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International Working Group on Fast Reactors

Specialists Meeting

on

IN-SERVICE INSPECTION AND MONITORING OF LMFBRS

Bensberg, Federal Republic of Germany

March 9-11, 1976

SUMMARY REPORT

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INTERNATIONAL WORKING GROUP ON FAST REACTORS

Specialists Meeting

on

IN-SERVICE INSPECTION AND MONITORING OF LMFBRS

Bensberg, Federal Republic of Germany
March 9-11, 1976

Chairman: G. Herberg
Interatom
Internationale Atomreactorbau
GmbH, Qualitätsstelle, FRG

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International Atomic Energy
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* This paper was submitted by the French delegation after the meeting at Bensberg and was not presented or discussed at the meeting.

International Working Group on Fast Reactors
Specialists Meeting on In-Service Inspection and Monitoring
Bensberg, F.R.G. 9-11 March 1976

Summary Report

I. Introduction

On the recommendation of the International Working Group on Fast Reactors, an IWGFR Specialists Meeting on In-Service Inspection and Monitoring was held at INTERATOM, Bensberg, F.R.G. from March 9 to 11, 1976.

Dr. E.A. Khodarev, Scientific Secretary, IWGFR, welcomed the participants on behalf of the Director General of the International Atomic Energy Agency (IAEA).
Dr. G. Herberg, Meeting Chairman, also welcomed the delegates.

The list of meeting participants is given in Appendix I and the meeting program is provided in Appendix II. The papers submitted by the meeting participants are provided in Appendix III.

Summaries for each item of the program are given below. The general meeting conclusions and recommendations follow these.

II. Summaries for each Item of the program

1. Inspection requirements and concepts

1.1 The first session was devoted to a review of inspection requirements and concepts. Papers from France (Mr. Gallet), Japan (Mr. Abe), W.-Germany (Mr. Leder) and Netherlands (Mr. Tromp) reviewed the present proposals for the inspection of the Superphenix, Monju and SNR 300 reactor systems respectively, and described the equipment and techniques being developed for periodic non-destructive examination and viewing. An UK paper (Mr. Bolt) made a more general review of the historical development of in-service inspection requirements and the associated philosophy leading to some suggestions for guidelines and preliminary proposal primarily based on the CFR design concept.

1.2 Subsequent discussion was vigorous and several important points were apparent. First, there were differences in terminology between different speakers and it was suggested that further discussion was desirable to establish a common terminology. The term "in-service inspection" was probably best reserved as a general term embracing examination made during shut-downs ("periodic inspection"), devices operating continuously throughout operation such as leak detection and boiling noise detection ("continuous monitoring devices") and tests or devices applied periodically under operational conditions ("periodic operational testing"). Finally, materials surveillance has to be regarded as a part of in-service inspection.

1.3 It was agreed that assurance of the continued satisfactory condition of power reactor required all these forms of in-service inspection and that the formulation of appropriate requirements and the development of techniques to achieve these were essential to the practical installation of commercial LMFBR systems. Because of the nature of the system, full use would have to be made of operational monitoring techniques to infer the continued satisfactory condition and behaviour to a greater extent than in thermal power reactors where periodic non-destructive examination for defects played the predominant role.

1.4 It was also clear that such procedures in most countries were currently directed to assurance of safety. Commercial requirements lead to increasing demands for in-service inspection as an aid to reliability by indicating when to take preventative or remedial actions before structures involving large investments suffer damage.

1.5 In no country were the requirements formalised and published, although there were active and constructive discussions currently in progress in several countries esp. in USA which would culminate in such requirements being established in the next few years. Further international discussion in the interval was desirable.

1.6 Many of the proposed techniques still require considerable development and the essential need for appropriate techniques indicate that increased effort will be needed in order to provide solutions in time.

1.7 The actual requirements could vary with detail design. The differences between pool and loop concepts between systems with and without guard vessels and between those with and without appropriate cleaning arrangements in gas spaces were specific examples. The importance in choosing designs that facilitated inspection, maintenance and repair procedures and that provided adequate accessibility was emphasised most vigorously. Associated with this was the need to consider for each design the potential modes of failure and the associated safeguards so that the most relevant regions for inspection for defects, the defect acceptability standard and the appropriate selection between operational monitoring and periodic examination techniques can be decided.

2. Development of inspection methods

2.1 Ultrasonic inspection of austenitic welds

The conventional single probe ultrasonic techniques in weld testing are not applicable to austenitic welds, since increased scatter echoes from the austenitic weld metal cause a low signal to noise ratio. The testability of austenitic welds by ultrasound depends on the structure of the welding deposit. If it is possible to adjust the welding parameters in such a way that the ultrasonic transmission is improved the signal to noise ratio is also improved. An example of such improvements was reported.

Furthermore there are different ultrasonic techniques by which an improved signal to noise ratio might be attainable. The application of specialised transducers of the focused singly crystal type and also custom made transducers for tube/tube welds in steam generators were reported. Details on the development of the transmitter-receiver technique using broad-band transducers for application to flat surfaces were also reported. Using these probes, testing for longitudinal flaws in welds was satisfactorily conducted, whereas the testing on transverse flaws is still a problem and further developments are necessary.
Practical work in the field on austenitic welds, using the commercially available receiver/transmitter transducers, did not yet yield good results. Radiographic examinations served here as a basis for comparison.

T/R angular beam probes operating at an environmental temperature of 250 °C are under construction.

It was concluded that there is progress in this field but a lot of work remains to be done.
Another current subject of R+D is to improve the welding technique to gain a more testable weld. Thus requires modifications to the metallurgical structure.

2.2 Electro-Thermal Method

The infrared electro-thermal concept is a new method that offers potential for examining austenitic stainless steel components, and for inservice inspection of LMFBR's. In principle, this method consists of passing a short, high-amplitude electrical current pulse through a test object, and monitoring the resulting surface temperature profiles using an infrared scanning camera or similar sensing device. Experimental investigations provided a demonstration of the basic sensitivity of this method under laboratory (room temperature) conditions, and indicated that further development work was needed and justified.

2.3 Eddy current and ultrasonic methods for heat exchanger tubes

Eddy current methods are more or less limited by the material that has to be inspected. In austenitic material good quality volumetric testing is possible. The application today of eddy current methods on ferritical material does not give adequate results for volumetric testing. For surface crack detection eddy current is suitable.

The magnetic saturation technique may procedure in the future acceptable results for ferritic material.

Multi frequency systems is a future development which can be used either with ferritic or with austenitic tube material.
This techniques can eliminate the influences of: sodium contamination, variations in electro-magnetic properties and variations in tube dimensions.
However, the problems associated with sodium deposits on the "contact" surface have not yet been solved by multifrequency methods.

For ultrasonic testing, transducers must be developed and tailored for special applications. These are, for instance: tube/tube welds; internal bore welds; wall thickness-measurements.

The beam characteristics of ultrasonic transducers should get more attention. Improvement is necessary in that field, because calculation methods to improve beam characteristics are not yet standard practice.

Not all the problems associated with coupling for use in non-laboratory application have been solved.
Ultrasonic testing on tube welds in austenitic material needs further investigation.
Data processing and data storage for in-service inspection should be developed.

Sodium deposits on the "contact" surface (the surface to which the probes are coupled) of tubes cannot be admitted neither for application of ultrasonic nor eddy current testing. The effects of filled cracks on the detectability of flaws should be investigated.

In complex geometries the manipulation of sensors is a problem common to both eddy current and ultrasonic techniques. Presently very little in the way of practical experience is available.

2.4 Television and Periscope Inspection Methods

Three remotely operated camera systems have been developed at Berkeley Nuclear Laboratories, CEGB, UK, for application to reactor systems.

The first of these combines continuous TV viewing with the ability to take still photographs to provide high resolution records and has been applied in the core of PFR.

Miniature cameras have also been developed to inspect the superheater tubes in PFR from the outside and the evaporator tubes from the inside.

Periscopes and borescopes are used extensively in the fast reactors Rapsodie and Phenix.
Because of their good image definition obtained at the temperature of 150 °C they give valuable indications of the condition of the components.

2.5 Radiographic methods

Radiographic techniques will have value in the periodic examination of reactor systems despite moderate levels of background radiation. The use of chemical reduction on processed film which has been overexposed by such radiation can allow recovery of good quality images for interpretation. In addition, the use of image enhancement techniques can improve the ability to observe and measure details in radiographs that may lack clarity due to poor geometric conditions, radiation scatter and low contrast. Further work in this area is suggested.

2.6 Acoustic monitoring techniques

The presentations and discussions about the development of acoustic methods have shown the increasing significance of continuously monitoring systems. In the future acoustical and other unusual methods may substantially contribute to the reliable and safe operation of nuclear plants. The developments in this field are not in contrast or an alternative to in-service inspection methods but are supplementary to them. The advantages and disadvantages of both kinds of control methods may be somewhat compensating, Periodic inspection is very precise and gives clear indication of the position and the size of a failure, but it needs good accessability and takes much time. Continuous monitoring gives a very quick and integral message about the situation in a system, but localization and size determination of a failure are difficult. Thus a well balanced combination of both kinds of methods may be the optimum solution when concerning technical as well as economical aspects of the safety control of nuclear plants.

Since the uses of acoustic methods are many, a heterogeneous mixture of details was presented on the following topics: Acoustic emission analysis, sodium boiling detection, cavitation problems, leak detection in steam generators or other components, loose parts detection. Although the research and development work in laboratories and test facilities is going on, more and more people try to prove the developments by performing in-field measurements. These measurements do not only propagate the development of the hardware, but also yield knowledge about the noise behaviour of large installations. Useful information can be derived from such measurements, e.g. identification and localization of noise sources or correlation of noise events with certain procedures in the plant.

Further work should be directed to the following points: intensification of basic research work concerning LMFBR specialities, such as materials, sodium environment, high temperature transducers (though high temperature transducers nevertheless have given good results at C.E.A. even after 8800 h in sodium in the temperature range from 150 °C to 580 °C), experience of the acoustic behaviour of large sodium systems, development of signal processing methods which are capable of dealing with the complex noise generation and transmission in reactor systems and to cover the various tasks of acoustic surveillance.

2.7 Under Sodium Viewing Systems

A prototype Under-Sodium-Viewing and Ranging (USV) system has been developed and demonstrated as a possible in-service inspection method at HEDL. Special ultrasonic transducers were developed for use in the USV system to produce pictures of objects immersed in 5 m of liquid sodium. This system operates in two modes: viewing and ranging.

Scanning is accomplished by rotating a scanner arm that is positioned above the object to generate ultrasonic beams that are directed vertically downward. Typical viewing distances are 5 to 30 cm, although lower-resolution pictures can be formed at much greater distances. The viewing perspectives are changed electronically by adjusting two controls on the electronic coordinate transformation module. Thus, only a single scan of the object is required to store the data in memory, after which the scan data can be retrieved for display at will.

Objects in sodium may be precisely located at distances up to 5 meters by operating the system in the ranging mode. Ranging data are displayed on a memory oscilloscope using a "radar" type of presentation.

The HEDL development program resulted in the assembly and successful liquid sodium testing of a prototype USV system. Testing was performed in a 151 m^3 sodium facility which contained a full-scale model of one-third of the FFTF core. High resolution pictures permitted identification of core subassemblies by forming images of coded side notches and small indentations placed on the top surfaces of subassembly handling sockets.

The following capabilities were demonstrated while testing the prototype system in sodium during a two-week period.

- All of the 34 transducers used during these tests wetted immediately after being immersed in 177 °C sodium, and all operated satisfactorily throughout the two-week test.
- High-resolution pictures of objects under 5 m of liquid sodium can be constructed if the objects are located within the 1.8 m diameter field of view covered by the scanner arm.
- Objects up to 5 m from the scanner can be located to within ± 0.5 percent of the actual scanner-to-object distance.
- Core component identification, location, and orientation can be determined by forming pictures of coded notches or indentions.
- Adjustments in the position of in-vessel mechanisms can be monitored.
- The relative elevation of adjacent subassemblies can be determined to within 0.06 cm.
- Sodium level can be ultrasonically measured to an accuracy of 0.5 percent for depths of at least 5 m.
- The combination of ranging and imaging capabilities could assist in the location and retrieval of foreign objects or out-of-position components.
- Good signal-to-noise operation was achieved with the transducers immersed in sodium. Hence, certain inservice inspection functions are suggested such as periodic inspection of thermal baffles and critical welds.

Research at Marchwood Engineering Laboratory CEGB, UK, is being conducted to produce a medium-range ultrasonic scanning array for under-sodium visualisation in fast reactors.

An electrically scanned array system has been developed, based upon digitally produced phase delays and controlled by a microprocessor. Its advantage over conventional radio-frequency techniques is in its flexible soft-ware control. The system has been demonstrated under water.

Analogous results have been obtained at the C.E.A. with the use of one transducer, focused by a special device with mirrors. The visualizations, which were very clear of the assembly head and also of one heat exchanger tube sheet, encourage further experiments in the reactor.

2.8 Vibration and acceleration measurements

Following the experience with reactors, the monitoring of vibrations provides much useful information on the main components, such as the steam generators and reactor. With the help of concurrent vibration measurements and neutronic fluctuations it is possible to see the onset of defects.

3. Practical work and indications for future development

Under this topic was reported about radiographic and ultrasonic on austenitic pump barrel of SNR 300. Tests were made on a prototypical austenitic pump vessel for sodium use. The pump barrel had been in use for several thousand hours.

The tests were made by means of ultrasonic methods of which the results were verified by means of radiography and gammagraphy. The ultrasonic tests were made by means of the transmitter/receiver type transducer. The transducers used were types operating in the transverse and longitudinal mode in the 2 MHz range.

The transducers may be seen as advanced commercial transducers. The first results obtained were disappointing, good correlation between radiographical methods and ultrasonic methods could not be demonstrated. The x-ray photographs obtained were of a high quality therefore it can be concluded that the ultrasonic testing is not yet operational for austenitic weld material. The gammagraphy did not give good results.

4. Miscellanous subjects

In this session Dr. Nichols reported a contribution by CEGB, UK about in sodium materials monitoring. This materials surveillance method is necessary as an additional measurement to periodic inspection, continuous operational monitoring and periodic operational monitoring.

The provision of material samples for surveillance by periodic removal and examination to check for changes in properties is important, for example, to ensure that fracture toughness of the diagrid remains sufficient during the reactor lifetime.

III. Conclusions and Recommendations

1. The specialist meeting was regarded by the participants as very timely and led to a valuable exchange on the various aspects of in-service monitoring and periodic examinations of LMFBR systems. The discussions indicated that the major methods of approach were similar in the various countries and that, although final answers were not achieved, present-results showed considerable promise.

   The success of this meeting and the indication of continual development in the various countries emphasised the need for publication of the contributions and summaries and of continued exchanges between the participating countries.

2. There was a general view that this topic was an essential aspect in the development of practical, commercial LMFBR's and that there was an overall need for additional effort to be devoted to this important topic in all its aspects. I.W.G. members were recommended to advise their countries of this important need.

3. In no country were the requirements for in-service inspection or for the preferred choice of techniques yet established. Proposals were being discussed in several countries and further international discussion of these would be most helpful. It was therefore recommended that the IAEA organises a further specialist meeting on this topic in about two years time.

4. There are difficulties in technical terminology and it was recommended that an agreed terminology should be defined by specialists in the subject, to avoid ambiguous indexing. A separate letter including a proposal will be sent to the INIS by the chairman of the specialists meeting.

Appendix I: List of Participants

France	A.H. Bret STRS/LEIS Centre de Cadarache B.P. No. 1., 13115 St. Paul Lez Durance
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+ Recording secretaries

Appendix II Programme and Agenda of the Meeting

Tuesday, 9th March, 1976

10.00 Address of welcome
Dr. E. A. Khodarev
International Atomic Energy Agency
Vienna, Austria

Opening remarks
Dr. Herberg
INTERATOM, Bensberg, FRG

10.15 Confirmation of the proposed agenda

10.30 1. Inspection requirements and concepts

1. Proposals for In-Service Inspection and Monitoring of Selected Components Located within or part of the Primary Containment of Sodium Cooled Fast Reactors.
P. R. Bolt, CEGB, United Kingdom
(Presented by Mr. R. W. Nichols)

2. In-Service Inspection of the Main Vessel of Super Phenix
B. Gallet, CIRNA, Centre de Saclay, France

3. In-Service Inspection for "MONJU"
S. Abe, Power Reactor and Nuclear Fuel Development Corporation, Tokyo, Japan.

4. In-Service Inspection at the SNR 300 within the Range of Reactor Vessel
H. Leder, INTERATOM, Bensberg, FRG

5. Inspection Requirements and Concepts for LMFBR Heat Exchangers and Pump: a Manufacturers View
G. A. de Boer, Th. J. Tromp, Neratoom, Den Haag, Netherlands.
(Presented by Mr. Tromp)

Discussion

13.00 Lunch at INTERATOM

14.00 2. Development of inspection methods

1. Ultrasonic Inspection of Austenitic Welds
B. L. Baikie, A. R. Wagg, M. J. Whittle, D. Yapp, CEGB, United Kingdom
(Presented by Mr. Whittle)

2. Ultrasonic Testing of Austenitic Components of Sodium Cooled Fast Reactors.
E. Neumann, B. Kuhlow, M. Römer, K. Matthies, BAM, Berlin.
(Presented by Mr. Neumann)

3. Ultrasonic Testing, State of the Art and Possible Developments
W. Haesen, Th. J. Tromp, Neratoom, Den Haag, Netherlands
(Presented by Mr. Tromp)

15.45 Refreshments

16.00 – 18.00 Discussion

18.30 Cocktail party at INTERATOM

Wednesday 10th March, 1976

9.00 2. Development of inspection methods (contd.)

4. Preliminary development of in-service inspection methods for LMFBRs.
J. Spanner, HEDL, Richland, WA, USA

5. Studies in Non-destructive Testing with potential for In-Service Inspection of LMFBRs
R. W. McClung, Oak Ridge National Lab. Oak Ridge, Tenn., USA.

6. In-Service Inspection of Rapsodie's Safety Containment
E. G. Tomachevsky, DEMT, Centre de Saclay, France.

7. A Television/Still Camera with Common Optical System for Reactor Inspection
G. Hughes, P. McBane, CEGB, United Kingdom.

Closed Circuit Television Equipment Developed by Berkeley Nuclear Laboratory for Use on the Dounreay Prototype Fast Reactor
D. B. Friend, A. Jones, United Kingdom
(Presented by Mr. Whittle)

8. Inspection of PFR Steam Generators
K. J. Cowburn, UKAEA, Risley, United Kingdom.
(Presented by Mr. Nichols)

9. In-Service Inspection and Monitoring of LMFBR in France
A. Bret, B. Gallet, E. Tomachevsky, France
(Presented by Messrs. Gallet and Bret)

10.00	Refreshments
10.30	Discussion
13.00	Lunch
14.00	10. The Development of Acoustic Monitoring Techniques of LMFBRs E. J. Burtun, REML, United Kingdom (Presented by Mr. Nichols)
	11. Multi-Channel Acoustic Emission Surveillance of a Pressure Vessel during Proof Test A.C.E. Sinclair, A. Tobias, D.C.Connors (Presented by Mr. Whittle, CEGB, United Kingdom)
	12. An approach to the On-Load Surveillance of Sodium Cooled Reactors by Acoustic Methods. K. Förster, INTERATOM, Bensberg, FRG.
	13. Appliance of Stress Wave Emission in Phenix Reactor E. G. Tomachevsky, DEMT, Centre de Saclay, France.
16.00 - 18.00	Discussion
19.30	Dinner at Wald Hotel Mangold, Bensberg.

Thursday, 11th March 1976

9.00	14. Vibration-Acceleration Measurements on Prototype Steam Generators Th. J. Tromp, Neratoom, Den Haag, Netherlands.
	15. Vibrational Studies and Measurements on the Phenix Reactor Y. Tigeot, M. Livolant, CEA, France (Presented by Mr. Tobachevsky)
10.00	Refreshments
10.15	Discussion
12.00	Lunch at INTERATOM
13.00	3. Practical Work and indications for future development
	1. Radiographic and Ultrasonic Inspection of an Austenitio Pump Barrel W. Haesen, G. F. Klinkert, Th. J. Tromp, Neratoom, Den Haag, Netherlands (Presented by Mr. Tromp)
14.00	4. Miscellaneous subjects
	1. In Sodium Materials Monitoring for LMFBR. H. J. Blewden, K. S. Probert, United Kingdom. (Presented by Mr. Nichols)
14.30 - 15.00	Discussion
15.10	Discussion of the conclusions and recommendations of the meeting

Friday, 12th March 1976

Tour to the SNR-300 site

Appendix III. Papers Presented :

P. R. Bolt, "Proposals for In-Service Inspection and Monitoring of Selected Components Located within or part of the Primary Containment of Sodium Cooled Fast Reactors." (United Kingdom)

Abstract

Design and operational experience of CEGB gas cooled reactors and certain overseas reactor plant is reviewed in relation to in-service inspection and monitoring capabilities. Design guidelines and preliminary proposals are given for in-service inspection and monitoring of selected components located within or part of the primary containment of sodium cooled fast reactors. Specific comments are made on the items of further design and development work believed to be necessary.

Proposals for in-service inspection and monitoring of selected components located within or part of the primary containment of sodium cooled fast reactors

1. INTRODUCTION

Fossil fuelled generating plant has been designed and built to enable plant inspection to be carried out at regular intervals and on some plant items inspection has been a statutory requirement. Early gas cooled reactor plants were designed on the basis that man access within the reactor pressure vessel was not possible due to activity problems and that in vessel components should, therefore, be designed to last for the full reactor lifetime without the need for repair. Most of the early designs did not specifically provide facilities for inspection of structural components.

Operational experience with the CEGB gas cooled reactors since 1962 has shown that it was perhaps too optimistic to expect to design components which would be certain to last the reactor lifetime without failure. Whilst the initial design philosophy made little provision for inspection, many inspection and remedial procedures have been necessarily and successfully developed within the limits of accessibility determined by the layout, which was generally compact to limit pressure vessel size.

The environment experienced by components in large sodium cooled fast reactors represents a major departure from that in conventional plant and gas cooled reactors. The physical and chemical characteristics of sodium do not allow the inspection and remedial measures developed for the gas cooled reactors to be utilised to any great degree on LMFBRs. The techniques that are expected to be needed for LMFBRs include acoustic visualisation techniques, in sodium ultrasonic examinations of structures, component chemical cleaning or decontamination and possibly remote maintenance etc. Hence any repairs to or replacements of major components that may become necessary because of deterioration cannot be expected to be easier or less time-consuming than equivalent operations carried out on existing reactors. Outage costs can be very high and advantage should be taken of the significant reduction that could come from adequate early warning of developing faults and deterioration processes which could result in component failure.

The UK gas and liquid metal cooled reactor experience and that of overseas reactors is considered in this paper together with possible deterioration and failure mechanisms that can act in LMFBRs, from this data design guidelines relevant to LMFBR inspection are derived. From these guidelines the necessary scope of in-service inspection of selected LMFBR in vessel components is obtained.

The following proposals for in-service inspection have been prepared mainly from the viewpoint of pool type LMFBRs; the principles inherent in the proposals however, are applicable also to loop type LMFBRs, provided that the differences in component access and environment etc. are taken due account of.

The objective of this paper is to define the extent of in-service inspection that is considered necessary for LMFBRs, to give the necessary confidence to a Utility that adequate levels of plant availability and safety can be achieved throughout the required lifetime. For many of the LMFBR in vessel components in their present form, in-service inspection and repair will be difficult and some of the inspection methods are inadequately developed or even do not exist. The USA and UK development work although at a preliminary stage is encouraging and at HEDL in sodium inspection and visualisation devices have been tested in sodium.[1, 2] HEDL[1] state that, "Flaw detection using sodium as the acoustic coupling media was briefly explored. . . ., we could detect flaws as small as $\frac{1}{8}$ inch in diameter through $\frac{3}{4}$ inch of metal (not weld metal - author's note). This suggests that critical areas of the internal LMFBR components could be inspected for flaws during reactor shutdown without draining sodium from the reactor." This statement is possibly optimistic but it indicates that progress is being made in this difficult area. The design options and inspection techniques that can improve the inspectability and repairability of LMFBRs are more properly within the responsibility of the reactor plant developer and designer, but recommendations for actions in this area are made in the conclusions to the paper.

