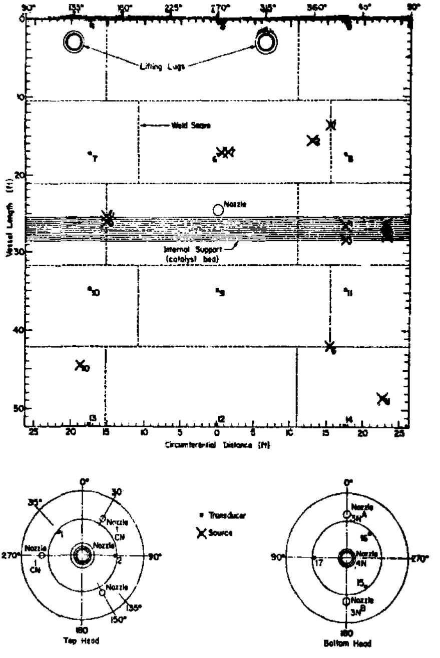
(2) *Recording of energy release signature* (ERS) is indicated below the data storage line. All channels are interconnected (it would be an advantage to connect the channels in 2 - 3 groups, each with an ERS instrumentation). The signal rate is derived and recorded by a pen recorder as the ERS curve which is carefully observed during the pressure test. A warning system is included which produces audible signals correlated to the AE signals from the vessel (Audio System).

(3) Triangulation for localizing of AE sources is shown at the bottom of the diagram. The crucial part is a time analysis computer (TAC), which is fed by 4 transducers chosen to cover the vessel as efficiently as possible. After filtering off of some noise signals the time elapsed between the arrival of signals from each of the four transducers is recorded by the TAC instru-

ment and stored in a memory. At appropriate times during the pressure testing, the memory may be read out to give the distribution of the recorded periods of time between the arrival of signals from all possible pairs of the 4 transducers. This information is fed to a digital computer (either directly or via a suitable terminal) which is programmed to calculate the location of probable AE sources. A network of numbers which covers a sketch of a layout of the pressure vessel is read out from the computer (Visual Read Out). Numbers 0 or 9 indicate respectively no or high probability that an AE source is present at the location concerned.

The choice of which of the 4 transducers is to be connected to the TAC system can be changed during the pressure test if it is considered appropriate; the pressure test can be suspended and the tape recorder from the data storage replayed for a repeat TAC analysis using any other choice of 4 transducers from among the number used on the pressure vessel. Further possibilities exist of making refined analyses to find less significant sources of AE with high reliability.

The result of such an investigation is shown in the figure which is a layout of a reactor vessel for the petrol industry. The positions of the transducers and the locations of AE sources are indicated. The source locations have been marked by superimposing the network of numbers from the digital computer.



Lifting Lugs
Weld Seam
Nozzle
Internal Support (catalyst bed)
Vessel Length (ft)
Circumferential Distance (ft)
Transducer
Source
Top Head
Bottom Head