2. REQUIREMENTS FOR IN-SERVICE INSPECTION OF FUTURE CEGB NUCLEAR STATIONS

2.1 General Requirements

Based on more than a decade of experience gained at CEGB nuclear stations, see Appendix 1, a view has been formed of the basic principles which should be used to determine whether a particular in-service inspection and monitoring scheme is adequate. The principles that follow are generally applicable to all types of reactor plant that CEGB might purchase and operate. They are:-

a) The need for man access to a hostile environment must be minimised, and man access required only for spaces containing sufficient oxygen to support life.

b) As a corollary to (a) the emphasis must be on the use of remote inspection. Suitable built in facilities must be provided for those items which cannot be easily demounted and then inspected. Details must be agreed before the reactor design is frozen.

c) The design should take account of the desirability of access during commissioning and early life to areas which may subsequently become inaccessible due to radiation levels and non breathable atmospheres etc.

d) It is considered essential to design the reactor so that all components whose failure would cause severe economic loss or have significant safety implications can be inspected or monitored at prescribed intervals during their life and repaired or replaced if necessary. All equipment and facilities necessary in carrying out this work must be available on site by the time of reactor commissioning or be available at short notice if this can be shown to be economic.

e) All components that are essential to reactor operation must be capable of repair and/or replacement unless an alternative remedial solution can be shown to be economic and is acceptable.

f) There may be components not included in classification (d) above, where access for inspection is very limited. The design should avoid such situations but where this is not possible an alternative partial solution would be to install permanent monitoring equipment which can, by remote means, give warning of unpredicted behaviour and indicate a need for remedial action. Situations that are intended to be dealt with in this way should be discussed with the Utility, preferably prior to design freeze and certainly prior to placing the station contract.

In all reactor systems essentially two basic types of in-service inspection are needed. The first is an ability to "visually" assess the surface condition, shape and relative position of components. The second is concerned with surface and/or volumetric inspection techniques which are capable of monitoring the behaviour of pre-existing defects and the further examination of adverse conditions detected during the more general visual inspection. Bench marks, identification numbers and reference co-ordinates are essential for proper inspection procedures.

With a relatively new system such as a sodium cooled fast reactor it is difficult to collect sufficient experimental data on materials etc., to be able to predict with sufficient accuracy component behaviour during its 30-40 year life. Accelerated tests and/or shorter term tests will form the basis of the design which hence will require the use of interpolation or extrapolation techniques in the use of the data. Both of these aspects are likely to require considerable margins in the design. CEGB and overseas[3] experience with both conventional and nuclear plant has highlighted the significant uncertainties inherent in such design methods and the consequent need for periodic in-service checks of component condition and fitness for further service.

2.2 Inspection Aspects Specific to LMFBRs

In Appendix I the degree of in-service inspection considered necessary for the economic and safe operation of CEGB gas cooled reactors and for USA light water reactors has been described and the general guidelines for the in-service inspection requirements of CEGB reactors have been described in Section 2.1.

It is difficult to justify treating sodium cooled reactors as a special case in which the reactor inspection experience in Appendix I and the general design guidelines evolved from that experience are set aside and considered not to be relevant. The main objectives of in-service inspection are common for gas cooled, water cooled and sodium cooled reactors, and these are to minimise reactor outage and repair costs and to assist in avoiding situations causing a public or operator hazard. The sodium coolant is opaque, solid at 98°C and chemically reactive with air, this makes in-service inspection of LMFBR in vessel equipment difficult and possibly very time consuming. The high thermal diffusivity of sodium (approximately 400 times that of water) allows temperature variations in the sodium to be rapidly transmitted with little attenuation to metal structures in contact with it. Hence unless sodium temperature variations are adequately controlled thermal fatigue problems can arise.[4, 5, 6] Sodium environmental effects on the mechanical properties of primary circuit materials are complex and service experience at representative sodium conditions in reactor circuits and test rigs is of limited duration. The total effect of these characteristics of the sodium coolant however, while making the main objectives of in-service inspection more difficult to achieve, cannot be said to lessen the need for in-service inspection in comparison with the CEGB thermal reactor systems. In addition it could be postulated, not unreasonably, that the faults and accidents that could arise due to structural failures in LMFBR[7] were potentially more hazardous than those that could occur in Magnox or AGR and hence required at least comparable standards of in-service inspection.

CEGB experience has shown that predictions of the behaviour of reactor materials during their service life are subject to considerable uncertainty. In the case of sodium cooled reactors it is noteworthy that significant adjustments have frequently been necessary, and are still being made, in accounting for the effect of the sodium/cover gas environment on material properties. Notable examples are carbon transport, nitriding and sodium effects on ductility and stress rupture strength etc.

Reviewing CEGB and other utility experience[8, 9, 10] it is not unreasonable to conclude that substantial operating experience must be obtained from a number of similar reactors before one can be certain that a very large proportion of the significant damaging processes can be adequately foreseen and accounted for during the design process. At the present time it cannot be claimed that such substantial operating experience exists for sodium cooled reactors and hence it is considered essential that the design criteria (a) to (f) above are fully implemented in the design of LMFBRs. This basic approach has been supported elsewhere[7, 11, 12] for other reactor systems and LMFBRs.

A question that naturally arises from the above discussion is the extent to which provision of redundancy and/or diversity could modify the need for in-service inspection. If one considers a component to which criteria (d) above is relevant then it is considered necessary to periodically or where appropriate continuously establish by in-service inspection, monitoring or test that an acceptable degree of redundancy or diversity has been retained. If a satisfactory test of continued redundancy or diversity can be devised then to achieve the required safety standards, in-service inspection of the component might not be necessary. This however, is unlikely to be satisfactory in terms of economic criteria for a component essential for continued reactor operation, e.g. the diagrid or core support structure, as the costs arising from a serious or gross failure of the component could be many times more than the costs arising from the work necessary to remedy a fault which was still developing and which had been detected at an early stage in its evolution. Additionally, remote inspection would be needed to initially assess the required remedial work on the failed component.

However, for the majority of cases of structures in which redundancy and/or diversity is provided it is unlikely that a satisfactory test could be devised for both the main and back up structure. As a specific example a rod system hung from the reactor roof could be used to provide diversity of support for the reactor diagrid and core and each rod might be inspectable by ultrasonic methods applied to the accessible top end of each rod. Assessment of the main strongback core support structure would probably require more complex inspection methods possibly using preset or moveable probes in conjunction with under sodium visualisation techniques. A basic design approach which has been proposed by various design organisations for critical structures immersed in sodium in a LMFBR reactor vessel is to use a large factor of safety in relation to design loadings,[13, 14] to minimise thermal stresses, hydrodynamic excitation and vibration and to use conservative values for material properties which would be checked by material samples subjected to equivalent or more severe environmental conditions in suitable reactors and in test facilities. The structure would initially be manufactured to high standards of quality and fully "finger printed" to identify all significant defects which would be assessed by a fracture mechanics approach. The uncertainties referred to earlier, particularly on the long term effects of the sodium/cover gas environment and the lack of operating experience on modern LMFBRs, are considered too great however, to allow this procedure to be followed without obtaining additional data from in-service inspection of these critical structures.

The NDT inspection methods used to "finger print" the structures after manufacture should be the same as those to be used during the in-service inspections. A full geometric survey should be carried out after completion of construction and where possible following each of the major pre-commissioning tests. The manufacturing standards and defect levels etc., should at least be equal to or more stringent than those necessary for satisfactory plant behaviour during the lifetime of the reactor plant.

With some sodium cooled fast reactor designs it may be claimed by the designers that a public or operator safety hazard can be avoided by design actions, e.g. by containment of the incident. Present information is insufficient to allow a clear view to be taken of whether adequate containment of all incidents can be achieved. But even if adequate safety standards could thus be achieved it would not meet a further objective of the plant owner and operator which is as stated in criteria (d) given earlier, to protect the investment represented by the reactor plant. The most satisfactory method of meeting the criteria (a) to (f) above and of achieving the required plant safeguards is to start with a plant of demonstrated adequate quality in design, manufacture and construction, to operate it within valid limits and to periodically inspect the plant to ensure that known or unknown deterioration processes are not developing at unacceptable rates.

The next section discusses in outline the scope, type and degree of inspection considered necessary for LMFBRs to allow the above objectives to be achieved.

3. PROPOSED SCOPE OF IN-SERVICE INSPECTION FOR LMFBRs

The objectives of the inspection proposals are:-

1. To detect and assess the progress of all deterioration processes which could result in significant economic loss or in a safety hazard.

2. To provide data to guide planned and unplanned maintenance and repair operations aimed at achieving the required high levels of station availability.

3. To meet the Licensing Authority's expected requirements for inspection.

At least the following failure modes and deterioration processes should be considered for their applicability to LMFBR components to allow achievement of the above objectives:-

a) Mechanical failure due to static and pressure loadings.

b) Thermal distortions including those causing loading changes particularly if sudden.

c) Fatigue failures caused by thermal cycling and flow/acoustic/ mechanically induced vibrations.

d) Fretting type failures.

e) Fast fractures due to inadequate material ductility.

f) Propagation of material and fabrication defects/dents and tears by local loadings and/or cyclic conditions.

g) Deterioration or seizure of any structurally significant fixings.

h) Changes in material integrity due to erosion and/or corrosion.

i) Environmental effects on material properties due to irradiation, sodium, gas and impurities etc.

In-service inspection methods which may be used to assess these failure modes include:-

i) Evaluation of spatial geometry, i.e. measurement of displacements and angular rotations, visualisation techniques, "diving bell" methods.

ii) NDT surface and volumetric examination.

iii) Excitation frequency measurements of structures.

iv) Stress wave emission techniques and measurement of plant noise.[15]

Additional relevant data should be obtained from material property tests on rigs and from material samples in LMFBRs. This data in conjunction with that obtained from monitoring of liquid and gas conditions (e.g. flow, pressure, temperature, activity, chemical changes, impurities, tracers etc.) can be used to assist the operators in diagnosis of abnormal operating conditions and possible developing faults and deterioration processes.

At the design stage of a power plant it is sometimes claimed that the known failure modes and deterioration processes such as those listed above can be taken account of in the design process and steps taken to ensure that the failure modes are either designed out or made to have an acceptably low economic or safety significance. The complexity of a nuclear installation, the human element in design, fabrication and operation and incompleteness of design and materials data can however, often combine in subtle and unforeseen ways to cause component failures that were previously believed improbable or unrealistic. Examples of such failures have occurred on many power stations built in the UK and throughout the world and a limited sample of such cases is given in Appendix II. Adequate levels of in-service inspection, monitoring and test are necessary to provide early detection of such failure and deterioration processes and to then permit remedial action to avoid unacceptable economic penalties and safety hazards.

Inspection of recent LMFBR designs shows that failure of the core support and diagrid structures could result in a major core incident. An investigation within UK concluded that structural failure of the diagrid or core support system could have serious consequences, causing reactivity insertion and/or major loss of coolant flow. The speed of the incident was too great to allow instrumentation to provide protection. Single failures of other in vessel plant could be acceptable provided that propagation did not occur. Propagation of damage due to missiles released from a failed pump or pressure part was believed unlikely particularly if a minimum separation of the order of 2 m was provided. This study will require updating if significant design changes occur but its conclusions are for the present taken as valid.

It may be possible to provide diversity (redundancy is unlikely to be adequate) in the core support structure which is adequate in terms of the safety hazard. This would not however, meet the requirement to avoid major economic loss which will require periodic inspection (and remedial work if needed) of the core support structure.

It is very much more difficult to provide diversity and/or redundancy of pressure parts involved in the transmission of sodium from the primary pump outlets to the core inlet and in this case it is envisaged that thorough in-service inspection procedures would be the main line of protection against deterioration processes acting during the lifetime of the reactor plant. Although in some designs a degree of pressure part redundancy may be practicable for the more critical components involved in the transmission of sodium to the sub-assembly inlets, and sub-division of flow paths is often provided.

Other reactor components which can have considerable economic and/or safety implications if significant failure occurs are the above core structure, sub-assembly carriers and items forming the containment boundaries, e.g. primary vessel, IHX, vessel penetrations and roof liner. Adequate in-service inspection of these items are considered necessary.

There are a considerable number of in vessel items which are essential to full power reactor operation and whose failure would not have immediate safety implications but could carry significant economic penalties in terms of outage and/or loss of output. In-service inspection is proposed in Table 1 for some of those items where appreciable cost savings could be expected from reductions in outage cost etc., due to the information gained from periodic inspections.

A list of components which should be periodically the subject of in-service inspection and monitoring on either grounds of overall reactor economics and/or safety is given in Table 1. The list is not intended to be exhaustive but is given to provide guidance on the envisaged scope and depth of an acceptable in-service inspection scheme. For completeness the data obtainable from monitoring instruments is included in Table 1.

In many cases of component failure either replacement or repair can be an acceptable remedial action. CEGB experience on gas cooled plant has shown that repair procedures often involve unexpected remedial works that are appreciably affected by the type and conditions of failure. Because of the inherent difficulties of making provision in the design for such uncertainties it is considered advisable that the initial design emphasis should be to provide the capability of removing and replacing all items which are essential for reactor operation. Where such provisions are believed to adversely affect reactor plant reliability it is suggested that the options be discussed with the Utility.

There are certain design features which could make in-service inspection of some components extremely difficult, e.g. presence of thermal insulation not designed for adequate removal/replacement procedures. It is suggested that where inspection is needed arrangements are made to permit remote removal and replacement of insulation if this can be achieved without reducing the overall reliability of the reactor. Removeability/replaceability may be easiest on upwards facing horizontal surfaces. Fixings should be simple and not liable to seizure and the insulation should not require close positional tolerances.

4. CONCLUSIONS AND RECOMMENDATIONS

CEGB and overseas experience has shown that the in-service inspection capability of a newly introduced nuclear reactor type tends to be insufficient to meet the operational and repair problems that arise. Later developments of the nuclear type, due mainly to feed back from the utilities operating it, tend to have improved inspection capabilities. In these circumstances inspection and remedial procedures are often developed by a "learning by experience" approach which as can be seen from the data in Appendix II can result in major reactor outage times and costs.

It is considered most undesirable to follow a similar route for LMFBRs principally because of the major economic penalties and safety implications that could arise if satisfactory inspection and replacement/repair procedures were not developed in advance of their required use.

Current practice on the inspection and monitoring of gas cooled and light water cooled reactors has been reviewed and this experience has been utilised as the basis for design guidelines on the extent of in-service inspection believed to be necessary for future CEGB nuclear plant. In Section 2.2 these guidelines have been interpreted into recommendations specific to LMFBRs. From these recommendations the proposed scope of in-service inspection has been derived. Detailed inspection proposals for many of the critical in vessel components are given in Table 1.

The inspection methods and equipment to carry out some of the proposals in Table 1 e.g. on the diagrid and core support structures, are either non existent or at an early stage of development. The identification of suitable inspection devices and their application to such components is not within the scope of this paper which is concerned essentially with the identification of the inspection data necessary to achieve the objectives given in Section 2. The current state of the in-service inspection capability of LMFBRs is believed analogous to that achieved on LWR systems more than a decade ago. Although the bulk of the USA

LWR inspections have been carried out in the last 5 years it represents the result of a considerable expenditure of development resources. By comparison the reported worldwide design and development effort on fast reactor inspection techniques has been at a low level incommensurate with the unfamiliarity and complexity of the problems posed by NDT examinations and other operations carried out under sodium.

It is proposed that the following areas should be urgently considered by the organisations responsible for LMFBR design and development:-

1. It is suggested that the design organisations should review their LMFBR designs considering the inspection proposals given in Section 3 and the more detailed data in Table 1.

2. Following the design review, the relevant design organisations should prepare a more detailed and comprehensive version of Table 1 and identify the required items of further development work and options for inspection, monitoring and remedial methods.

3. The development organisations should allocate adequate resources to develop the main and back up inspection, monitoring and remedial methods identified in 2 above. They should provide the necessary data to allow the inspection facilities etc. to be built into the pre-contract designs and to establish prior to the station contract the availability and effectiveness of the proposed inspection, monitoring and remedial systems.

Specific aspects of the above actions which require detailed consideration by LMFBR design and development groups are:-

a) Austenitic weld metal under certain conditions can be ultrasonically inspected - can these conditions be applied to all LMFBR welds that need to be inspected? If this is not the case then the options of design changes, other welding or NDT methods or even change of material require urgent examination. This aspect is further described in the paper presented at this meeting by Dr. Whittle (CEGB).

b) Development of reliable transducers for in sodium visualisation and inspection work - for periodic immersion (and "permanent" immersion, if possible) in sodium. The USA work at Hanford 1, 2, and elsewhere is preliminary but encouraging particularly in showing that a probe stand off technique can use sodium as the couplant medium.

c) Development of handling devices to prepare in vessel components for inspection and to manipulate the NDT sensors. The LMFBR fuel element handling equipment and the manipulators used on the larger LWR vessels provide some relevant experience.

d) The in-service inspection capability of critical in sodium structures such as the core support structure or diagrid can most reliably be achieved by designing these structures with inspectability as one of the principal design criteria and by providing adequate accessibility. As a preliminary proposal it is suggested that LMFBR designs are arranged to provide a general geometry and visualisation check of such structures as a whole and that arrangements are made to allow a volumetric inspection of critical areas e.g. those subject to the most adverse combination of local conditions and as manufactured defects, together with a representative sample of other areas of the structure. The design should be arranged so that the critical areas are directly accessible or that superimposed components e.g. insulation or sub-assembly carriers are removeable from the critical areas. Arrangements to remove any insulation from upwards facing surfaces should be more easily achieved than from vertical.

e) There has been very little work done on the remedial processes that can be applied to a failed or unacceptably defected structure located in sodium and/or cover gas. The problem is apparently greatest with structures that can only be removed with great difficulty or need practically to be regarded as unremovable. Removeability should be a prime design objective and in all cases repairability either in situ or after removal or by replacement must be achievable. In situ repair techniques of crack arrest and material jointing under sodium etc. should be examined as soon as is practicable as potential fall back measures.

The currently deployed design and development resources on the above aspects are believed insufficient to carry the work forward on a timescale compatible with many of the worldwide LMFBR projects. It is recommended that consideration be urgently given to increasing these resources and in parallel with this steps should be taken to obtain effective international collaboration between organisations actively working in this field.

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APPENDIX I

INSPECTION AND MONITORING APPROACH ON EXISTING REACTORS

A.1. CEGB gas cooled reactors[17, 18, 19]

Although on the early Magnox reactors the design concept did not envisage appreciable maintenance of much of the fixed equipment contained within the reactor pressure vessel it was thought that access to the steam generators would be possible and later experience has shown this to be the case. Man access to the steam generator spaces has been achieved regularly when required, after depressurisation of the reactor primary circuit and establishment of air cooling flow through the vessel. At Oldbury and Wylfa an internal shield was provided to allow direct man access to the steam generators which in this case are located within the concrete pressure vessel. At Wylfa a shield was provided below the reactor core which also allowed access to almost the whole of the inside of the pressure vessel. For the earlier Magnox designs inspection within the reactor vessel was mostly provided for components associated with movement of fuel. All Magnox reactors have equipment which allow visual inspection of the fuel channels and recovery of any items accidentally dropped into them.

Up to 13 years of operation of the Magnox reactors has shown that very much more remedial work has had to be carried out inside the reactor vessel than was envisaged by the plant designers. On many of the reactors the detailed visual inspection of the reactor internals following the seven day proving test has shown the existence of serious defects that required in vessel remedial work prior to power raising. It is a matter for concern that using existing inspection techniques only a limited form of this inspection will be possible on LMFBRs. Some other notable in vessel operations have been charge chute dismantling within the reactor vessel at Trawsfynydd and remote fitting of a new core restraint at Bradwell. There have been many other operations involving CO_2 corrosion remedial work, dropped or damaged components and inspection or repair work not adequately provided for in the original design.

Current estimates show that the in vessel environment in the AGRs is appreciably less favourable for man access than for the Magnox reactors. Hence remote inspection methods will be more extensively used on AGRs[20] and man access will only be asked for if the task is beyond the capability of the remote methods.

The experience gained during the design and operation of the Magnox and AGRs has been utilised in the HTR design proposal particularly for access, inspectability and replaceability. For example, the main and auxiliary SGUs, circulators and moderator are replaceable; the core support structure and the bottom insulation are removeable in a recent HTR design. High levels of access for both remote inspection and remedial work have been provided. Facilities for man access have been provided but an attempt has been made to minimise the need for it.

Specific proposals have also been made for the in-service inspection of possible gas cooled fast reactor designs[21] on lines similar to those envisaged for the HTR.

A.2 American LWRs[22, 23]

The American procedures aimed at the achievement of adequate levels of integrity and reliability of their LWRs start with requirements placed on the reactor user by the USAEC* which include the use of ASME Code Section III for the design and Section XI[12] for in-service inspection and test. ASME III places the responsibility for meeting the code entirely on the manufacturer who must certify that all the requirements have been met. The USAEC* places the responsibility for quality assurance on the reactor user who must ensure that both the plant component purchaser and manufacturer have satisfactory quality assurance programmes which are monitored by periodic audits by the component purchaser, user and by the USAEC*. Section XI defines an inspection and test practice which is mandatory and in which the responsibilities of the reactor owner and vendor are clearly defined.

* now NRC and ERDA.

Section XI places the responsibility for the adequate coverage and performance of in-service inspection on the reactor owner. A complete inspection of critically important parts of the primary circuit, reactor pressure vessel, reactor core etc., is carried out as a "finger printing" operation before the reactor plant is commissioned. A 100% examination of each of these components is not specified, the inspection areas are predominantly concerned with welds. The basis for this approach is that the integrity of the parent plate and pipe material is mainly achieved by quality assurance during manufacture and by pre-service inspection. The parts of a component to be examined are selected with two particular guidelines in mind, they are, (a) to give particular attention to those areas with the highest fatigue conditions in service and (b) a representative sample of other areas of the component to provide an assessment of the general overall condition. To consider the reactor pressure vessel as a specific example, category (a) areas include the knuckle joint between the reactor vessel head and the flange, the inside radius section of primary nozzles and vessel material exposed to significant neutron irradiation. Category (b) areas include, representative longitudinal and circumferential weld seams on the reactor vessel, internal supports and bolting.

The interval between inspections for components of the above type is 10 years commencing at first start up of the reactor. Inspection is allowed during normal plant outages. A minimum of 25% of the required inspection programme has to be completed during the first third of the 10 year interval; 50% of the inspection programme must be carried out before two thirds of the 10 year period has elapsed.
Data is given in Section XI which defines whether the inspection method should be visual, surface or volumetric and the scope and frequency of examination. Ultrasonic methods are principally used for volumetric examinations.

Section XI also gives guidance on acceptable repair procedures and acceptance standards to determine component suitability for further service.

Most current designs of PWR allow removal of essentially all the reactor vessel internals and all important welds are designed to allow ultrasonic inspection. Due to the high radiation levels the ultrasonic inspection of the reactor vessel etc., is carried out remotely and under water. The remote inspection requires ultrasonic probes to be positioned to the nearest quarter of an inch or so from distances up to 100 ft away. The water is used as a couplant allowing a stand off probe technique to be used rather than by direct contact. Using these techniques the time taken to examine a typical circumferential seam on a PWR vessel is of the order of 6 hours. An underwater television camera is used in conjunction with the ultrasonic probes which can give visual images of extremely good resolution.

In-service inspection of the reactor vessel alone during reactor shutdown has in some cases taken up to 2 months. In most cases it is now expected to be able to carry out each of the necessary inspections at the 3rd, 6th and 10th years within a time of approximately 10 to 14 days.

APPENDIX II

SOME PLANT FAILURES AND DETERIORATION PROCESSES THAT HAVE OCCURRED ON NUCLEAR PLANT

a) LMFBR plant

REACTOR	TYPE OF FAULT OR ITEM AFFECTED	REMARKS
EBR I (1957)	Partial fuel melting.	Requiring removal of entire core.
SRE (1959)	Partial fuel meltdown due to flow blockage.	Extensive recovery operation needed.
Enrico Fermi I (1961-2)	Repair of eroded core sub-assembly seating surfaces.	
Hallam (1963)	Replacement of control rod thimbles.	
Enrico Fermi I (1966)	Vibration resulting in component failure, fuel sub-assembly blockage and partial meltdown.	Limited core access, no provisions for draining sodium from the vessel or for storing the complete core, resulted in a 3 years and 9 months outage.
Rapsodie (1966)	Sodium flooding of containment.	Modification to containment penetrations and separation of double walls of the containment.
EBR II (1967)	Seized breeder fuel elements.	Sectional cutting of upper core plate needed.
DFR (1967)	NaK leak at a faulty weld between the primary loop and the reactor vessel.	Section of pipe removed and replaced using a remotely controlled orbital welder. Approximately 12 months outage.
Rapsodie (1968)	Bent jaws of control rod gripper.	Replacement of control rod gripper mechanism.
PFR	Seizure of primary pump.	

b) Water and gas cooled reactor plant

REACTOR	TYPE OF FAULT OR ITEM AFFECTED	REMARKS
SENA (1962)	Vibration loosening of core shell bolts.	Repair carried out under water remotely, 1½ year outage.
Big Rock Point (1964)	Thermal shield supports were removed and replaced remotely under approximately 30 ft of water.	
Chinon (~1966)	Failure of BCD pipework.	Thermal stress/shock. Extensive replacement work.
Oyster Creek 1 (1968)	Nozzle safe ends. Control rod drive tubes.	Stress corrosion cracking. Weld flaws.
St Laurent-des-Eaux No. 1 (1969)	Meltdown of 5 fuel elements.	One years outage.
Indian Point 1 (1970)	Thermal fatigue cracks in a 24 inch primary coolant pipe.	
San Onofre (1970)	Thermal shield damage.	Flow vibration.
Indian Point 1 (1970)	Thermal sleeve failure.	Thermal shock.
Turkey Point (1971)	Failure of safety valve header and complete rupture of main steam line.	
La Crosse (1971)	Brittle failure of main reactor pressure vessel cover bolts during nut removal.	
Oconee 1 (1972)	Fatigue failures of thermal shield and vessel internals.	Flow vibration.
Stade (FDR) (1973)	Modifications needed to the core support to secure loose items.	Carried out by divers under 17 m of water.

Table 1

Inservice inspection and monitoring proposals*

Component	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
1. Diagrid	(a) Deformation due to stress relaxation etc. (b) Fast fracture due to irradiation induced loss of ductility. (c) Fatigue due to flow or acoustic excitation	Facilities for mounting and removing a comprehensive set of specimens are ideally required supplemented by instrumentation to record the thermal, strain and pressure cycling histories and the integrated irradiation dose.		Visualisation/geometry checks, ultrasonic exam of selected welds.	Uncertain, may be be 5-10 years.	Shutdown.	Diagrid will be subjected to influences which will modify ductility, embrittlement, fracture toughness and fatigue properties of the material. Irradiation creep will be induced. Provision to remove sodium and fuel needed or ability to carry out the work under sodium. *Proposals by French* to measure displacement.
2. Primary Vessel and Y Section	(a) Leakage of Sodium arising from (i) deterioration of undetected manufacture defect (ii) penetration by loose object via fretting mechanism (iii long term deterioration of material properties by Sodium. (b) Rupture at roof joint due to failure to retain controlled temperature gradients in top strake (Insulation/cooling system failure). (c) Fatigue failure due to acoustic excitation (hi-cycle) superimposed on: primary stress concentrations, Y-section region ; thermal stress cycles, Na level change region . (d) Buckling due to excess external pressure or non uniform loading.	(a) Na leak detectors and microphones mounted on lower sections of vessel. (b) Thermocouples and strain gauges disposed circumferentially at top strake roof connection and at lower parts of vessel (embracing Na level change region and Y junction etc). (c) Differential pressure device sensing cover gas and primary tank/vault liner interspace controlling interspace relief 'valve'.	Continuous for leak and pressure detectors. Intermittent on load scanning by other sensors.	Visual and ultrasonic inspection of selected vessel welds and adjacent parent metal.	5% ultrasonic inspection of selected welds after 1st hot run 15% ultrasonic inspection of welds (distributed) every 3 years thereafter. 30% visual inspection of vessel surface at each ultrasonic inspection.	Shutdown.	Inspections required imply removable top strakes insulation (external) sections.
3. Strongback and Strongback Support Straps	(a) Deformation due to thermal effects and stress relaxation. (b) Thermal fatigue and/or loss of material properties.	Thermocouples and strain gauges.	On load, periodic scans.	Visualisation/geometry checks. Ultrasonic examination of selected welds.	To synchronise with diagrid inspection.		

* The data given in this table in respect of scope and frequency of inspection is preliminary and will be subject to revision as more data becomes available. The proposed use of the table is to provide only perspective on the scope and type of inspection believed to be necessary. The list of components and deterioration mechanisms is not intended to be regarded as complete.

Table 1 continued.

Component	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
4. Core Catcher	Corrosion Deposition, Distortion Thermal/Mech fatigue			Visualisation/geometry checks.	Coincident with diagrid inspection.	Shutdown.	Depending on the final design, NDT examination of selected welds may also be needed.
5. S/A Carriers	Irradiation creep & neutron voidage effects. Failure of stellite seats in S/A hold down mechanism due to deterioration by corrosion or thermal cycling. Dynamic loadings due to S/A accident.	O.o.p. examination of in-pile surveillance samples.		Visual and dimensional examination. NDT exam.as required by design	Remove 1 carrier for inspection after 5 years.	Shutdown.	Some S/A carriers may need to be removed for the diagrid inspection.
6. Above Core Stuctures grids, deflector, C/R guide tubes	(a) Positional and Dimensional Instability arising from: 1) thermal stress and creep induced by (i) anisothermal & varied temperature history (ii) power cycling & transients. 2) thermal ageing & hydraulic loading. (b) Fatigue arising from hydraulically induced vibrations. (c) Surface Interactions eg fretting between guide tubes and grid.	(a) Monitoring of spatial positions and instrument grid required. Techniques not developed - ultrasonic viewing of an array of "sight" points may be a suitable possibility. (b) Combination of strain gauges and transducers on selected C/R guide tubes & grid plate.	On load. For (a) intermittent scans following refuelling, power cycles and transients. For (b) intermittent at changes in power/flow conditions. For (c) infer from (b) if possible	Ultrasonic and visual to detect cracks and/or local deformation/wear.	Dependent upon monitoring data but say at 5 year intervals. Commissioning test data may also influence frequency.	Shut down with bulk or local Na level reduction to expose at least C/R grid.	Monitoring and inspection technique development required.
7. Insulation, cover plates fixings, etc, on structures separating hot and cold pools and at roof.	Failure of fixings arising from creep and stress relaxation and fretting/wear mechanisms in fastener/insulation components.	Deduce failure of individual insulation panels via thermocouples.	On load, frequent scans.	Visual on outer surface visible parts. Ultrasonic crack detection in fixing studs.	Inspect all after commissioning dynamic run. Inspect (condition of fixings in particular) damage prone areas, eg. Na/cover gas interface after 2 years and thereafter at 4 yearly intervals.	Shutdown. Na level lowered as necessary.	1) Failure of insulation could release loose parts to the circuit. 2) Failure of insulation in roof regions could lead to excessive thermal stress at roof connection.

Table 1 continued.

Component	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
8. Inner Tank	(a) Structural failure at or near strongback connection or near reinforcements. (b) Excessive distortions in tank arising from thermal stress at insulation discontinuities or points of insulation failure.	Use thermocouples as under Insulation etc, and strain gauges.	On load, frequent scans.	Visual and ultrasonic inspection of strong-back connection. Visual inspection of outside surface of upper end of tank and structural support members.	Dependent upon monitoring data and thermal cycling history but, say, at 5 yearly intervals.	Shutdown.	Provision to remove sodium and fuel needed or ability to carry out the work under sodium.
9. HP Ducts	Fracture of pipe at joint with diagrid or pump valve casing caused by high cycle fatigue due to acoustic excitation or flow induced vibration.	Strain gauges on one duct from each pump mounted at diagrid and valve casing connections. Transducers mounted in bores of same ducts.	On load, intermittent scans and at power changes.	Visualisation/geometry checks.	After 2 then 5 year intervals	Shutdown.	Extended life proving of transducers in Na at 400°C required. Provision to remove sodium and fuel needed, or under sodium visualisation techniques.
10. Primary Pump Valve and Casing	(a) Failure to operate on demand due to fretting/galling/seizure caused by acoustic or flow induced mechanical interactions. (b) Fracture of casing due to fatigue damage by mechanical vibration transmitted from pump. (c) Failure of Valve actuator shaft due to fatigue damage arising from flow or acoustic excitation of local valve parts. (d) Na hammer	Use combination of strain gauges and thermocouples (see under insulation) etc located on casing.	On load, frequent scans.	Functional test of valve actuation. Check actuator power. Visual inspection of removable parts. Need for inspection of fixed parts determined by inspection of removed parts and outcome of functional test.	Test each valve in functional mode sequentially at 1 year intervals. Supplement by off load full open/closed/open test on all valves at 6 monthly intervals.	On load and off load for functional tests. Shutdown and valve removed for fixed parts inspection.	
11. Primary Pump Pod Casing and delivery Pipe	Fracture of casing or delivery pipe caused by fatigue due to acoustic excitation, mechanical and hydraulic vibration and strains induced by power cycling and transients.	Use combination of strain gauges and thermocouples (See under insulation etc) mounted on pod at or near roof connection. Use accelerometers/strain gauges to monitor delivery pipe excitation.	On load, frequent scans.	Visual inspection of inner or outer surface of pod casing. Ultrasonic inspection of pod/roof connection weld(s). Ultrasonic inspection of pipe welds.	Inspection frequency of roof connection area as suggested by monitoring data. Conduct pod ultrasonic test (in any event) on 1 pump after 1 year, and at say 5 yearly intervals sequentially thereafter. Conduct delivery pipe ultrasonic test as suggested by monitoring data and on 1 pump after 1st year.	Reactor shutdown with appropriate pump removed. Local Na level depressed as required for inspection area.	

Table 1 continued.

Component	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
12. IHX Pods	Structural failure at or near roof connection as a consequence of local insulation or cooling failure leading to excessive thermal stress or structure vibration leading to fatigue.	(i) See under insulation etc; (ii) Use accelerometers in dynamic commissioning tests to determine structural response behaviour. (iii) Mount strain gauges at or near pod/roof connection.	On load, frequent scans of thermocouples and strain gauges.	Visual inspection of pod/structure above tube plate. Ultrasonic inspection of pod/roof connection welds.	Inspect above tube plate zone after 1 year. Inspection frequency of roof connection area as suggested by cycling history and monitoring data. Conduct ultrasonic test (in any event) at 5 year intervals in each pod sequentially.	Shutdown with lowered Na level. Visual inspection in above tube plate zone may be possible with IHX in situ. Other inspection may require IHX removal.	(i) Extended life proving of high temperature strain gauges required. (iii) Partial or total failure at roof connection could cause loss of primary containment integrity.
13. Neutron Shield Rods	Leakage of Graphite filling into primary circuit Na.	Embody tracer (Gold?) in rods and install tracer monitoring equipment.	Intermittent scans.	Visual to detect gross displacement at upper ends.	At the time of inspecting above core structures.	Shutdown with Na level lowered to reveal rods.	Note: Monitoring method does not identify leaking shield rod merely that a leak exists. Graphite may swell after Na contact.
14. Above Core Instrument Shroud Assemblies	Shroud failure/BPD pump and pipe malfunctioning, thermal or flow induced failure of sensors and grids. Na effects on electrical connections.	BPD flow measurement. Instrument outputs.	On load.	-	-	-	Materials monitoring by sampling required.
15. Primary Pumps	(a) Failure of feed flow to hydrostatic bearing. (b) Loss of lubricant supply to rotating shaft seal. (c) Erosion (d) Cavitation	(a) Monitor pressure difference across bearings via pressure tappings and differential pressure transducers. (b) Oil supply alarms (c) Vibration and acoustic sensors	On load, continuous.	Visual and NDT inspection of impeller, casing and bearing surfaces.	One pump after commissioning hot run. Thereafter inspect as determined by operating behaviour or pump components endurance test data.	Shutdown.	
16. Roof Structure (containment aspects only)	(a) Excessive Leakage in diaphragm, penetration liners and penetration seals. (b) Deterioration or Incorrect application of penetration hold down devices. (c) Deflection of roof structure. (d) Failure of roof cooling system.	(a) Monitor argon and sodium vapour leakage into roof and cooling circuit. (b) Monitor argon leakage above penetrations. (c) Mount thermocouples in roof cooling ducts and roof penetration liners.	Intermittent scan of all sensors.	Visual inspection of penetration hold down devices. Leak sense roof penetration seals. Pressure and leak test. Geometry and deflection check of whole roof.	Inspect all items after commissioning hot run and thereafter as:- hold down devices annually and after every disturbance. Revalidate pressure and leak integrity of roof by pressure test every 5 years.	On load except for pressure test.	
17. Intermediate heat exchanger Tubes	Primary side deposition.	P. Sodium ΔP or level.	In operation.				Fall off in thermal performance will also occur.
	Secondary side deposition.	S. Sodium ΔP.	" "				Fall off in thermal performance will also occur.
	Vibration failures.						Monitored during Na and water commissioning by accelerometers and strain gauges.
	Corrosion				After ~14 months for insitu or out of reactor inspection then at periods indicated by experience.	Shutdown.	

Table 1 continued.

Component	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
	Cracking/leakage	NDT and leakage rate.		Leakage test, insitu or removed. As in column (5).	" "	Shutdown.	Stress wave emission techniques should be vigorously pursued. If in situ methods are ineffective then IHX removal after ~14 months will be required for inspection. A sensitive method of detecting IHX leaks in service is needed.
Tube plate	Corrosion/cracking/ leakage failure.	NDT and leakage		Leakage test, insitu or removed. As in Column (5).	After ~ 14 months for insitu or out of reactor inspection then at periods indicated by experience.	Shutdown.	The proportion of IHX's to be inspected will depend on their differences in operational and environmental conditions etc.
Tube supports	Fretting, wear and failure.			remote viewing	" " "	Shutdown.	Changes in support assessed by vibration excitation and measurement of response.
				accelerometer	" " "	Shutdown.	
				eddy current/	" " "	Shutdown.	Wall thickness changes under support measured.
				ultrasonic	" " "	Shutdown.	
Tube/tube plate welds	As for tubes			intra tube	" " "	Shutdown.	
				eddy current/	" " "	Shutdown.	
				ultrasonic	" " "	Shutdown.	
Control/shut off valve	Sticking, failure to operate correctly, distortion, etc.	Valve position indicator	In operation.	On load test operation or simulation.			
		Leakage/Na temperature at IHX outlet.	In operation.	Visual inspection/ examination.	One valve inspected after 14 months, then at periods indicated by experience.	Shutdown.	NDT examination carried out on each valve removed.
	Vibration.						Accelerometers on spindle during Na and H_2O commissioning.
IHX support structure	Distortion	Dimensional/geometry checks.	In operation/shut down.		After 14 months then every 2 years.		Proximity/geometry gauges needed, possibly at high temperature. NDT and visual examination after IHX removal The need for visual examination will depend on the structure behaviour and experience.
	Piston ring deterioration.	Leakage test/visual	In operation/shut down.	The majority of the leakage tests may have to be carried out at shutdown. Thermocouples may give operational indications.			
	O ring failure/ leakage.	Leakage test.	In operation.				
	Vibration.	Accelerometers.	In operation.				The monitoring and inspection that can and should be carried out depends greatly on the detailed design.

Table 1 continued.

Components	Deterioration Mechanism	Monitoring Method or Sensing Equipment	On or Off Load Monitoring	Type of Inspection or Test	Frequency of Inspection or Test	State of Plant during Inspection/Test	Remarks
	Over-stressing.	Thermocouples and strain gauges.	In operation.				
IHX insulation	As for the primary circuit insulation. (item 7)						
IHX complete penetration	Distortion etc. casing leakages.	Activity monitor (portable).	In operation.		Each shift day.		
		Gas interspace leakage.	Shutdown.	Fall in pressure test.		Shutdown.	
	Hold down defects.	Visual examination.	In operation/shutdown	NDT examination.	After 14 months then every 2 years.	Shutdown.	

B. Gallet, "In-Service Inspection of the Main Vessel of Super Phenix". (France)

1. IN-SERVICE INSPECTION OF THE MAIN VESSEL OF SUPER PHENIX

DEFINITION OF PROBLEM

In-service inspection of the main vessel of Super Phénix is an innovation with respect to Phénix. The vessel designer has been asked to incorporate into the system means for detecting surface and volume defects and for following their evolution.

Because of the heat shielding baffles, access to the main vessel from the interior is impossible. It is for this reason that a sufficient gap for access is provided between the main vessel and the guard vessel. This gap also allows inspection of the safety vessel.

2. TWO TYPES OF INSPECTION ARE EMPLOYED

- Visual inspection of the outside of the main vessel, the inside of the guard vessel and the gap between these vessels. Anomalies (e.g. cracking) can be revealed in this way.
- Inspection of the volume of the main vessel, and, in particuliar, of welds. Material defects can thus be located and their evolution followed.

3. PARTS SUBJECT TO EXAMINATION (Fig. 1)

The main vessel is made of austenitic steel while the guard vessel is made of ferritic steel. They are both suspended from the slab and together form a double walled envelope with a torispherical bottom. The dimensions of the main vessel are as follows : diameter : 21 m, height : 18,5 m, thickness : 25 to 60 mm. Theoretically the gap width between the two vessels is 700 mm. In practice, temperature variations, fabrication tolerances and obstables lead to a width of between 500 and 700 mm.

4. INSPECTION CONDITIONS

Inspection is carried out during reactor shutdown simultaneously with fuel handling operations. The maximum temperature of the sodium and of the main vessel is 180° C.

Under nominal conditions the sodium temperature varies between 400 and 430° C.

TABLE OF APPROXIMATE VALUES OF ACTIVITY IN GAP

	RADIATION	THERMAL NEUTRONS	FAST NEUTRONS
Reactor in operation	10^5 rem/h	10^4 to 10^6 n/cm²/s	0
Reactor shutdown	500 mrem/h	0	0

The gap between the two vessels is filled with nitrogen.

5. MATERIELS USED

The multiple constraints have led us to envisage a mobile inspection device (Fig. 2) capable of being moved anywhere in the intervessel gap. This device is provided with :

- a television camera for the visual inspection of the both vessels and the location of defects.
- an ultrasound transducer for inspecting the volume of the main vessel, and, in particular, welds.

The mobile device is introduced into the intervessel gap during reactor shutdown. 12 oblong hatch (500 x 700 mm) in the slab are used for this purpose.

The mobile device is provided with caterpillar tracks equipped with permanent magnets. It can thus climb anywhere over the guard vessel walls to which it is attached. A parallelogram system enables the device to press against the walls of the main vessel and takes up any variations in the gap width. The speed of the device during inspection is of the order of 5 m/h.

Another solution to this problem is currently being studied : the caterpillar tracks are replaced by two sliding parts equipped with suction devices or permanent magnets, these sliding parts being displaced with respect to one another.

The mobile device is provided with iodine lamps, the luminous intensity of which can be varied.

The location of welds and the positioning of the module are ensured by engraved plates welded onto the main vessel. at the intersection of the welds.

This system might be completed with guide rails fixed to the guard vessel.

A 64 mm diameter, 225 mm long television camera of the type commonly used in nuclear installations (high performance under irradiation) is employed. This camera is housed in a casing provided with all the motorized parts necessary for its functioning ; the camera is gas cooled. A set of mirrors is used for axial and radial slighting over 360°. The system must be sufficiently sensitive to locate a 0,5 mm defect.

The ultrasound control system uses a focused transducer of the type developed for the in-service inspection of PWR's. Longitudinal inclined waves 2MHz are employed ; the resolving power is of the order of 1 mm. The transducer moves across the weld. Liquid in the housing enclosing the transducer provides ultrasonic coupling. Leaktightness with the main vessel is ensured by a flexible joint. The housing is mounted on the parallelogram of the mobile device.

This technique which currently appeared to be the only one which is valid from the ultrasound coupling of view imposes :

- Constraints for the reactor :
  - All welds in the main vessel must be milled to ensure leaktightness.
  - The incorporation of facilities for evacuating liquid from the bottom of the guard vessel
- Constraints for the liquid :
  - The liquid must not boil at 180° C.
  - The liquid must not react with either of the vessels.
  - Nor must it form deposits on the main vessel at operating temperatures as this would render useless inspections, and would risk forming carbon deposits on the vessel surface.
  - Nor must it react with sodium.

A cable brings energy, fluid and control signals from the control station. This cable is suspended from a monorail above the slab.

The control station consists of :

- the controls,
- the cable winder together with a permanent means of controlling tension,
- energy and fluid supply units,
- visual display and recording of images seen by the television cameras,
- the recording and visual display of information collected by the ultrasound transducer.

In the case of breakdown of the motorized parts or the module supports, it is possible to withdraw the module with the feed cable.

6. The mobile device is not yet at the project stage : its development still requires extensive studies and tests. The final decision on whether or whether not this procedure will be adopted depends on the results obtained.

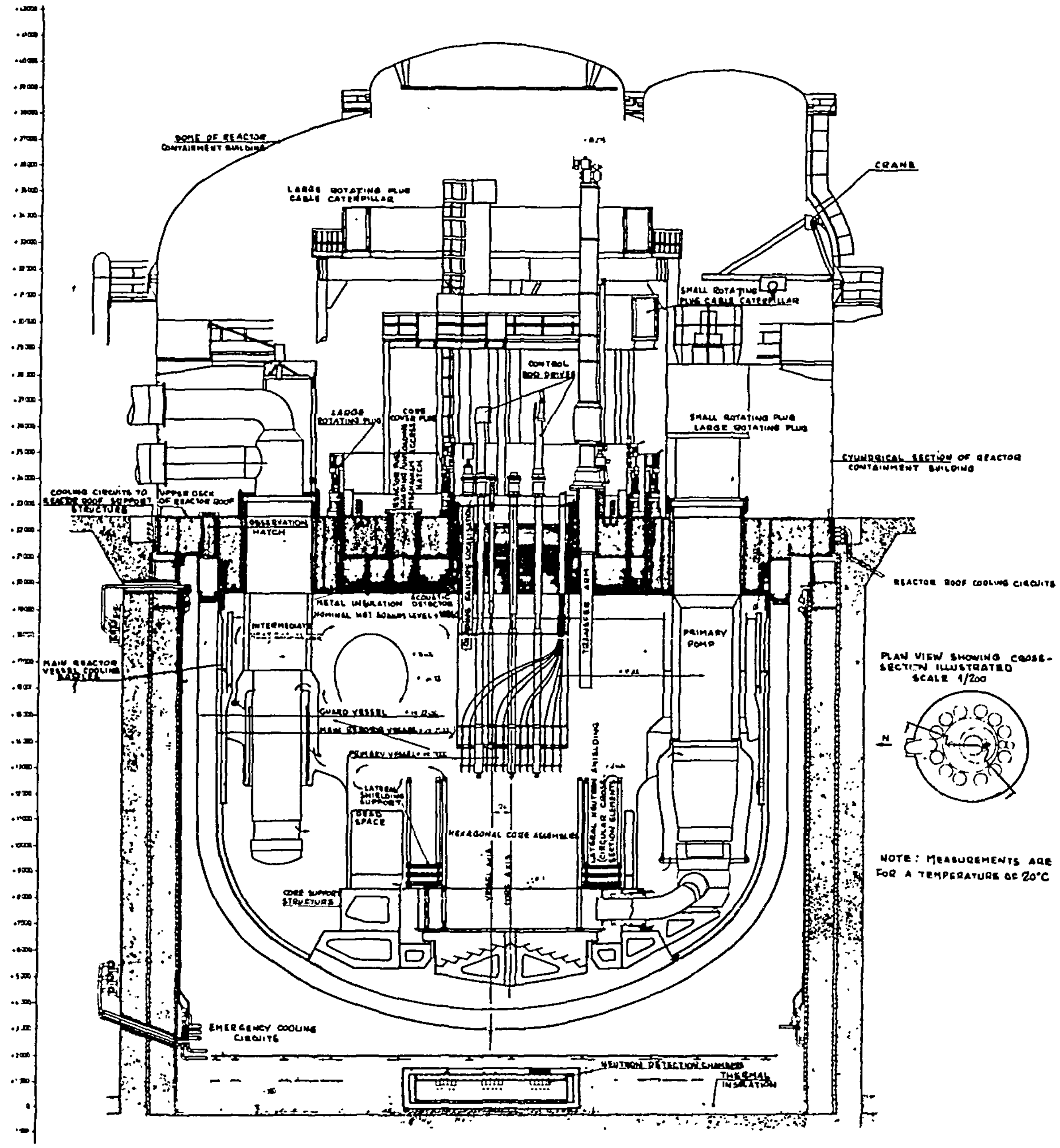


FIG. 1

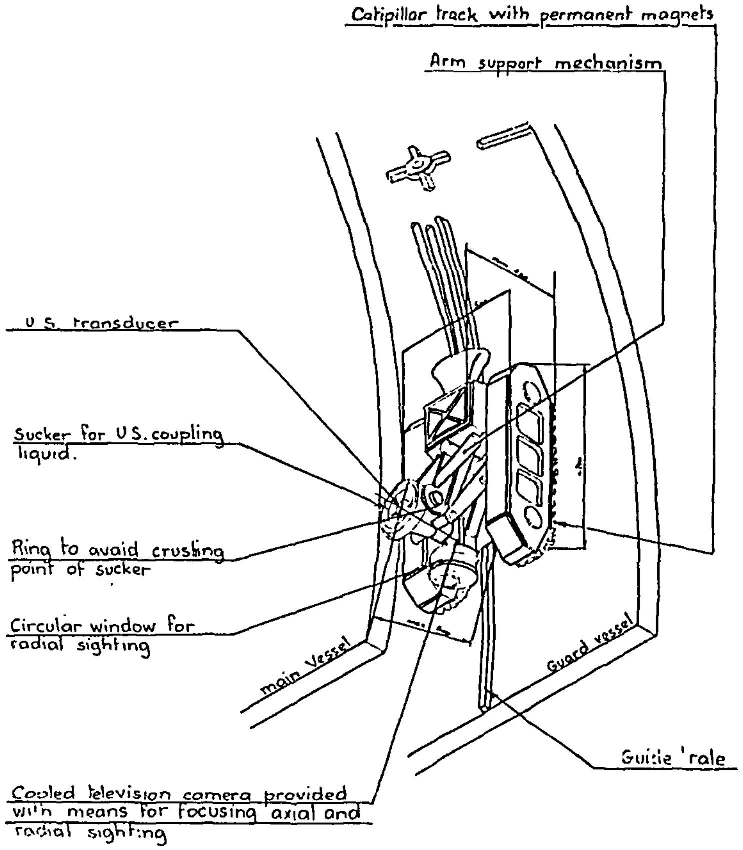

Catipillar track with permanent magnets
Arm support mechanism
U.S. transducer
Sucker for U.S. coupling liquid.
Ring to avoid crushing point of sucker
Circular window for radial sighting
main Vessel
Guard vessel
Guide rale
Cooled television camera provided with means for focusing axial and radial sighting

FIG. 2.

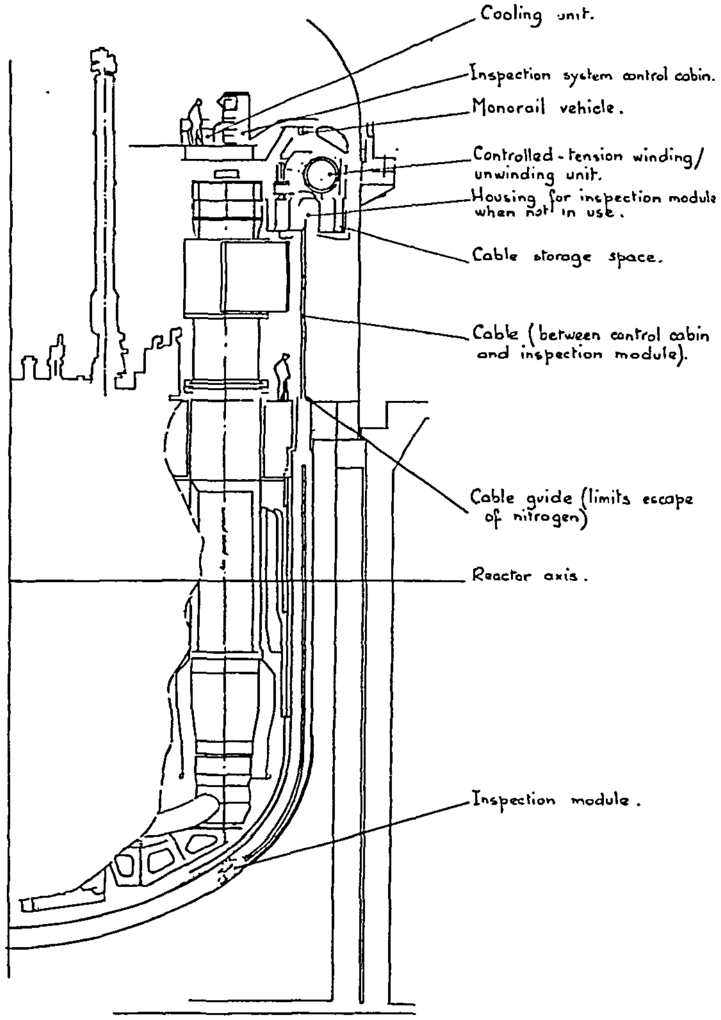


FIG. 3.

S. Abe, "In-Service Inspection for "Monju". (Japan)

1. The Philosophy of in-service inspection for Monju

The object of in-service inspection is to assure the integrity of pressure boundary for protecting the public health, and safety. The light water nuclear power station have had many experiences for in-service inspection in Japan, but LMFBR no experience. ASME Section XI division 3 (draft) for in-service inspection for LMFBR was issued in 1974. Under such circumstances, the approaches of design and R&D of in-service inspection for Monju is tried.

2. Requirement of in-service inspection for Monju

In-service inspection for Monju is now considered in view point of importance and protection of system and component as follows.

(1) Reactor vessel — visual or surface inspection

(2) Primary heat transport system

(a) Inlet pipe to reactor vessel
visual and volumetric inspection

(b) Pipe from IHX to main circulation pump, and main circulation pump
visual or volumetric inspection

(c) IHX and hot leg pipe
visual or surface inspection

(3) Heat transfer pipe of steam generator and IHX

visual and volumetric inspection

3. Approach of in-service inspection for Monju

In-service inspection equipment for LMFBR will be located, in many cases, in a limited space with high irradiation and high temperature. Therefore, it needs to have complex mechanism and to be proof against these atmosphere. Design and R&D of in-service inspection for Monju is introduced as follows.

3.1. Inlet pipe of reactor vessel

Visual and volumetric inspection for weld and the heat affected zone will be applied in the inlet pipe to reactor vessel. Visual inspection equipment is mono-color ITV with optical flexible fibre scope. Volumetric inspection is performed by ultrasonic inspection. The inspection procedure is shown in Fig. 1.

The preliminary design of the travelling device of these ITV camera, and ultrasonic transducers is shown in Fig. 2. The design condition is written as follows:

Dimension of the inlet pipe 24B x 9.5mm thick

Atmosphere N_2 gas ~220°C

The travelling equipment moves on the guide rails attached inside the guard pipe. Grimbal with the sensors is set in moving rail. These sensors are positioned by moving this device at the longitudinal direction and pushing it up by air cylinder, and then the sonsors are scanned around the pipe by rotating the rails. Many R&D for these inspection apparatus were conducted.

Irradiation test under $10^4 \sim 10^5$ R for the ultrasonic sensor, the silicon oil couplant, the optical fiber scope and ITV camera were conducted wit good results Besides, the illumination test for the optical fibre scope and cooling test by gas for these inspection apparatus were performed.

3.2. Reactor Vessel

Visual or Volumetric inspection for weld and the heat affected zone will be applied in reactor vessel. Visual inspection equipment will be mono-color ITV, and volumetrical inspection will be ultrasonic or electrical resistance inspection.

The concept design of these inspection equipment is shown in Fig.3.

The design condition is written as follows.

Dimension of reactor vessel 7.1mø x 17.8m

Atmosphere N_2 gas ~220°C

Inspection device consists of moving box and inspection box. The Inspection device is transported to the reactor vessel from operation floor, and it moves on the transport rail fixed on guard vessel. The guide rails will be arranged along the weld lines of the reactor vessel. The inspection box is positioned at the inspected weld line by moving on the guide rail, being hung down by ropes from the moving box.

ITV and ultrasonic probe will be used much the same as the inlet pipe to the reactor vessel.

3.3. Heat transfer tubes of IHX

The eddy current inspection inside the tube will be adopted for IHX after drain of sodium at room temperature.

The eddy current semsor is inserted from the top for the main straight tube and the ECCS tubes.

Research and development of the eddy current inspection for the heat transfer tubes is described in Appendix I.

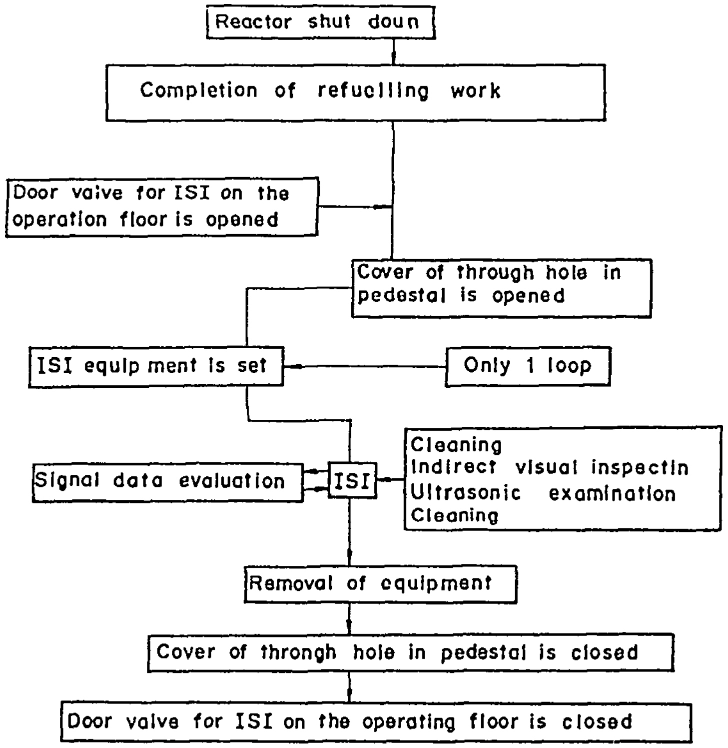


Fig I Flow chart of inspection procedure for inlet pipe of RV

3.4. Heat transfer tubes of steam generater

Ultrasonic inspection will be adopted in the heat transfer tubes of SG after drain of sodium and water at room temperature. One of the technical problems lies in inserting the probe inside the long helical coil tube.

There are two methods, that one is cable type, and the other wireless type.

The study for these methods have been conducted, and is described in Appendix II.

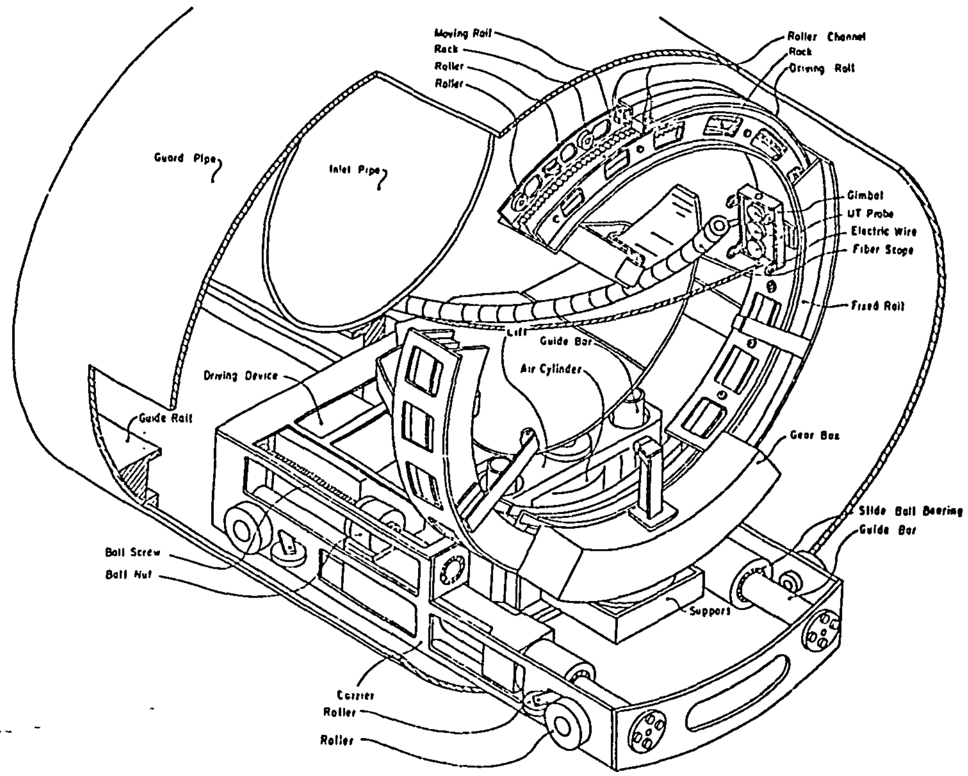


Fig. 2 Travelling Equipment

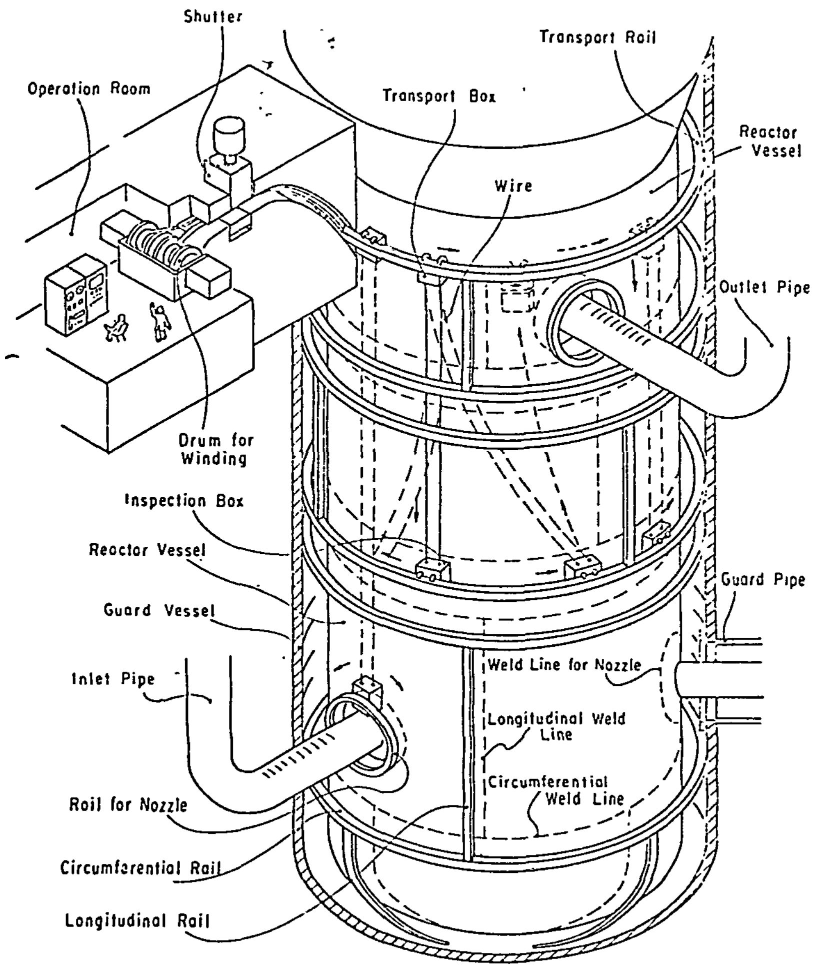


Fig. 3 Inspection Equipment for Reactor Vessel

Appendix I

Eddy Current Inspection Sensor for In-service Inspection of Heat Transfer Tube

1. Introduction

Eddy current inspection will be favourable for in-service inspection for heat transfer tube of IHX. But the following problems is considered in adopting eddy current inspection.

(1) Evaluation for signal of eddy current inspection from flaws.

(2) Effect of sodium attached inside tube for signal of eddy current inspection and sensor driving.

This paper describes the test results to clarify the above problems.

2. Sensor for eddy current inspection

The shape of the sensor is shown in Fig.1.

The frequency is A.C. 16 KHz. and diameter of the sensor is smaller by 0.4mm than inside diameter of tube to minimize the lift-off effect.

3. Test tubes

Test tubes have various flaws as shown in Fig.2. Test tube is made of SUS 304, ∿660mm in length, 21.8mmø in outside diameter, and 1.2mm, 1.4mm, 1.8mm, 2.2mm in wall thickness respectively.

4. Methods of Measurement

We measured the induced voltage across the research coil as the signal. This voltage E_2 is shown as below, when the supplied voltage is $E_0 \sin wt$

$$E_2 = E \sin (wt + \theta) = E \sin\theta \cos wt + E \cos\theta \sin wt$$

where θ is delayed phase.

Sin θ, and cos θ becomes function of time, when the sensor moves across the flaw. Therefore, a Lissajous figure can be given by feeding E sin θ and E cos θ in X-Y Recorder. An example of a Lissajous figure like this is shown in Fig. 3, and E, ΔE and θ gives respectively the relative magnitude of a flaw.

5. Test Result

(1) Atmosphere Test

Test results of eddy current inspection using 4 test tubes with various flaws (as shown in Fig. 2) are shown at Table 1.

(2) Test with sodium

Test of test tubes with sodium was conducted, but the signal of eddy current inspection was disturbed with irregular noise by sodium.

(3) Lift off effect

The distance between the sensor and the wall of the tube gives much effect to the output of the coil as shown in Fig. 4. It is necessary, therefore, that the sensor passes through the center of the tube. On account of this purpose, the sensor with spring or elastic body placed symmetrically in its circumference would be effective.

(4) Effect of Support

Heat transfer tubes are ordinarily supported with the plate. The complex shape of this part gives much effect on the output of the sensor. Therefore, eddy current inspection test was conducted about test tubes with a ring. The obtained output of the sensor is different from normal tube. It will be necessary, therefore, to adopt the comparison method or finger printing in order to remove the effect of the support.

6. Effect of Weld

The output of the sensor obtained from weld of tube is different from the normal tube.

This causes are considered as follows.

(1) shape of welding deposition

(2) electro-magnetic property

Fig. 5 shows the variation of permeability by the heat affected zone.

7. Conclusion

It was found in this test, that the magnitude of the signal of eddy current inspection varies with the shape and dimension of flaw. But the signal from the test tube with support and weld is different from normal tube. In case like this, it will be favourable to adopt finger printing method.

As the signal of eddy current inspection for the tube with sodium has much noise, further researches will be needed.

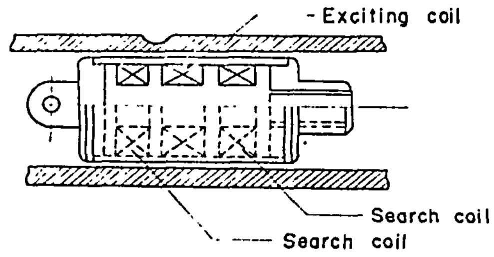


Fig 1 Sensor

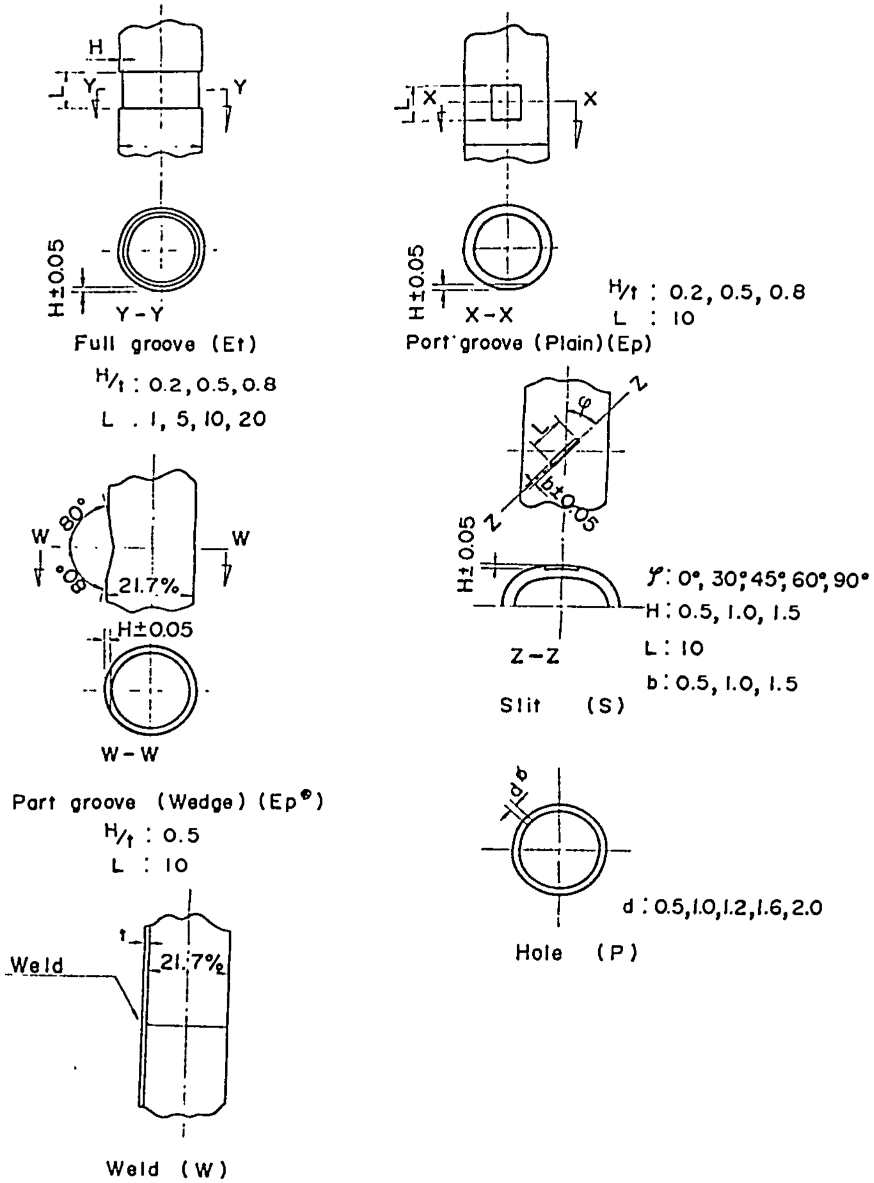


Fig 2 Artificial Flaws and Weld

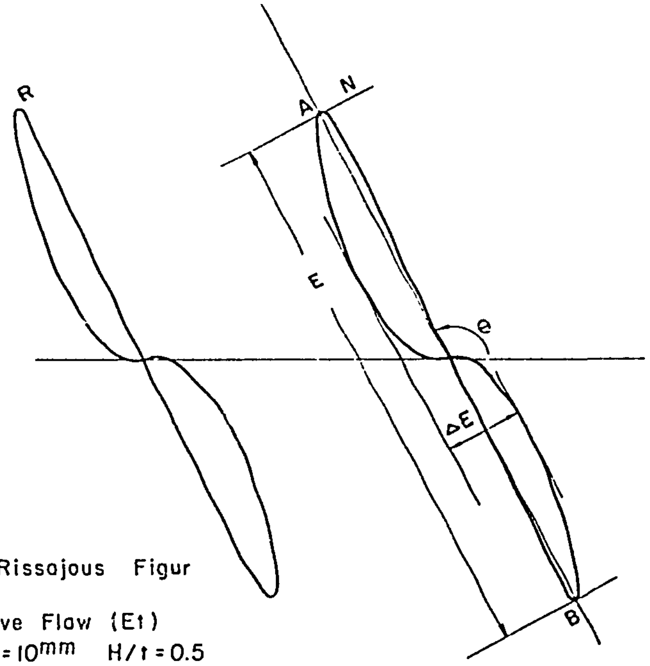


Fig 3 Rissajous Figur

Full Groove Flaw (Et)
L = 10mm H/t = 0.5
(30dB 0.1V/mm)

Flaw or weld	Parameter	E	θ	Remarks
Et	t	Proportional Increaso	Proportional Increase	
Ep	t	Proportional Increase	Proportional Increase	
P	t	Increase	Proportional Increase	
S	t	Proportional Decrease	Proportional Increase	
P	d	Constant	Proportional Increase	
S	θ	Decrease	Constant	
Et	H/t	Proportinal Increase	Proportional Decrease	
Ep	H/t	Proportinal Increase	Proportional Decrease	
Et	L	Proportinol Increase	Constant	
S	L	Proportinal Increase	Constant	
S	H	Proportinal Increase	Constant	
S	b	Proportinal Increase	Constant	
W	t	Random change	Proportional Decrease	

Table 1 Change of E and θ with parameters about various typs of flaw

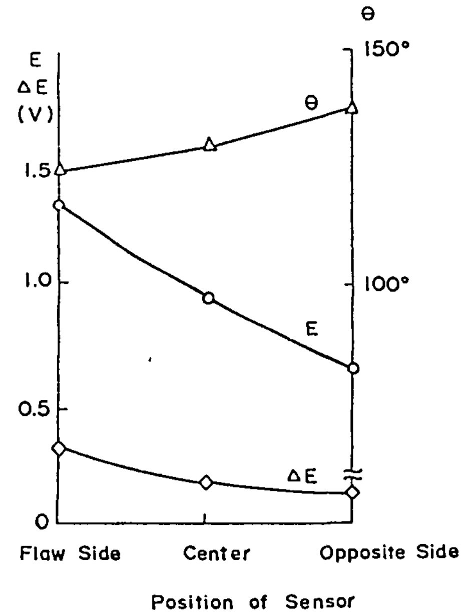


Fig 4

Lift off Effect
in Part Groove Flaw

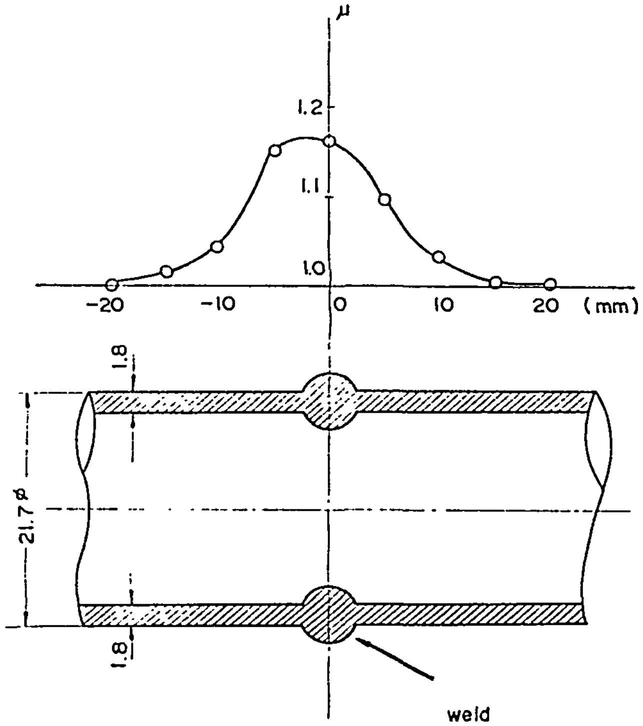


Fig 5

Permeability of Weld

Appendix II

Inserting characteristic of Probe for In-Service Inspection of Heat Transfer Tube

1. Introduction

It has been found that ultrasonic inspection is successful to heat transfer tube of steam generator, and eddy current to that of intermediate heat exchanger. One of the technical problems is inserting the probe inside the U-bend shaped or helical coil shaped tube.

There are two methods for inserting probe, that one is wireless type, and the other cable type. This paper describes the study of these probe inserting.

2. Tested Pipe

Tested Pipes have the same dimension and material of Monju component

(1). Helical coil shaped tube

Dimension	outside diameter	25.4 mmø
	wall thickness	3.2 mm
Material	SUS304	
Weld	butt weld at the center of length.	

(2) J-stick shaped pipe (J-A)

Dimension	outside diameter	25.4 mmø
	wall thickness	3.2 mm
Material	SUS304	

(3) J-stick shaped tube (J-B)

Dimension	outside diameter	25.4 mmø
	wall thickness	3.2 mm
Material	SUS304	

3. Probe, and Cable

Dimension, and material of probe and cable is shown in Fig.1 and Fig.2.

4. Cable type probe inserting test results

4.1 Helical coil type tube

The force on inserting and drawing the probe increases machrographically in proportion to the cable stroke, but micrographically periodic, and has the minimum and maximum force as shown, in typical example Fig.3.

The force on inserting increases remarkably from the third coil.

In this test, the probe was capable of inserting by 11 m by hand.

It is estimated that the force is generated from friction of the cable to the wall, and the spring force caused by the cable bending.

4.2 J-stick shaped probe (J-A, J-B)

A typical example of this test results is shown in Fig. 4. The force on inserting and drawing the probe is not changed at the straight tube, but increases rapidly at the bend. The force increases in proportion to the number of the passed through bend, and to the radius of the bend.

5. Wireless type probe test results

Wireless type probe was inserted into tube by using pressurized water and air for the probe driver. The probe speed for passing through the tube was measured in flow rate variables.

It was found that there were some probes which were impossible to insert by the probe shape and size. The tests, therefore, were conducted about the probes capable of passing through the tube.

5.1 Helical coil shaped tube

The probe was possible to be inserted into full length of tube. The speed of the probe increases linearly in proportion to the flow rate as shown, for an example, in Fig. 5.

The probe was not transported in less than a certain flow rate.

The speed of the probe also increased in proportion to the air pressure for the probe driver.

5.2 J-stick shaped tube (J-A, J-B)

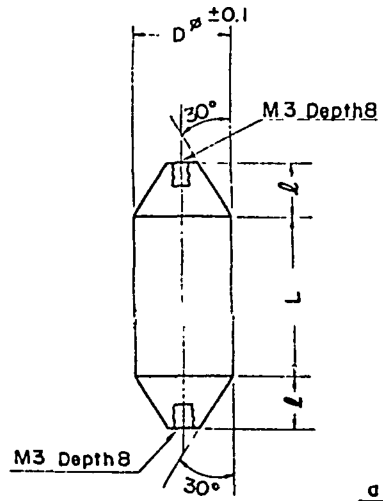
The speed of the probe increases linearly in proportion to the flow rate.

6. Conclusion

(1) In cable type probe, it was possible to insert in less than three coils of the helical coil type tube. But this merit is that the cable type probe is easy to show the probe position and to control the speed of the probe.

(2) In wireless type tube, it was possible to insert the probe at full length of the helical coil type tube by using the proper size and shape.

(3) In the bend and straight tube, it was possible to insert both the cable type probe and the wireless type.

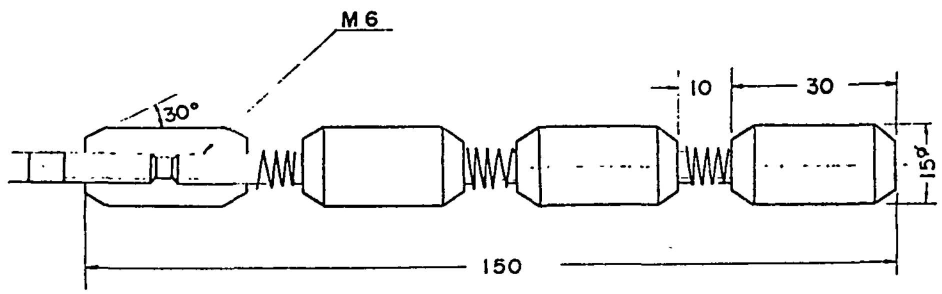


unit mm

	D	L	ℓ	Material
Probe A	18	50	10	Teflon
Probe B	16	40	8	Teflon
Probe C	16	40	8	Duracon
Probe D	15	30	6	Teflon

a) Probe (Single)

For wirless and Cable type (except B)



b) Probe Series
(with 4 probes)

	Material	
Probe	Teflon	
Coil Spring	SUS 304	Wire Dia. 0.8 Out side Dia. 0.4

Fig 1 Shape, dimqension, and material of probe

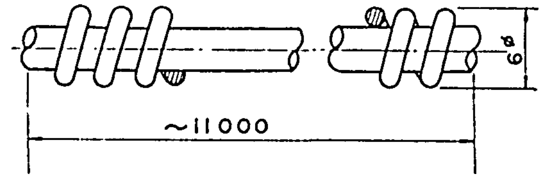


Fig 2 Shape and dimension of flexible hose

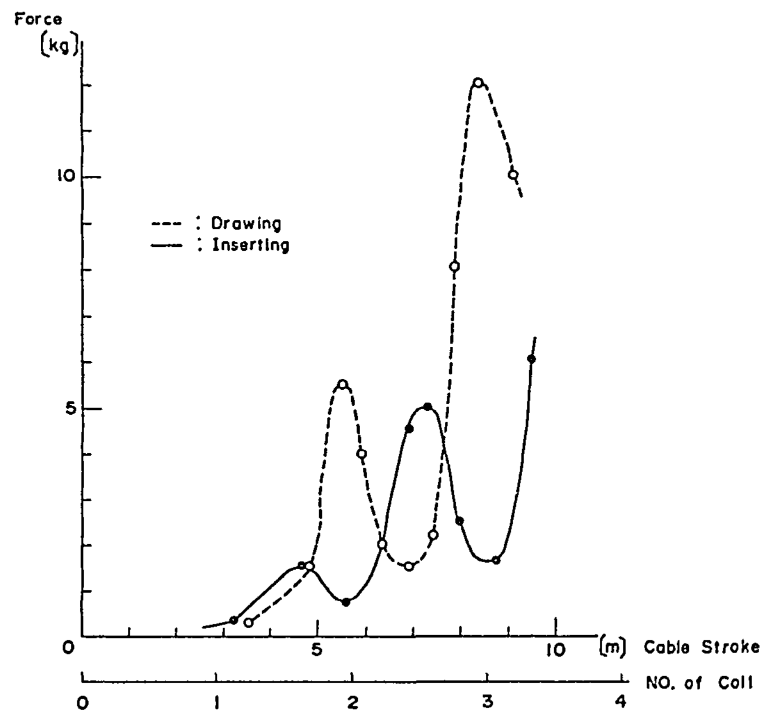


Fig 3 Inserting characteristic of sensor sieries
in helical coil

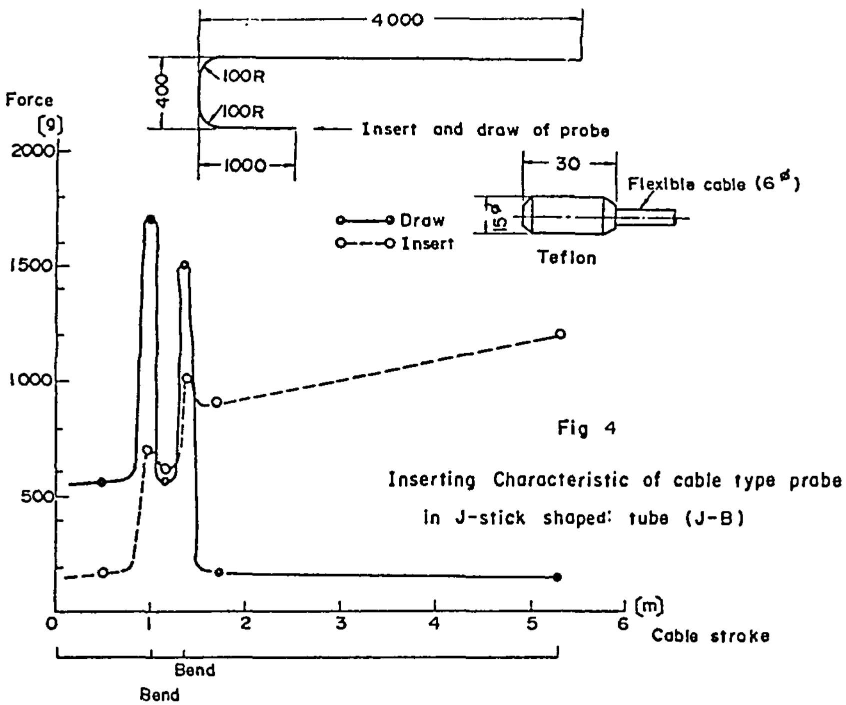


Fig 4

Inserting Characteristic of cable type probe in J-stick shaped tube (J-B)

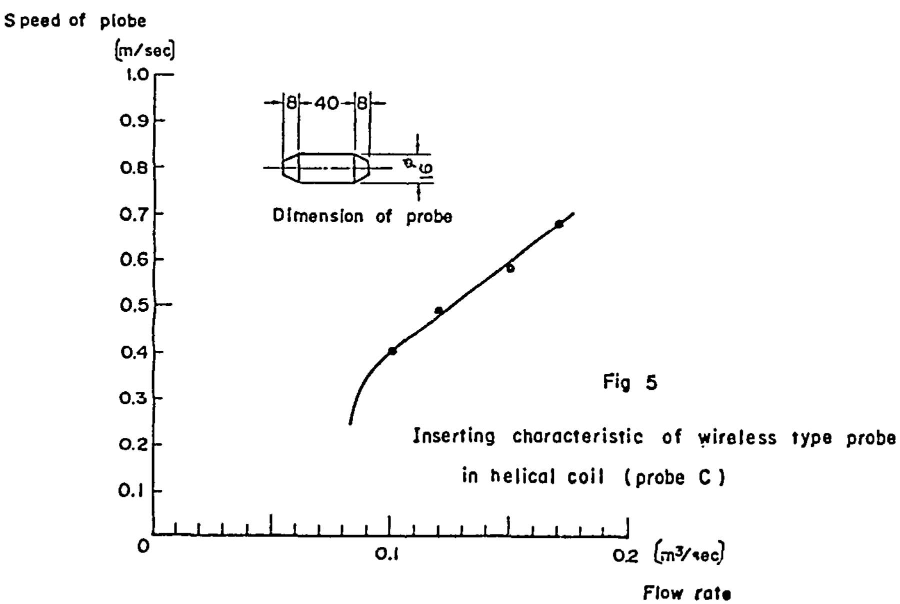


Fig 5

Inserting characteristic of wireless type probe in helical coil (probe C)

H. Leder, "In-Service Inspection at the SNR 300 with the Range of Reactor Vessel". (Federal Republic of Germany)

In the course of this specialists meeting concerning "Inservice Inspections on LMFBRs" a general view of the inservice inspection situation of the SNR 3oo within the reactor vessel is conveyed.

Particulars of the specifications, instructions, recommendations including the licensing procedure for the SNR 3oo put into practice in Germany are shown.

Referring to this the inservice inspection concept of the SNR 3oo reactor vessel shall be introduced which results from these directions as well as from SNR-specific realities. Finally in some words the further development in the field of inservice inspection for further projects aimed at.

Premising however several important facts have to be made evident - it is supposed - which had considerable influence on the present inservice inspection concept.

In the first instance the instruction, conditions and recommendations beeing valid in the FRG are largely not tailored for the characteristics of LMFBR.

When building nuclear power stations in Germany the following directions and recommendations have to be considered in order to execute inservice inspections.

- BMI - Criteria

  Published by Minister of Interior
  They settle for example the aims of the inservice inspections for nuclear plants.

- RSK-Guide Lines

  Published by Reactor Safety Commission
  These directions have passed for PWR, for BWR they are still in the planning stage.

- ASME-Code, Section XI

  ASME-Code's validity extends to pressure leading components of the nuclear steam generator system of LWR.

- The trade association safety rule VGB17 for pressure vessel.

  The present valid version from April 1974 is still not dealing with pressure vessels in nuclear plants. There exists however a rough copy on this subject from April 72, which is being corrected and completed at the moment among experts.

This addition makes it quite evident, that non of these directions is specifically concerned with LMFBRs. All these directions mainly deal with the interests of water reactors which require a corresponding interpretation. Applicant and expert are endeavoured to do so.

At their decisions concerning inservice inspection problems manufacturer and owner are exposed to the competitive situation between the relevance of the highest possible operation and maximum availability on one side and the consequences of inservice inspection on the other side, giving evidence according to safety conditions.
Necessarily the solution must be a compromise.

Furthermore it has to be taken into consideration that during the past years the importance of inservice inspection is on general expressed in the rising demands on force of statement. This increasing coincided with the planning phase of the SNR 3oo-concept. Consequently it is extremely difficult today to consider certain inservice inspections in their intirety.

In this connexion as third point should be mentioned the philosophy being observed by the manufacturer, that implies to construct the plant so that additional safety barriers for example disposition of a guard vessel can be reached in order to release the inservice inspection side.

The licensing authority then gave directions - basing on the plant's interpretation - to construct the plant so that all components and systems being essential for safety can be inspected after operation start.

For that purpose an according inservice inspection plan has to be provided.

Additionally it is demanded a further development of existing, respectively a supplementary development of new methods of non destructive material tests for those materials coming to use.

On the basis of the above mentioned instructions of experts demands and characteristic SNR-realities the plan for recurrent tests had been composed.

As consequence to the intensive discussions with experts in the matter of inservice inspection of the SNR 3oo, it must be expected that the present inservice inspection concept - which is now described - must be modified.

Before describing the real inservice inspection concept, some words on SNR specific realities must be said.
For better comprehension a portray of the SNR 3oo reactor vessel is premised, considering only those points more detailed which are essential within this lectured subject.

The SNR 3oo project (Fig. 1) represents a sodium cooled fast breeder reactor with a power of 3oo MW electrical. In the main this plant is of prototyp character, although the reactor shall serve the purpose of generation of electricity. The almost unpressurized reactor vessel (the only pressure load to the vessel results from the cover gas pressure of max. 1,55 bar and from the geodetical sodium height) is closed gastight by a triple rotating plug system using inflated sealing. The extreme low pressure load to the vessel is achieved by special disposition of the lower collecting tank, which leads up the cooling sodium - being under 7 bar pressure - through the grid plate to cool the core. The lower collecting tank is fed via enclosed inlet pipelines.

Above the core the instrumentation plate is placed, formed as carrier of invessel instrumentation. From here the heated up sodium flows across the top edge of the shield tank in the outside collecting room and then, across the enclosed outlet pipeline to the primary heat exchanger. Inside the outer collecting room the emergency cooler is arranged among sodium pipelines. These emergency coolers take over the decay heat removal if the primary coolant circuit system fails.
Till the height of the emergency level the vessel is enclosed by the guard vessel which collects sodium flowing out of the vessel and so guarantees the emergency level. The emergency level is defined as the lowest sodium level where decay heat removal through the primary circuit is still possible.

Vessel and guard vessel shape a annular gap of approximately 3oo mm corresponding with the chosen dimensions. The size of the annular gap is fixed by the fuction of the guard vessel to guarantee the emergency level. Consequently the gap volume corresponds with the sodium volume of the vessel on top of the emergency level.

Below the described vessel system the heat retention system is arranged which catches the molten core and leads off the decay heat during a supposed Bethe-Tait-accident.

The most important feature of the above pictured plant is the intended safeguard oversize. Supplementary to the construction of the components and according to general safety standards in reactor design, guard vessel and emergency cooler as well as heat retention system were created as additional safety barriers. This additional measures guarantee safe condition of the plant if reactor components being necessary for operation fail.

So a leakage of the sodium pipe lines, the collecting tank or the vessel themselves do not lead to any precarious conditions of the plant regarding the safety. From the operating point of view a smaller leakage of the enclosed pipe lines as well as of the lower collecting tank can even be accepted. As to a certain degree they represent no inadmissible influence on the operating course.
It is the aim of this oversized safety condition - which has been realized under considerable expenditure - among other the necessity to diminish inservice inspections in regions difficult to access. This would allow to realize a plant which corresponds better to the operating requirements.

Characteristics of the SNR 3oo, especially the application of sodium as cooling system require substantial attributes in constructive and industrial respect. From this follow also essential consequences on the inspection concept, as that inservice inspections at the SNR 3oo simply cannot be compared with those at the LWRs.

Sodium characteristics coming into consideration are:

- The remaining Na_{22}-activity; with radioactive half life of 2.6 a makes inspection handling more difficult.

- The lowest temperature of 2oo^{o}C must be maintained everywhere during fuel handling to prevent local freezing of the coolant. Consequently all inspection procedures must be practiced by temperatures of about 2oo^{o}C.

- The coolant is opaque, which makes visual inspection under loaded condition impossible. The region above the sodium level exclusively can be inspected.

- The positive thermal conductivity of the sodium makes it necessary to cover shock endangered regions with heat shielding baffles which handicappes the accessibility of the covered walls badly. So for example the vessel inside wall is covered by a heat shielding baffle in the region of the sodium.

- The remaining coolant film in the components deteriorate faults recognition.

One must realize, that the choice of this coolant in the main affects adversely the inservice inspection.

In the case of choise of material - austenitic material X6CrNi 1811 is applicated - positiv aspects as well as negativ aspects are present.

Of positive consequence is the extreme toughness of the material, which guarantees large critical crack lenght.

Even taking into account the interpretation against accidents the wall thickness of sodium carrying components are low. The wall thickness of the vessel is 4o respectively 6o mm and of the primary pipes 8,8 mm. It can be assumed that half elliptical cracks on the surface with a length of 6 multiplied by wall thickness in any case form a reliably discoverable leakage. This length of the crack is in any case smaller than the critical crack length.

Consequently, before a break happens one can always prove reliably an existing leakage. A quick crack growth can be excluded, as the chosen material has no brittle fracture region. The influende the neutron radiation has on material behaviour, shall be investigated by prerunning material tests. The fundamentals of this discussion are not sufficient to dispense with a 2. safety barrier.

It has to be badly valued that at the time being austenitic welding seams cannot be tested by U.S. examination of satisfactory evidence. The research program RS 143 however - which aims at the U.S. examination of austenitic welding seams - shows promissing results, so that we have the quite legitime hope to apply this method efficiently for austenitic welding seams also for inservice inspections in the near future.

The inservice inspections are subdivided into two main subjects the vessel outside wall inspection and the vessel inside inspection.

The vessel outside wall inspection can be realized by the chain-rail-inspection system particularly developped for this purpose by MAN (Fig. 2). MAN is one of the leading manufacturers in the field of development and production inspection equipment in Germany. The equipment consists of one control casket, one guide tube, twelf 3-point rail tracks being connected with the guard vessel, one chain with examination vehicle and two television cameras. The visual inspection takes place from the fixed plug of the closure head cavity.

At that point the control casket is installed being gastight connected through a guide tube with one of the 12 inspection ducts. The casket contains a hoisting unit with position indicator for the link car chain.
The chain runs along the triple rail track into the annular gap between reactor vessel and guard vessel. It contains the different cable pipes and supply pipes. Arranging cables and tubes that way it can be obtained that they cannot touch container walls. Besides that they cannot be exposed to additional undue strain during the process. At the end of the chain the inspection car is placed, fastened on it two cooled TV cameras together or separately and illuminating equipment. One of these TV cameras is portable laterally under assistance of a claw. During the examination process camera I inspects always a tract 75o mm wide left or right of the rail by moving out and moving in of the movable arm and gradual lowering of the examination vehicle. The remaining central tract is observed by camera II. The examination of the

nozzle takes place by combined horizontal and vertical motions of camera I and its revolving and folding mirror.

The nozzles can be inspected by simultaneous operation of the inspection car and the movable arm and with help of a revolving and folding mirror.

The inspection facilities can be brought into a reproducible position.

Position indicator, limit and special mechanism protect the cameras against unintended butting. All facilities can be installed so that supported by full automatic control quick and smooth inspection operation is guaranteed.

The test volume of the tank outside wall and guard vessel inside wall being provided, consists of visual inspection of the welding seam including about 2o mm external welding zone following from the U.S. examination conditions. This technique is still developed (Fig. 3). It depends completely on the still unsolved question of coupling medium not esteemed the difficulties concerning the probe heads.

At the moment U.S.-probes are undergoing tests, for the present only under cold conditions. Prevaling investigations have proved it n cessary to subdivide the 6o mm thick tank wall into 3 or 4 test zones and to use a separate U.S.-probe for each zone. Proceeding on the assumption that it can be worked with coupling medium, intensive investigations are in progress, being concerned with the problems which result from the remaining rest wetting with coupling medium on the tested tank wall. High boiling oils and greases are coming into consideration. Referring to the manipulation devices - basing on the according concept - investigations concerning tank outside wall are in progress. There are considerable problems arising from the existing space, but it can be said that the required manipulation technique can still be realized.

During the process of this outside wall test respectively inside wall test the reactor is shut down at Na-temperature of about 25o°C, which means that the inspection device works in a nitrogen atmosphere of 25o°C. Additionally the devices are exposed to radiation, which is of great influence concerning the choice of the cables and the charging time of the TV cameras.

The vessel inside inspection takes also place at reactor shut down and at handling temperature of 25o°C. The visual inspection is practiced with cooled TV cameras and corresponding illumitation equipment. The inspection devices shall be brought into all inspection regions across the insertions of the shield plug supported by available handling machines.

IA starts at present a development program studying the specific problems of those devices. The devices are not only exposed to temperature and radiation but also to reactor cover gas atmosphere and consequently Na-aerosols.

In order to raise the number of construction units being inspected, the Na-level has to be lowered from the operating level of +4,6 m heigth to the emergency level of 1,9 m heigth for the reason of inside inspection. Following from that all instruments being placed there can now be approached for inspection.

Resting upon these realities the following devices can be submitted to a visual inservice inspection:

- shield tank
- shock plate inside wall
- fixed plug ring
- penetration tubes of heat exchanger
- suction bending of outlet tubes
- inlet tubes in the bending region
- insolation of inlet tubes
- suction liners for BE-damage proof
- dip plate of the closure

- convection interruption plates
- columns of instrumentation plate
- instrumentation plate

The competence of the visual inspection depends on different factors, which are in the main of geometrical kind. Resulting from that arrangement and design of components as well as from the possibilities to place inspection units often prevents the examination of the complete components.
In regard of faults recognition we have to make cuts in respect to those wellknown, volumetrical non destructive examination methods for example x-ray, U.S. etc.
Besides that residual sodium wetting hinders considerably the recognition of small gaps.

Splitting gaps and deformations of devices can be recognized easily.

Following to the experts condition the vessel inside inspection can only take place at the empty tank. It has to be objected that it is very time consuming to empty the tank (6 months). Secondly it should be very difficult at the present stand of the project to solve the problem of the remaining decay heat without additional cooling measurements.

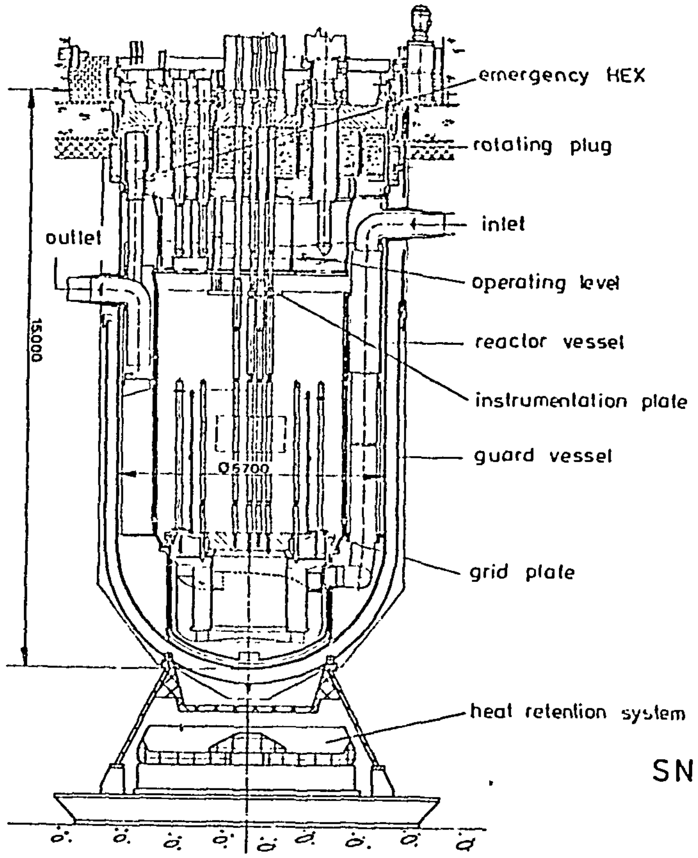
It must be assumed that for future breeder generations a U.S. examination at vessel wall must be regarded as a fixed status of the art.

In the case the inside wall inspection should become stand of the technique as well, alternative procedure ought to be developed permitting inspection under sodium.
Here the "Under Sodium U.S.-Sight Procedure" ("Unter Natrium U.S. Sichtverfahren") being developed by HEDL could bring the wanted success.

Surely efforts should be worthwhile to reach volumetrical U.S.-examination under sodium, which means sodium as coupling medium. In case they should be successful they should be applied as permanent inservice inspection. That would signify the last step in respect of the equivalence of breeder reactors compared with water reactors referring to inservice inspections.

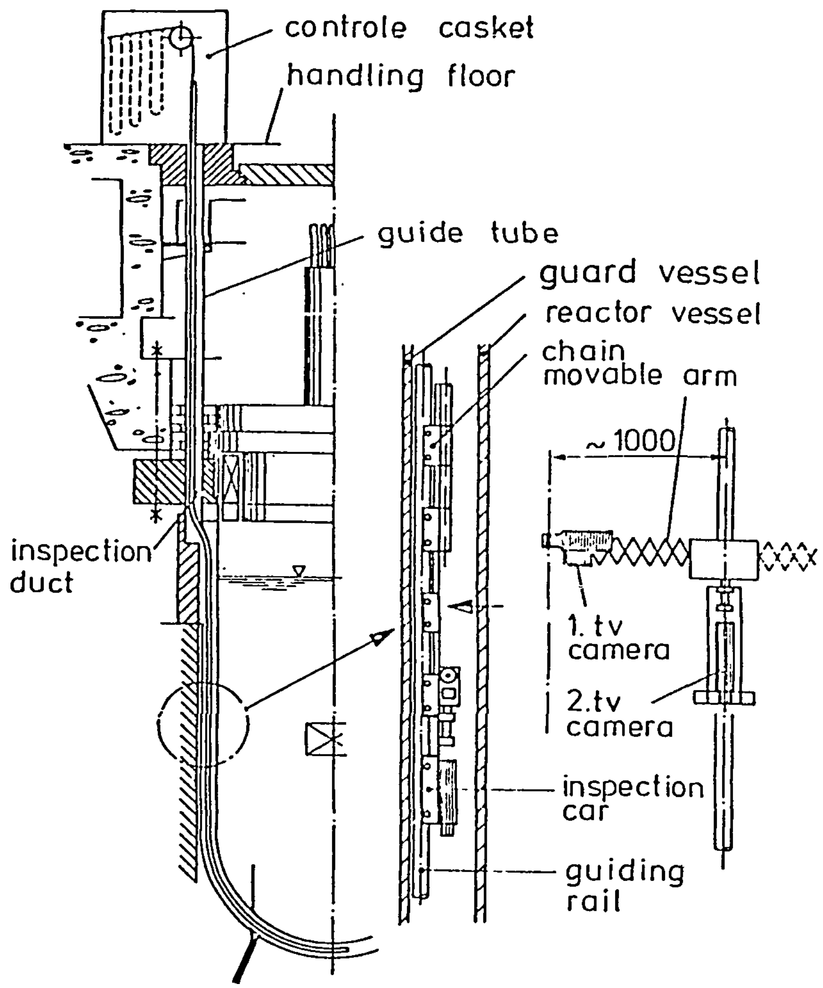
Besides these efforts it is absolutely necessary to improve and expand the inspection methods and to pass a valid standard work of inservice inspections for LMFBRs, which determined specification on technical safety and the inspecting conditions connected on the basis of technological characteristics of a LMFBR.

In the appendix an abstract of the plan for in-service inspections of the whole plant is represented. This is not a final schedule, but it shows the present status. The licensing discussions with respect to periodic inspections are at full tilt but not yet concluded.



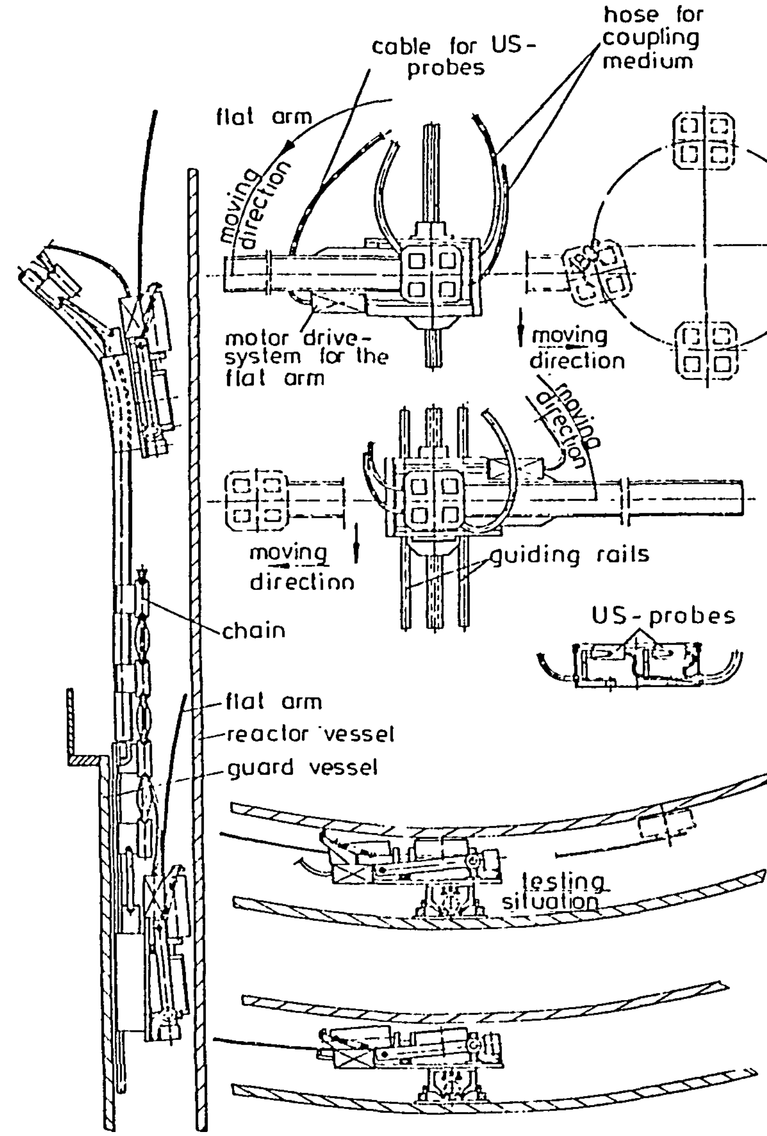
SNR 300

FIG. 1.



inservice inspection

FIG. 2.



inservice inspection
US testing device

FIG. 3.

Abstract of the Plan for Inservice Inspection SNR 3oo

8.3.76

Plant Range: Proj.-No. Designation	Plant Range: Components	Inspection Extent	Type of Inspection or Test	Remarks
21oo Reactor Vessel with Inside Installations	Reactor vessel	vessel wall from bottom to inlet nozzles	visual and ultrasonic from outside	Remote controlled by inspection system, difficulties with coupling medium not yet clarified. Problems of corrosion and transfer of the decay heat in the case of the drained tank are not yet solved. Under sodium viewing systems have to be developed
		welds above inlet nozzles	leak detection or visual	
	Inside Installations	inlet pipes, outlet pipes, core clumping, grid plate, gas bubble precipitator	visual (TV or under sodium viewing)	
23oo Rotating Plug	Rotating Plug	dipping plate, instrumentation plate, heat insulating plates, plug gaps	visual	The remote controlled systems have to be developed
24[illegible]o Guard Vessel	Guard Vessel	welds	visual from inside	with TV-system as reactor vessel
31oo Primary Heat Transfer System	Piping	selected welds (in situ-welded, highly stressed)	visual (ultrasonic if available)	partly remote controlled partly from movable shielded cabin
		representative calibrated part	control of plastic deformation	
	Valves	highly stressed welds, parts with safety function	visual (ultrasonic if available) eventual vibration control	
	Primary Pumps	casing, rotor	visual (whole casing from outside), selected parts ultrasonic if available rotor visual removed, eventual vibration control	
	Intermediate Heat Exchanger	casing, tube bundle and plate	visual whole casing from outside and tube bundle from inside, selected welds ultrasonic	
	Pump- and IHX-Cavities	walls	visual from inside	
32oo Secondary Heat Transfer System	Piping	see 31oo Piping	see 31oo Piping	
	Straight Tube Steam Generator	casing	visual and ultrasonic from outside, pressure test	
		tube bundle and plate	visual from inside eventual eddy-current or UT, pressure test	
		bellow	functional gauging	
	Helical Coil Tube Steam Generator	casing, tube bundle and plate	see straight tube steam generator	Here exist difficulties with inspection of the helical tubes, destructive testing of one component is considered
	Secondary pumps	see 31oo primary pumps		
3[illegible] Emergency Cooling System with Auxiliary System	Compensating Vessels Tanks of Drain System Cooler (Air/Sodium)	selected welds whole System	visual and ultrasonic if available pressure test	
3[illegible] Primary Auxiliary Sodium System	vessels (Drain System etc.)	selected welds	visual and ultrasonic	
3[illegible]oo Secondary Auxiliary Sodium System	vessels (Drain System etc.)	selected welds	visual and eventual ultrasonic	
	Rupture Disks I	rupture disks I	destructive testing after 1o[illegible] workinghours	
3[illegible] Primary Argon System	Gas Storage Vessels Decontamination Vessels Vacuum Vessels	vessel walls	visual pressure test	
3[illegible]/3331 Sodium Cooled Storage Tank with Cooling System	Sodium Cooled Storage Tanks	vessel wall from bottom to uppermost nozzles uppermost welds inside installation: support structures	visual and ultrasonic (welds and highly stressed parts) leak control or visual geometric control	same devices as reactor vessel
	Compensatory Vessels Heater Cooler (Sodium/Nitrogen) Cooler (Sodium/Air)	selected welds	visual, pressure test	
[illegible] Handling Devices	Transfer Machine Invessel Fuel Handling Machine etc.	casings, sealings	visual, leak test, pressure test	not yet clearified with authorities
54[illegible] Steel Covering of the Outer Containment with Locks	Steel Covering Locks	steel covering with locks and other penetrations	visual, partial and total leak tests	

G. A. de Boer, Th. J. Tromp, "Inspection Requirements and Concepts for LMFBR Heat Exchangers and Pump: a Manufacturers View" (Netherlands)

1. INTRODUCTION

Inservice inspection requirements and techniques concerns B.V.NERATOOM* as designer of steam generators, heatexchangers and pumps. The inservice inspection requirements for the SNR-300 components are of present interest. Therefore it is logical to use these components as a back drop for this paper, although the requirements and concepts apply to LMFBR components in general. The main data and dimensions of the various components are given below:

1.1. Straight tube steam generator

See figure 1.

Dimensions	Evaporator	Superheater	
Tube diameter x wall thickness	17.2 x 2	17.2 x 2.9	mm
Tube length between tube-plates	20	15.3	m
Number of tubes	211	211	
Shell diameter	650	650	mm
Overall height	22	17	m
Diameter sodium nozzles	300	300	mm

Material (both) 10 CrMoNiNb 9.10

Working Data			
Capacity	55.4	30.1	MWth
Sodium inlet temperature	455	520	°C
Sodium outlet temperature	335	455	°C
Sodium flow	362.5	362.5	kg/s
Steam/water inlet temperature	253	357	°C
Steam outlet temperature	357	500	°C
Steam outlet pressure	181.8	167	bar
Steam flow	40.5	38.5	kg/s

*) The Hague/Holland

1.2. Helical coiled steam generator

See figure 2.

Dimensions	Evaporator	Superheater	
Tube outer diameter x wall thickness	26.9 x 2.9	26.9 x 4.5	mm
Tube length in the helically coiled tube bundle	40.56	30.74	m
Number of tubes	77	77	
Shell diameter	1400	1400	mm
Overall height	12	10.5	m
Diameter sodium nozzles	300	300	mm

Material (both) 10 CrMoNiNb 9.10

Working Data			
Capacity	54.7	30.9	MWth
Sodium inlet temperature	453.2	520	°C
Sodium outlet temperature	334.8	453.2	°C
Sodium flow	362.5	362.5	kg/s
Steam/water inlet temp.	253	358	°C
Steam outlet temperature	359	500	°C
Steam outlet pressure	185.5	166.8	bar
Steam flow	40.5	38.5	kg/s

1.3. Intermediate heatexchanger

See figure 3.

Dimensions		
Tube diameter x wall thickness	21 x 14	mm
Tube length between tube-plates	7.60	m
Number of tubes	846	
Diameter of central tube	400	mm
Vessel diameter	1360	mm
Overall height	12.8	m
Nozzle diameter	300	mm

Material austenitic steel 1.4948

Working Data

Capacity	85	MWth
Primary outlet temperature	375	°C
Primary inlet temperature	546	°C
Primary flow	392.6	kg/s
Secondary inlet temperature	335	°C
Secondary outlet temperature	520	°C
Secondary flow	362.5	kg/s
Working pressure on primary side	11.2	bar
Working pressure on secondary side	11.8	bar

1.4. Sodium pumps

See figure 4.

	Primary	Secondary	
Capacity	5300	4600	M^3/h
Design temperature	555	345	°C
Working temperature	546	335	°C
Total head	140	100	m
NPSH	13	40	m
Max. speed	960	960	rev/min
Shaft power	2220	1460	kW
Vessel diameter	1370/1670	1360/1670	mm
Nozzle diameter inlet	620	620	mm
Nozzle diameter outlet	550	550	mm
Construction material	Austenitic Steel 1.4948		

Since Inservice Inspection covers quite a few subjects it is sensible to subdivide the total field in:

1.5. Inservice inspection

	SAFETY	RELIABILITY (availability)
PERIODIC TESTING	A-1	B-1
ON LINE MONITORING (continuous or sampling/scanning)	A-2	B-2

1.6. LMFBR and periodic testing

Because of the fact that little operating experience and very little statistical data is available on LMFBR, inservice inspection requirements for LMFBR's seem to be moving. With most components now under construction the discussions with the licensing authorities on inservice inspection are now being finalised.
In our situation we are dealing with a set of comparatively recent detailed requirements. For completeness sake some conspicuous differences between LWR's and LMFBR's are:

1.6.1. Additional safety barrier in the form of a secundary system on account of the nature of the coolant.

1.6.2. The secundary system is a low pressure system.

1.6.3. The primary system (radioactive) is also a low pressure system.

The levels on inspection as presently required are given in Appendix 1.

2. RELIABILITY (availability)

This aspect (area B) is of course very important for a utility. This means good quality control and a sound and most likely a simple design. Although the situation is clear in this respect it is not easy to describe reliability in such a way that it can be a clear part of a set of specifications. Usually safety requirements form fixed conditions for a designer to start with in case of conventional equipment.

3. SAFETY ASPECTS AND INSERVICE INSPECTION

3.1. Fixed conditions

The safety guide lines were during the design phase not yet "translated" in detailed design presciptions.

This also applies to inservice inspection requirements. Because of the rather novel nature of LMFBR's let us try to review what inservice inspection can do for: safety.

In LMFBR's it is proposed to have approximately every four years a series of periodic tests.

Why should we have periodic inspections?
The answer looks straight forward, to assure a sound level of safety by checking if:

3.1.1. the various components are in the same, sound, condition as when they left the manufacturer.

3.1.2. there are signs of flaws which may lead to a dangerous situation.

These two points cover in fact the whole range of:

- material and materials selection; material behaviour;
- design;
- manufacture/quality/workmanship;
- operating history of the component.

3.2. Materials

Structual materials and their selection should not be a part of the inservice inspection complex. We feel that there should be separate programs to investigate the materials selection, such as the existing research and development program for SNR-300, the so-called "F+E program".
This can be either a program that is terminated before the selection and use of the materials involved or a program which is ahead in time in order to assure timely information.

3.3. Design

Here we have a need for sound and simple design with ample soft ware support. Furthermore an adequate set of quality assurance procedures must be in operation in the engineering phase of a LMFBR component.

3.4. Manufacture/Quality/Workmanship

It is in our opinion mandatory that the highest possible standard of workmanship should be attained by means of exhaustive programs.

Such programs should come in operation long before the manufacturing starts. This is necessary to assure that all the equipment and expertise will be available during the construction of the components.

3.5. Operating history

Modern data logging techniques and monitoring systems should cover this point. These systems can show in many cases whether inspection is necessary (see 3.6.4.). This point brings us to the fact that malfuncion of a component may originate somewhere else in the system but not necessarily in the faulted unit.

3.6. Origin of malfunction

Multiple causes are known, to name a few:

3.6.1. Stresses due to static and pressure loadings.

3.6.2. Vibration.

3.6.3. Fretting and friction.

3.6.4. Thermal transients.

3.6.5. Corrosion.

The relevant question here is: is it possible to detect flaws (see 3.1.2.), due to 3.6.1. - 3.6.5., early enough?

Point 3.6.1. can and should be covered in the design and test phases. The same applies to most other points. However some may lead to such a rapid deterioration of a component that it is questionable whether periodic testing will be an adequate prevention.
Take for instance waterside corrosion. The cause of failure may originate outside the steam generator but the steam generator can be affected in a very short time. Although this may be not the time and place to mention it, but as a steam generator manufacturer we deem it more than highly desirable that we have butt welded condensor tube-to-tubeplate connections with first grade tubing.

4. PERIODIC TESTING

4.1. Which parts?

Probably most of you will agree that volumetric testing of plates, forgings for heatexchangers and pump vessels is not necessary since in most cases ample margins are build in.

This applies not to highly stressed joints or weld as are found in nozzle/vessel welds etc. volumetric testing is a logical choice.

4.2. Heattransfer pipes

4.2.1. Requirements

The pipes in heatexchangers form a case in itself. They are the most important single items which warrants extra emphasis. Because of the fact that, on account of various considerations, such as tube wastage, substantial allowances on wall thickness are not feasible periodic measurement of wall thickness is required.
The reasons behind these measurements are ofcourse safety aspects. In steam generators sodium/water reactions is what one tries to prevent. In intermediate heatexchangers it is the containment function of the pipes which is all important.

4.2.2. Quality of inspection

What levels of inspection can we attain?
An answer is to be found in the Quality of inspection that is reached during the manufacturing of the tubes.

The inspection methods involved during manufacturing of the tubes are among others:

a) visual
b) outside diameter measurement ($\pm$ 1% D)
c) wall thickness check ($\pm$ 10% t)
d) ultrasonic
e) pressure testing

Small surface scratches etc. have to be spot grinded. The total area which is allowed to be grinded is specified.

The ultrasonic testing is continuous with twin transducer sets operating in opposite directions. The transducers rotate around the tube. The testing is a go/nogo method with a CRT setting of 80%. Calibration is done by means of a test tube with "V"-groove artificial defects. After each 20 production tubes a calibration test run is made.

On the test tube are 4 "V"-groove defects, axial ones on inside and outside of the tube and transverse ones also on inside and outside.
In total four line focused 4 MC/s transducers are used; focal length 8 mm. One of the transducers is of the transmitter receiver type. The quality of the production process and of the inspection techniques used is such that no tubes with too thin a wall are produced.

The wall measurement techniques that are available today for the periodic inspection have an accuracy which is smaller than the corrosion allowances that we have on the steam generator tubes. Yet we have to measure in situ, changes in wall thickness.

4.3. Practical experience

Our practical experience is based on testing a:

- intermediate heatexchanger;
- helicoil evaporator;
- straight tube evaporator;
- " " superheater;
- " " reheater;
- sodium pump

As an example it is useful to mention the phantom leak in the straight tube evaporator. It took eight months to establish that no leak was present.
The point here is that in the eight month period various inspection techniques were developed and used and every time we suspected the tests that were made.
Every test brought us a new round inconclusive tests and experiments. Only disassembling the evaporator in the clean-room of the manufacturer, after an additional 2000 hrs of operation, gave the final answer that the unit had no leak.

If one would like to test, in situ, all the steam generator tubes, of which approximately 3800 are to be installed in SNR-300, one would create an expensive situation.
This seems not very economic, so only x-percent will be inspected. Again one wonders if this is really a sound

approach. One should bear in mind that during manufacturing all tubes are tested with various techniques.
The conclusion is that the production inspections are much more detailed than inservice inspections can be.
This does not imply that we dismiss periodic inspection as useless but we feel it is only of specific value.

5. ALTERNATIVE APPROACHES

The logical route to improve safety is: assure high quality and improve and extend on-load surveillance.

5.1. Quality

High quality must be attained as mentioned before in all stages of the design process, materials manufacturing, construction and acceptance testing.
The validity of the design concept should be checked by realistic testing of (near) full scale pre-production units, as is the case for the SNR components.

5.2. On-load monitoring

On-load monitoring (continuous or scanning) can yield relevant data in an early stage in case of defects. Monitoring will involve integral type of measurements, for instance it will not be possible to guard each steam generator tube. But this is not necessary since the integrity of components can be established with monitoring systems.

As an example can serve the leak detection systems that are already available today. Such on-line systems have a great potential to ascertain the integrity of a component.

6. CONCLUSIONS

Periodic testing can as far as we know, only give a contribution to safety. This does not mean that we want to reject periodic testing ,only we want to put it in its proper perspective. Therefore it is sensible to improve the on-load surveillance methods which one enhances reliability at the same time.

Steam generator

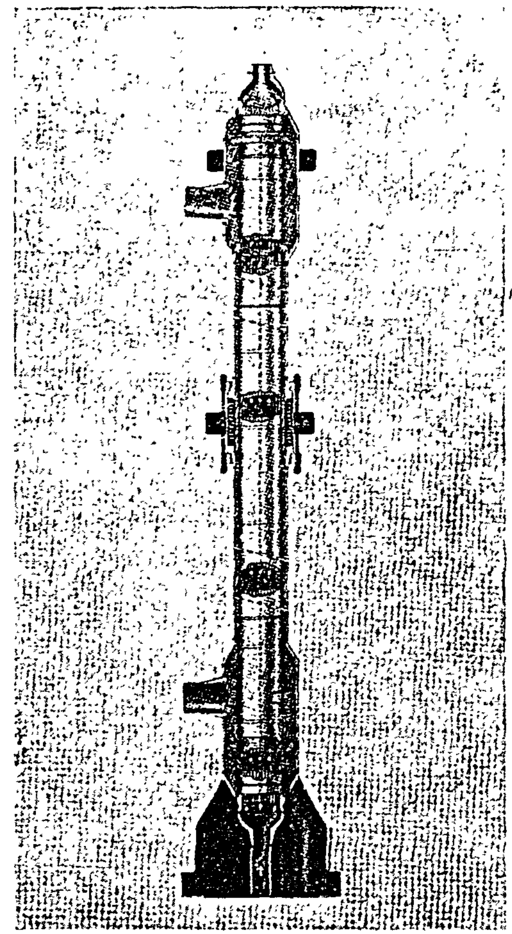


FIG. 1.

Steam generator

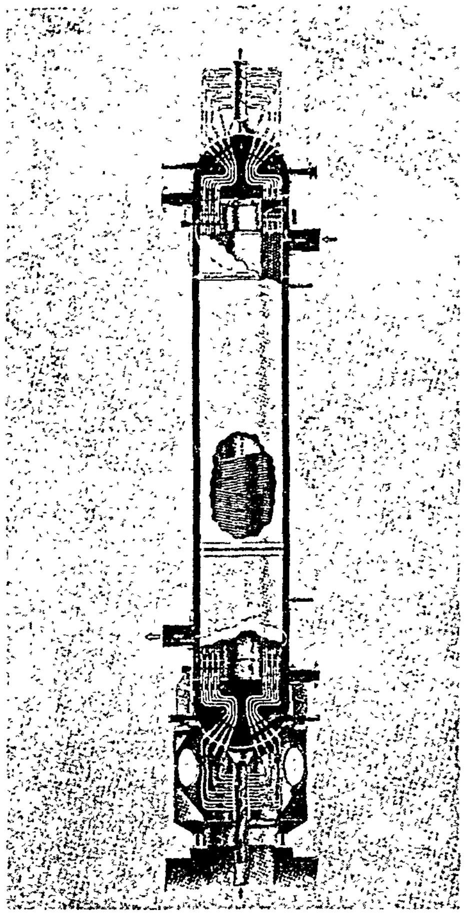


FIG. 2.

Intermediate Heat Exchanger

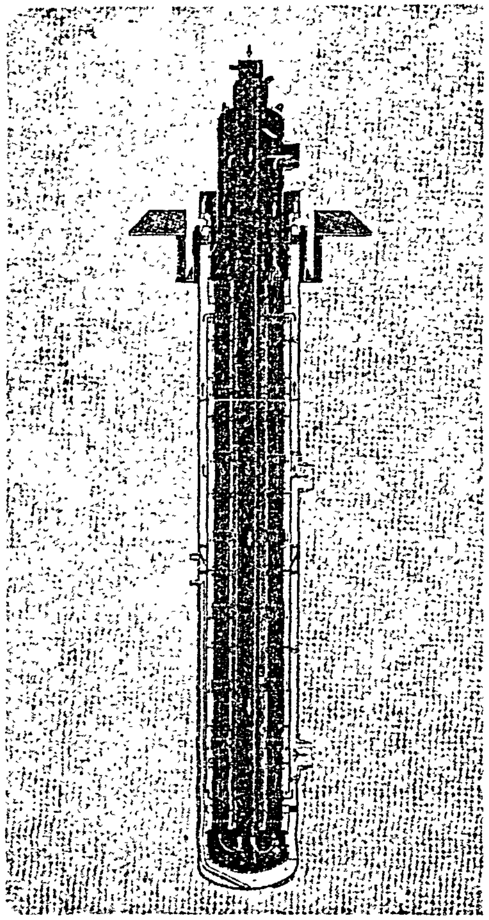


FIG. 3.

Sodium Pump

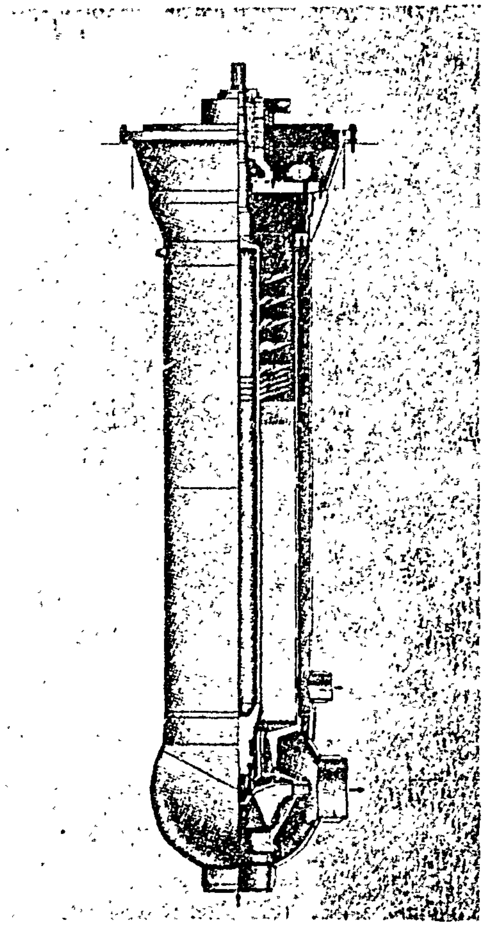


FIG. 4.

APPENDIX I

INSERVICE INSPECTION REQUIREMENTS* FOR SNR-300 COMPONENTS

Component	Parts to be inspected	Type of inspection or test	Remarks
Straight tube steam generator	- shell; outside	visual	removable insulation and trace heating
	- " ; highly stressed area, viz. nozzle welds etc.	volumetric, ultrasonic or eddy current	---
	- other area's	---	surface crack detection should be possible
	- tubes	wall thickness, full length	dangerous wall thickness decreases should be detectable Number of tubes to be inspected, X-percent at random → additional checks.
	- tube/tube sheet welds	volumetric	X-percent at random → additional checks
	- tube sheet bores	surfaces crack detection	X-percent at random → additional checks
	- tube supports	positioning	spacing of grids as designed must be established.
Helicoil steam generator	- shell; outside - " ; highly stressed area's	see: straight tube steam generator.	see: straight tube steam generator
	- tubes	see: straight tube steam generator	see: straight tube steam generator entry after removing outside portions of the tubes

* = these requirements have been formulated lately and may change in the near future; table is indicative only; inspection period approx. every 4 years.

→ = may result in ....

Component	Parts to be inspected	Type of inspection or test	Remarks
	- bundle support	visual and/or ultrasonic and/or monitoring	probably redundant support required; still under consideration.
	- tube supporting hangers	see bundle support	see bundle support; tubes are fixed without play, no grids are present no checks on tube clamping are necessary
	- tube header welds	volumetric inspections	after removal of steam and feed water lines
Intermediate heatexchanger (straight tube floating head design)	- shell	visual by means of TV-camera/ manipulator	this component is radio-active after use. component is situated in a cavity
	- highly stressed area's of the shell, viz. nozzle welds etc.	volumetric/manipulator	
	- tubes	wall thickness, full length	X-percent at random via inspection nozzles or equivalent → additional tests. Tube bundle can be removed.
	- tube/tube sheet welds	volumetric-manipulator	see: tubes
	- tube sheet bores	surface crack detection/manipulator	see: tube
	- tube supports	positioning	spacing of grids must be established
Primary sodium pump	- barrel general	visual by means of TV-camera manipulator	pump is situated in a cavity
	- " ; highly stressed area's nozzle welds	volumetric/manipulator	---
	- " inside	visual inspection, if required TV-camera/manipulator	after removal of impeller/ shaft assembly; check on loose parts
	- rotating parts	visual	
Secundary sodium pump	- see: primary pump	basically the same as for the primary pump	pump is not radio-active and is accesible, no cavity

B. L. Baikie, A. R. Wagg, M. J. Whittle, D. Yapp*, "Ultrasonic Inspection of Austenitic Welds". (United Kingdom)

SUMMARY

The ultrasonic examination of austenitic stainless steel weld metal has always been regarded as a difficult proposition because of the large and variable ultrasonic attenuations and back scattering obtained from apparently similar weld deposits.

The work to be described shows how the existence of a fibre texture within each weld deposit (as a result of epitaxial growth through successive weld beads) produces a systematic variation in the ultrasonic attenuation coefficient and the velocity of sound, depending upon the angle between the ultrasonic beam and the fibre axis.

Development work has shown that it is possible to adjust the welding parameters to ensure that the crystallographic texture within each weld is compatible with improved ultrasonic transmission.

The application of the results to the inspection of a specific weld in type 316 weld metal is described.

1. INTRODUCTION

Ultrasonic testing is now in common use for the detection of cracks and inclusions in metallic components. The method normally used is to observe reflections from defects in the path of a high frequency (1-10 MHz) sound beam. The location of the defects is determined from the time of travel of the ultrasonic beam to and from the defect, and its size is estimated by observing the amplitude of the reflected beam as the transducer is moved. Defect detection is limited by scatter from the grain boundaries in the metal, which act as acoustic discontinuities and reflect the sound beam. As a result, the amplitude of the defect signals is reduced due to attenuation of the sound beam, and the signals reflected from the grain boundaries appear as "grass" on the oscilloscope screen, reducing the signal to noise ratio. At each acoustic discontinuity, the incident beam can either be transmitted or scattered in the form of a shear or compression wave, and the intensity ratio of shear to compression waves in the scatted sound is approximately 4:1 regardless of the nature of the incident beam. Accordingly, by using a compression wave transducer, which detects only reflected compression waves, the signal to noise ratio is increased, compared to an equivalent shear wave probe. The signal to grass ratio can be further improved by using short pulse probes (1,2). In most metals, the attenuation and "grass" are sufficiently low to present few problems in the observation of significant defects. However, austenitic steels, with welded or cast structures are notorious for the high and variable scatter they produce, with the result that satisfactory ultrasonic inspection is difficult to achieve.

Considerable variations in attenuation have been observed in welds made to the same procedure and exhibiting apparently similar metallurgical structures. The work to be described began as an attempt to understand and control these variations and has led to the isolation of the most important factor governing attenuation in austenitic welds.

* D. Yapp is with Marchwood Engineering Laboratory, C.E.G.B.

2. EXPERIMENTAL TECHNIQUES AND RESULTS

2.1. Metallurgical

The experimental techniques used during this research programme have involved the use of optical and X-ray metallography, combined with ultrasonic testing by compression waves. The initial studies of crystallographic texture and ultrasonic attenuation were made on weld samples made by depositing austenitic stainless steel weld metal onto stainless steel base plates using the manual metal arc process, to form a block of weld metal, (approximately 75 mm cube). Three different blocks were made, using "flat", "horiztonal-vertical" and "vertical-up" techniques. In the "flat" welding case the base plate was in a horizontal plane, and linear beads of weld metal were deposited to build up planar layers, always welding in the same direction and with the same bead sequence. For "horizontal-vertical" welding the base plate was in a vertical plane, and horizontal beads of weld metal were added, with beads one above another. In the "vertical-up" case the base plate was again in a vertical plane and weld beads were added welding vertically upwards.

X-ray metallography was carried out using a Siemens X-ray diffractometer, fitted with a Schulz reflection goniometer stage which enable the selected crystallographic texture to be determined. During this work the X-Ray source (Cu Kα) and the detector were adjusted to give information on the location of $\{100\}$ planes within the specimens and the pole figures were plotted manually on a Wulff net, using X-Ray intensity values measured from the diffractometer traces. X-Ray specimens were obtained by machining 3mm thick discs (30mm diameter) from selected regions in each weld sample and these were deeply etched to remove the mechanically deformed surface layer. FIG. 1 shows the $\langle 100\rangle$ pole figure, characteristic of the "horiztonal-vertical" weld pad, obtained from an X-Ray specimen machined from a horizontal plane of the original weld block.

By obtaining pole figures from each sample it was possible to conclude that each weld possessed a characteristic $\langle 100\rangle$ fibre textured structure with an angular spread in grain axes of approximately $\pm 10^{\circ}$ about the mean fibre axis. Furthermore, the results of several texture determinations showed that the orientation of the fibre axis within each weld pad was unique and a characteristic of the particular welding technique. Optical metallography has also shown that each weld is characterised by an array of columnar grains (FIG. 2), whose grain axes are parallel to the fibre axis, as determined by X-Ray diffraction. This information has enabled a generalised scheme of fibre (columnar grain) axis orientation to be established, as shown in the stereographic projection in FIG. 3. In this diagram the fibre axes are shown relative to three orthogonal directions L^+, W^+ and P^+ which refer to the direction perpendicular to the plane of weld layers, the direction of welding and the direction of adding successive weld runs within each layer respectively.

The existence of an extensive columnar grain structure within these welds is in itself unusual and differs markedly from the structure observed in ferritic steel welds. In low alloy steels the solidification process during welding initially produces a columnar grain structure in each weld bead. Subsequent weld beads partially remelt those from the underlying weld run and the new columnar grains adopt an orientation that is identical to those of the previous columnar zone. This phenomenon is known as epitaxial growth. In addition, the effect of depositing successive weld runs is to thermally cycle regions of the solidified weld metal through the ferrite/austenitic phase fields which causes recrystallisation to an equiaxed grain structure.

Austenitic stainless steel, however, does not undergo a phase transformation during thermal cycling and the "as solidified" structure survives in the completed weld. In the case of 316 stainless steel, this mechanism can produce columnar grains several centimetres long. Metallographic evidence suggests that the development of the fibre texture is due to the mechanism of competitive growth. The model is based on the ssumption that growth in one crystallographic direction (in this case the ⟨100⟩ direction) is energetically more favourable and is therefore faster than in other directions. This process leads to the rapid disappearance of unfavourably oriented grains. During solidification an additional constraint is applied by the need for the growth direction to be along the line of maximum thermal gradient which, in the case of a weld, is a function of the position on the fusion boundary. Across successive weld beads, the line of maximum thermal gradient can change by as much as 40° and hence epitaxial growth under these conditions is severely restricted. The effect of this additional constraint is to further limit the range of favourable orientations such that the predominant grain orientation is that which possess a ⟨100⟩ direction perpendicular to the average fusion boundary.

The results of the optical metallographic examination have shown that the orientation of the average fusion boundary is determined by the welding technique and by gravity. Each weld bead is deposited into the corner formed by the previous weld bead and the underlying layer of weld beads, so that the relative heat flow components, downwards into the weld pad and sideways into the weld bead determine the orientation of the fusion boundary. The geometrical shape of the corner into which the weld beads are deposited is itself determined by the effect of gravity on the molten weld pool. Thus, in the "flat" welding position, gravity causes the weld pool to be flattened, and the wide weld bead forms only a shallow corner, with the fusion boundary then inclined at 15° to the base-plate. In "horiztonal-vertical" welding the weld pool cross-section is more circular, and the deeper corner results in a fusion boundary at 30° to the base-plate. These observations can be extended and developed, so that it is possible to predict the orientation of the ⟨100⟩ fibre axis if the weld geometry and welding procedure are known.

2.2. Ultrasonic Examination

Ultrasonic examination of the test weld pads was initially carried out using a conventional 2½ MHz short pulse compression wave contact probe and attenuation measurements were obtained in the three orthogonal directions L^+, W^+ and P^+. These examinations produced the variable ultrasonic transmission characteristic of austenitic stainless steel weld metal, with attenuation coefficients in the range 0.1 to 0.4 dB/mm. The realisation that a columnar fibre-textured structure existed and that the fibre axis orientation was a function of welding technique led to the search for a relationship between attenuation and orientation of the ultrasonic beam relative to the fibre axis. To achieve this cylinders were machined from the weld samples with the columnar grain axes running parallel to one diameter, permitting the measurement of velocity and attenuation as a continuous function of grain orientation. These cylinders were approximately 50mm long and 38mm in diameter, and were precisely located on a table which allowed them to be rotated about their own axis. The system was immersed in water and an ultrasonic probe was mounted on each side of the cylinder so that a beam could be transmitted from one to the other across the diameter - FIG. 4. Attenuation measurements were made by comparing the signal transmitted between the probes in the presence of the sample, with that obtained when the sample was replaced by a fine grained,mild steel cylinder of identical diameter, located in the same position. The velocity was obtained by recording the difference in transit time between the probes for an ultrasonic pulse passing through the ferritic and austenitic cylinders. This time interval was measured using a crystal controlled timer which was able to average over many repetitions of the ultrasonic pulse frequency. The velocity in a parallel sided block of mild steel was recorded in a separate experiment using the same apparatus. The attenuation as a function of beam orientation with respect to the columnar grain axes is shown in FIGS.5 a,b & c for samples from the "flat", "horizontal-vertical", and "vertically up" welds respectively. Two general conclusions may be drawn from these results. Firstly, the behaviour of all three samples is essentially the same and secondly, the attenuation is strongly orientation dependent. Miniumum attenuation occurs at approximately 45° to the fibre axis and maxima at 0° and 90°.

The orientation dependence of compression wave velocity is shown in FIG. 6 for the "horizontal-vertical" weld. A maximum velocity occurs at 50° to the grains, exceeding that in mild steel, while minima exist parallel and perpendicular to the fibre axis. The velocity variations are readily explicable as an expression for the ultrasonic velocity as a function of propagation direction in an elastically anisotropic medium has been derived by Musgrave (3). This expression gives the velocity as the solution of a cubic equation whose coefficients depend upon the elastic constants and cosines of the direction of propagation. In general three solutions exist, of which the largest value corresponds to a compression wave and the other two to shear waves. The velocity in a fibre textured polycrystalline material such as that formed by the weld metal is obtained by averaging the velocity over all directions which lie at a fixed angle θ to the [100] axis. FIG. 6 shows the measured velocity as a function of θ, compared with curves computed from the single crystal elastic constants measured by Salmutter (4) and Bradfield (2) for 12/12 and 18/12 austenitic steels. Good qualitative agreement has been achieved and it would appear that the alloys for which elastic constants are available possess greater elastic anisotropy than 316, for which no data could be found.

The attenuation results are more difficult to explain. Satisfactory theories have only been developed for equiaxed grains, whereas in the present case a highly elongated structure exists. Qualitative agreement with the experimental results can be obtained by suitable modifications to existing theories, although a satisfactory explanation of the attenuation behaviour must await further theoretical and experimental work.

3. APPLICATIONS TO AUSTENITIC WELDS

The existence of a periodic relationship between ultrasonic attenuation and the orientation of the ultrasonic beam with respect to the fibre axis is an experimental observation which is now supported by a wide range of measurements in different 316 welds and hence the inability to fully understand the phenomenon is no restriction on the practical application of this information. For example, the reasons for the apparently random variations in attenuation observed on stainless steel welds are now clear. In the past it has been normal practice for the welder to decide on the sequence to which weld beads are deposited and hence some regions of the weld could, by chance be close to the ideal 45° orientation (with low attenuation), while others might be close to the worst orientation, parallel to or perpendicular to the fibre axis. Furthermore, in combination with the knowledge that the orientation of the ⟨100⟩fibre axis can be varied over a wide range simply by controlling the welding procedure, this information clearly points the way towards a means of achieving routine ultrasonic inspection of austenitic stainless steel welds.

The problem which initiated this investigation involved an austenitic stainless steel fillet weld which was used to join two concentric stainless steel tubes. The initial weld profile - FIG. 7a was subsequently altered to a square profile - FIG. 7b to enable an ultrasonic inspection by compression waves to be carried out. Weld metal was deposited in layers at 90° to the tube axes, which were in a horizontal position. The initial welding procedure achieved this by allowing weld beads to be deposited circumferentially in alternative quadrants, starting at the inner tube surface on each weld layer and towards the 12 o'clock position in each quadrant. This procedure can be interpreted as consisting of "horizontal-vertical" welding at the 12 o'clock position, "vertical-up" welding at 3 and 9 o'clock, "overhead" welding at 6 o'clock and suitable mixtures of those extremes in the intermediate positions. With this information it is possible to produce a graph of the expected angular misorientation between the fibre axis and the ultrasonic beam for the two testing directions - axial and radial - (FIG. 8a)and conclude that high ultrasonic attenuations would be obtained in all regions except those near the 12 o'clock position.

For satisfactory ultrasonic transmission the weld procedure was adjusted so that successive weld layers were deposited on a conical surface at 55° (instead of 90°) to the axis of the inner tube. This was predicted to have the effect of changing the position of the curves in FIG. 8a towards the optimum position as shown in FIG. 8b. Subsequent weld procedure tests, followed by ultrasonic and metallographic examination, have shown that the agreement between the predicted grain orientations and those obtained in the weld is excellent and ultrasonic attenuations of less than 0.12 dB/mm have been obtained throughout the weld deposit.

However, the variation in grain orientation with circumferential position means that only in the local region of 10.30 are the grains at the optimum inclination of 45° to the ultrasonic beam. The rate at which the attenuation changes with the relative angle between the beam and the grains determines the maximum misorientation which can be tolerated.

In the fillet weld discussed above the volume of weld metal was large compared to the area of the weld at the fusion faces and so localised cooling effects at the fusion boundaries did not unduly affect the orientation of the columnar grains. The grain orientation was, therefore, substantially uniform throughout each weld. In general, welds are not expected to demonstrate such uniformity. For example, in a pipe to pipe butt weld the maximum thermal gradient is normal to the pipe axis in the centre of the weld but normal to the fusion faces at the edges. The etched section shown in Figure 9 illustrates this point. The effect of such a spread of orientations on an angled ultrasonic beam has been investigated using cylinders cut from the weld with their axes parallel to the direction of weld metal deposition. The results display a similar periodicity to that found in the welds above and the easiest penetration is with a 45° beam of compression waves. This explains the success of angled compression wave beams in inspecting austenitic butt welds.

The further investigation of butt welds and other weld configurations remains a rich field for study. For example, the effects of the weld preparation angles on the grain structure of a butt weld are likely to be significant and may point the way to improved inspection or the welding technique itself may be optimised to provide improved penetration. However it is possible to conclude that in all cases, we are unlikely to achieve the same sensitivity to small defects that we are accustomed to in ferritic welds. If ultrasonic inspection is considered essential to verify the integrity of a component, the critical defect sizes must be calculated from considerations of the operational stresses and compared to the capabilities of the inspection. Consequently, component design must include not only the inspection requirements to optimise the shape and metallurgical structure of the component,but also fracture calculations to determine whether the existing inspection sensitivity is adequate.

4. CONCLUSIONS

The experimental results obtained during this investigation have enabled the following conclusions to be made.

1. Strong <100> fibre textures are produced in stainless steel welds, with the <100> fibre axis parallel to columnar grain boundaries.

2. Ultrasonic attenuation is a strong function of the orientation of the ultrasonic beam relative to the fibre axis.

3. The orientation of the fibre axis in an austenitic stainless steel weld is a function of the welding procedure and can be varied over a wide range by simple modifications to the welding procedure, to improve ultrasonic transmission.

4. The ultrasonic inspection sensitivity to small defects is unlikely to be as high for austenitic welds as it is for ferritic even when the weld structure is optimised.

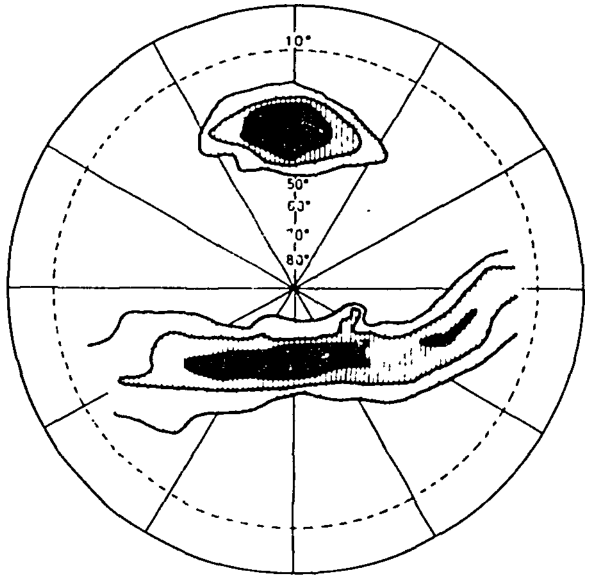


FIG. 1.

<100> POLE FIGURE OBTAINED FROM A HORIZONTAL SECTION OF THE 'HORIZONTAL - VERTICAL WELD PAD.

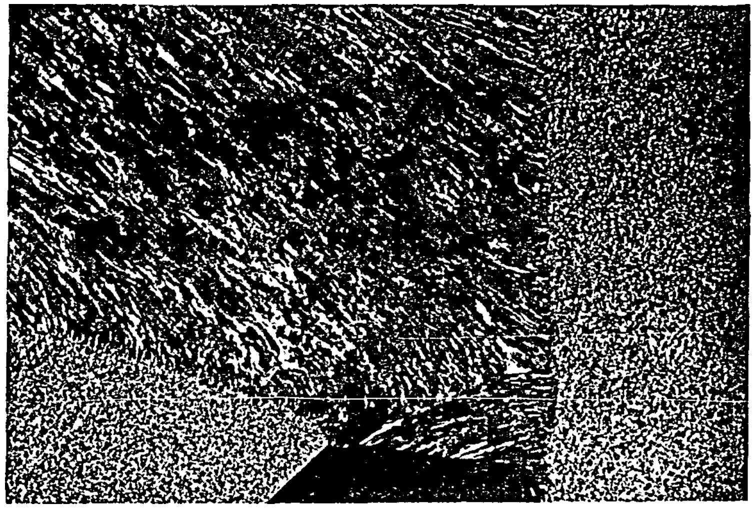


FIG. 2. OPTICAL MICROGRAPH OF A 316 FILLET WELD.

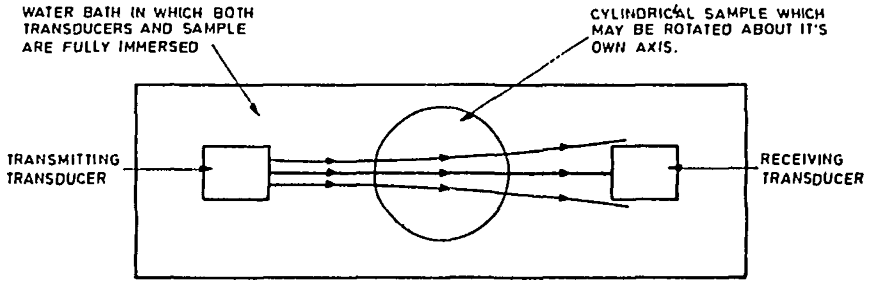


FIG. 4

APPARATUS USED FOR THE STUDY OF THE DEPENDENCE OF ULTRASONIC ATTENUATION UPON GRAIN ORIENTATION.

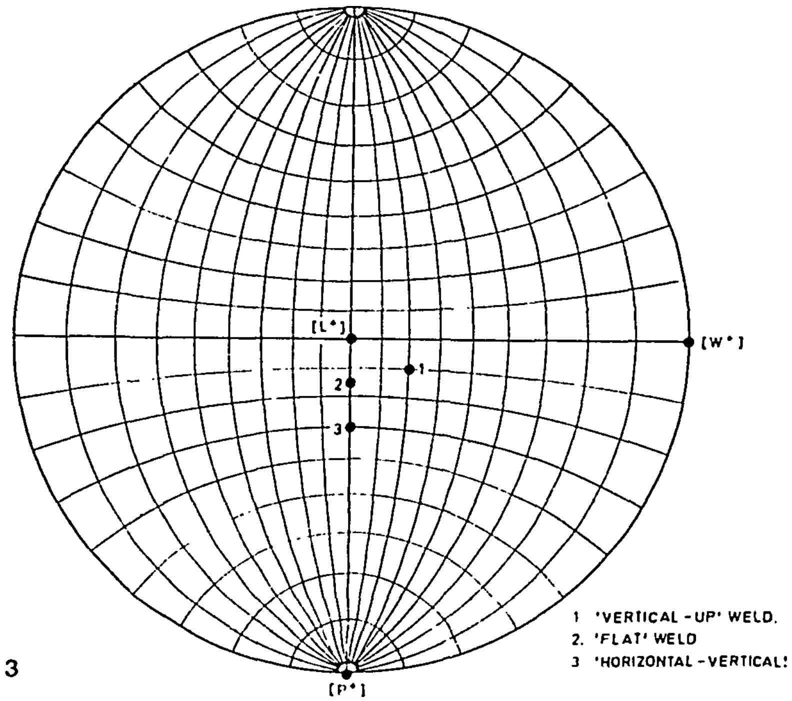


FIG. 3

STEREOGRAPHIC PROJECTION FOR THE GENERALISED SCHEME OF ORIENTATIONS IN EXPERIMENTAL WELD PADS.

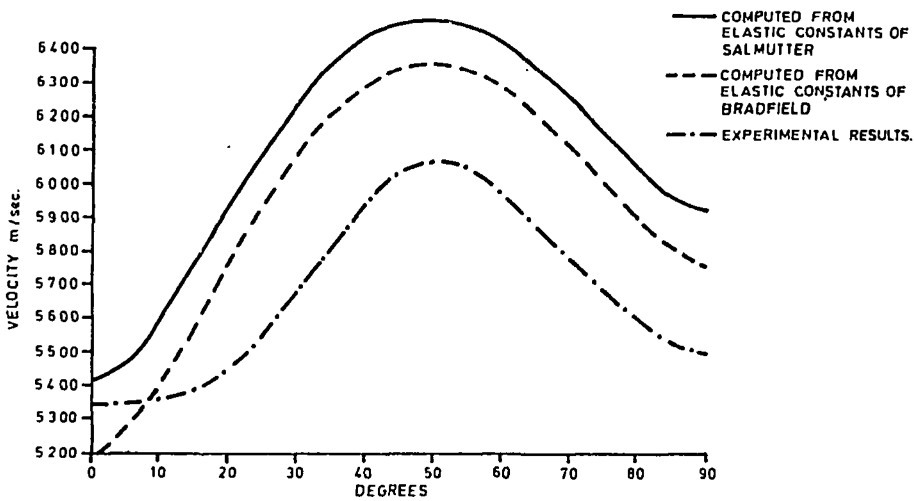
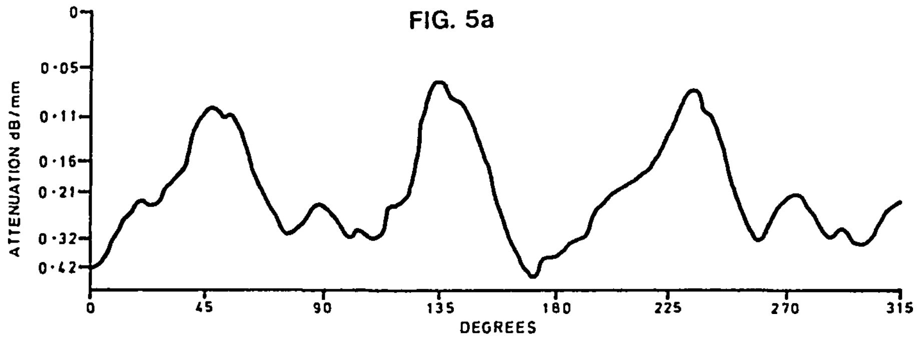
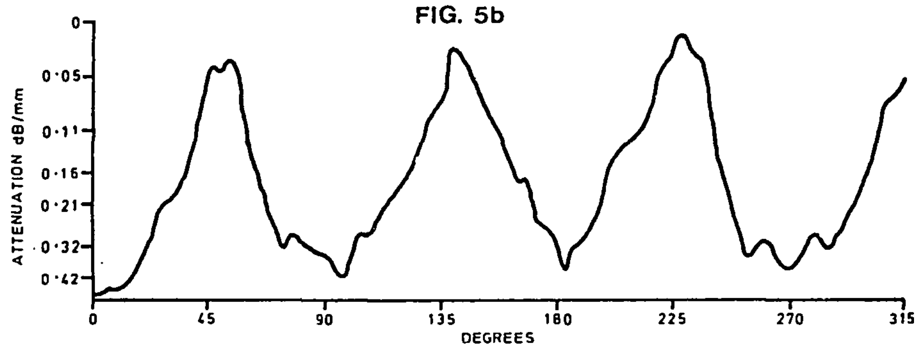


FIG. 6

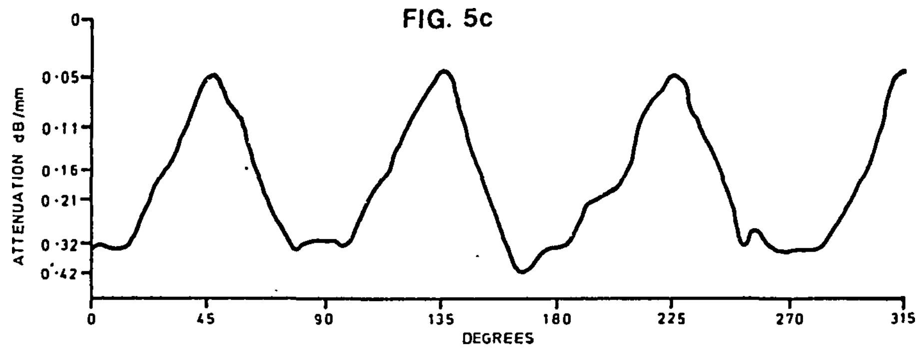
COMPRESSION WAVE VELOCITY AS A FUNCTION OF DIRECTION OF PROPAGATION RELATIVE TO THE COLUMNAR GRAIN AXES.



'FLAT' WELD



'HORIZONTAL–VERTICAL' WELD



'VERTICAL – UP' WELD

ULTRASONIC ATTENUATION AS A FUNCTION OF DIRECTION OF PROPAGATION RELATIVE TO THE COLUMNAR GRAIN AXES. (2MHz)

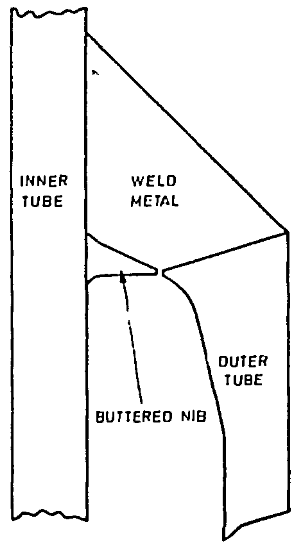


FIG. 7a

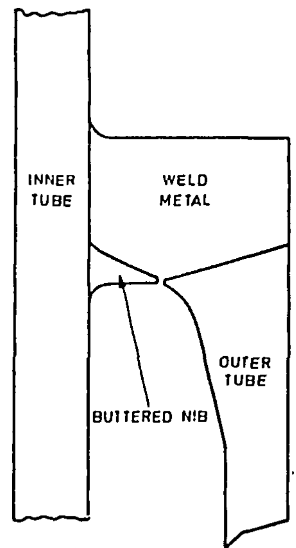


FIG. 7b

SCHEMATIC DIAGRAM SHOWING ORIGINAL (FIG. 7a) AND MODIFIED (FIG. 7b) WELD PROFILES.

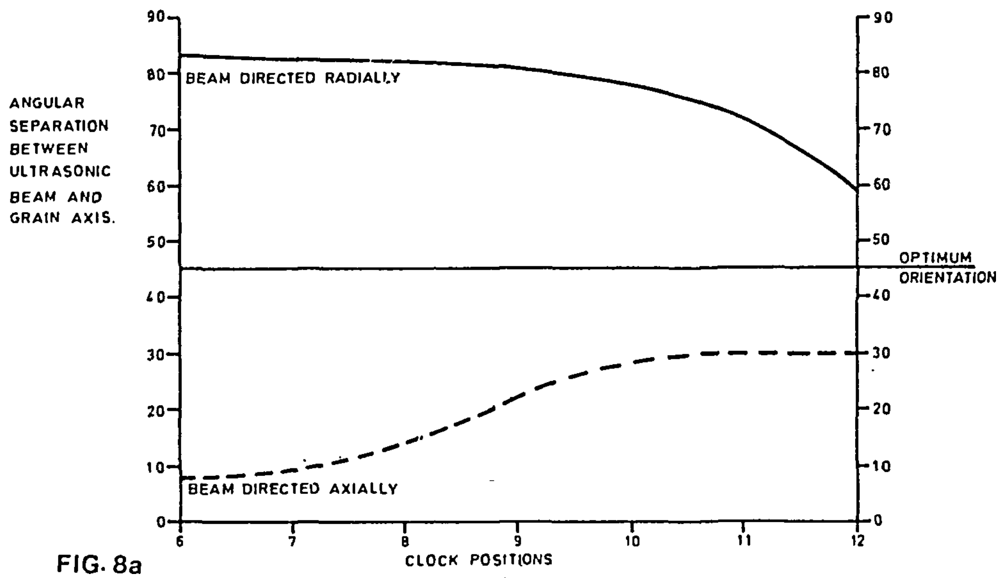


FIG. 8a

ANGLE BETWEEN COLUMN AXIS AND ULTRASONIC BEAM AS A FUNCTION OF CLOCK POSITION - 90° DEPOSITION ANGLE.

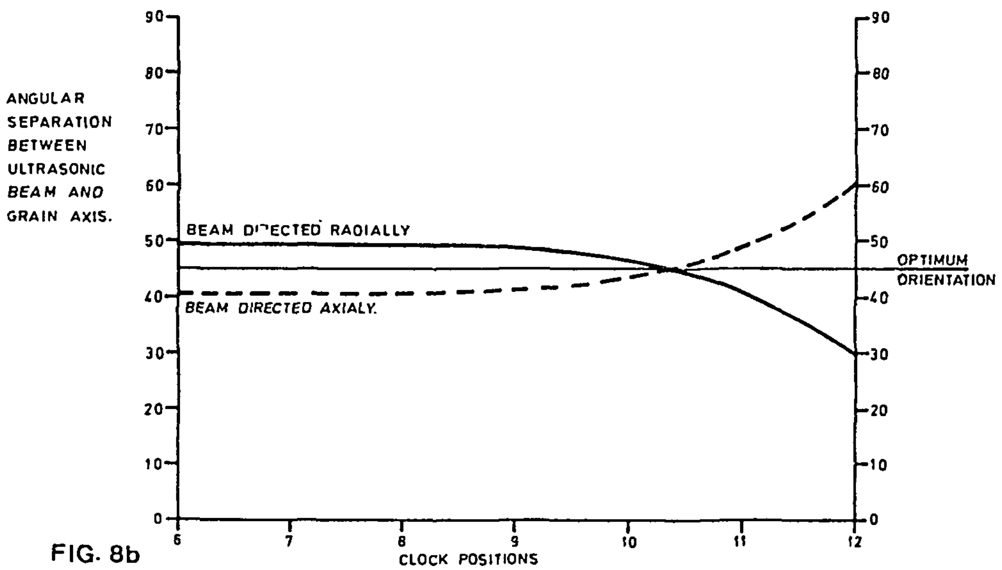
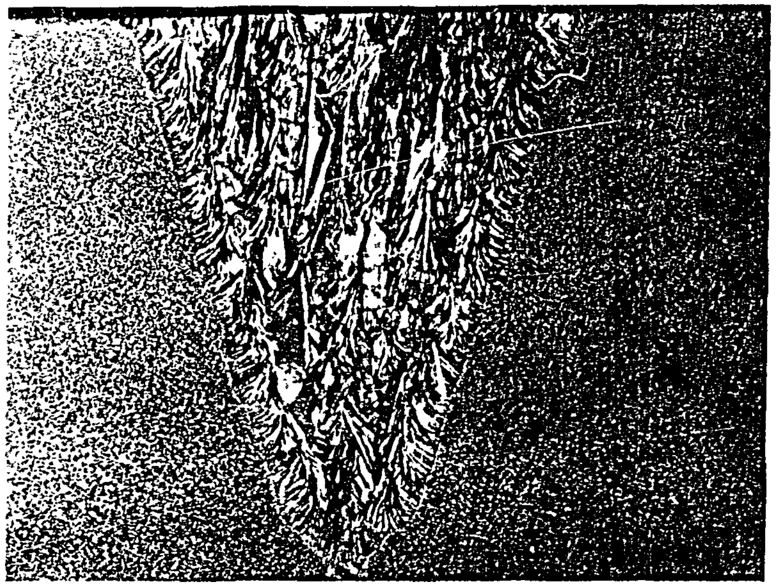


FIG. 8b

ANGLE BETWEEN COLUMN AXIS AND ULTRASONIC BEAM AS A FUNCTION OF CLOCK POSITION - 55° DEPOSITION ANGLE.



OPTICAL MICROGRAPH OF A 316 BUTT WELD.

FIG. 9.

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Introduction:

The primary loop components of the sodium cooled fast breeder reactor SNR 300 are built up by the high-temperature unstabilized austenitic steel X 6 CrNi 1811. The welded joints of these components are tested by ultrasound during production. Furthermore there will be the acceptance testing and the in-service inspection by ultrasound during shut-down periods. Because of the special conditions during these later tests (accessibility only from the outside, strong γ-activity, and high temperature) only an automatic inspection is possible. This paper reports on the development of a special ultrasonic testing technique for these purposes.

1. On the Mechanism of Ultrasonic Scattering

1.1 Description of the Grain Structure in Austenitic Weld Metal

During solidification of the weld metal there grow cellular or dendritic crystals whose fanning out depends on the velocity of solidification, on the concentration of segregating impurities and on the gradient of temperature [1]. Both types of growth have the common character that crystals grow predominantly in special crystallographic directions. Fig. 1 shows a micrograph of a part of an austenitic weld joint in the steel X 6 CrNi 1811. One can see the beads inside the weld joint. Furthermore one can see the characteristic texture inside each bead and in the left part of the picture the fine grained structure of the base material. The dendrites are directed perpendicularly to the sidewalls of the weld and grow perpendicularly to the isotherms of the solidifying weld metal. Thus curved dendrites in a fibrous structure run from the sidewalls of the weld to the centre of the weld surface. The fiber diameter is about 100 to 500 um. The fiber length reaches values up to 10 mm. The fibers occur in bundels with a diameter up to 1 mm. A limited extension of the grains in the weld could be reached by lowering the heat input during welding, i. e. by using lower currents and electrodes with smaller diameters, furthermore using higher welding speed and a greater number of beads. Furthermore one can use quick heat removal, to get a finer grained structure. Since the γ-α-transformation, i. e. the transformation of the face-centered cubic lattice into the body-centered cubic lattice, does not take place owing to the low cooling rate this leads to the formation of coarse grains in the austenitic weld metal which at first solidifies with a fine crystalline structure.

1.2 On the Ultrasonic Scattering in a Grained Structure

Ultrasonic scattering is observed only in polycrystalline materials and is caused by the grain structure and the changes of crystallographic orientations of the grains connected with this. The ultrasonic scattering depends on the wave length to grain diameter ratio. Three ranges are to be distinguished with different dependencies between the scattering parameter α_s, grain diameter D and ultrasonic wavelength λ:

- Rayleigh scattering $\frac{D}{\lambda} < 1; \quad \alpha_s \cdot D \sim \left(\frac{D}{\lambda}\right)^4$
- Stochastic scattering $\frac{D}{\lambda} \approx 1; \quad \alpha_s \cdot D \sim \left(\frac{D}{\lambda}\right)^2$
- Diffuse scattering $\frac{D}{\lambda} > 1; \quad \alpha_s \cdot D \sim \left(\frac{D}{\lambda}\right)^0 = 1$

Due to resonance effects in the stochastic scattering range (formation of standing waves in single grains) the scattering parameter here is greater than in the Rayleigh scattering and the diffuse scattering ranges [e. g. 2]. For a fibrous texture existing in the weld (fig. 1) the scattering mechanism depends on the angle between the ultrasonic beam and the fiber axis in the weld.

The effective grain diameter for an insonation of the weld seam in direction of the fiber axis is considerably smaller than for an insonation normal to the fiber axis [3, 4, 5, 6].

The ultrasonic inspection of austenitic welds is carried out using both longitudinal and transversal waves with a wavelength of about 3 mm. Since for the ultrasonic inspection with angle beam transducers the incident angles are between 45° and 70° in the austenitic workpiece, the orientation between the ultrasonic beam and the fiber direction in the weld is not always ideal. Therefore stochastic scattering occurs in most cases.

Precipitations, especially of carbides, have no measurable effect on the scattering parameter [3]. δ-ferrit, a concentration of which is desirable up to 5 percent in the high-temperature austenitic welds of steel X 6 CrNi 1811 to avoid hot-cracks [7, 8], does not influence the ultrasonic wave propagation even when it occurs in concentrations up to 30 percent [6]. The higher ultrasonic scattering in austenitic steels - compared with ferritic steels - is caused solely by the coarser grain. For equal grain size the ultrasonic attenuation, made up by ultrasonic absorption and ultrasonic scattering, is the same in ferritic and austenitic steels [9]. This is shown in fig. 2 too: The ultrasonic attenuation of longitudinal and transversal waves in austenitic steel X 6 CrNi 1811 does not differ from values of common ferritic steels. Ultrasonic attenuation of the welded joints measured normal to the surface is higher by a factor of 10 and rises greatly for shorter wavelengths. The attenuation of longitudinal and transversal waves does not vary significantly in the wavelength range under consideration. These results are in agreement with those of other authors [9]. Therefore both wave types are used for the ultrasonic inspection of austenitic welds. To secure a high probability of flaw detection the application of rather short wavelengths is advantageous. Because of the strong rise of attenuation at shorter wavelengths the use of a wavelength of 3 mm is a favourable compromise. Then the transducer frequency is approximately 2 MHz when using longitudinal waves and 1 MHz for transversal wave transducers.

1.3 Possible Techniques to Avoid Disturbing Influences of Ultrasonic Attenuation on Flaw Detection

The use of common single probe ultrasonic techniques in weld testing is not possible, since increased scatter echoes cause a low signal-to-noise ratio. For testing austenitic steel weld joints therefore one has to develop special techniques by which the noise level (grass) caused by grain scattering is decreased.

The testability of austenitic welds by ultrasound depends on the welding structure as mentioned above. Therefore general statements on the applicability of a certain technique are not possible. But in every case the testing technique has to be adapted to the special problem.

Different techniques are possible:

a) Transmitter-Receiver Technique with Separate US-Transducers [10 - 17]

The directional lobes of the two transducers (transmitter and receiver) are inclined towards one another and cross in a given area, i. e. in the sensitivity range of the probe. The advantage of this method over the normal "pulse echo" technique is that only echoes coming from this area are registered. Such an acoustical localisation leads to the desired diminishing of the structural scatter echoes. The noise level for a flaw echo is given by all scatter echoes including multiple scattering which have the same propagation time as the flaw echo. Therefore not only the lateral extension of sensitivity but also the extension of the sensitivity area between probe and flaw determines the amplitude of the noise. From the latter region echoes from multiple scattering may originate, which are higher the nearer the origin is located to the receiver.

b) Focussing Probes

By focussing the sound beam a limitation of the sensitivity area is also obtained. An increase of sound amplitude at the focal point leads to a higher signal-to-noise ratio. A disadvantage of focussing probes is their poor dynamic behaviour together with a rather narrow screen line distance. Furthermore these probes have often large outer dimensions. Focussing probes are used above all in France [18].

c) Multifrequency Probes

The structure of the dendrites in the weld metal is more or less periodic. Therefore interferences of the echoes coming from this structure lead to a periodic sound pattern of maxima and minima. The distance from one maximum to another depends on wavelength (frequency) of the sound and the average periodic distance between dendritic bundles. That means by moving the probe the noise coming from the scatter echoes runs through maxima and minima in amplitude depending on the sound frequency whereas an echo coming from a single flaw remains constant. When using a probe consisting of several transducers with different frequencies, chosen to correspond to the special grain structure in the weld, their maxima and minima of noise compensate one another if the different transducer signals are superposed e. g. by correlation analysis, whereas the echo from a single flaw is increased by superposition and becomes detectable [19].

The transducers of the receiver probe usually take the form of concentric rings with different resonance frequencies. Difficulties arise from the different vibration modes of each ring.

d) Probes with Broadband Transducers

For the ultrasonic testing of strongly scattering materials, it is more favourable to use broadband ultrasonic pulses. The signal-to-noise ratio of such short-time pulses is better because of their shorter coherence length.

Moreover, their local resolution for reflectors lying very close together is better.

2. Application of Transmitter-Receiver Technique

The main part of these investigations was concerned with further developing the transmitter-receiver technique. Since some knowledge was on hand on this technique it seemed to be most favourable to bring this technique to practical use within a short time. Meanwhile the probes for the testing of longitudinal defects in austenitic steel weld joints were tried out successfully (fig. 3). The problem of transverse defect detection could not be adequately solved. This problem will be considered shortly below.

2.1 Ultrasonic Testing on Longitudinal Defects

2.1.1 Description of the Probe Concept

Fig. 4 shows schematically the design of the transmitter-receiver-probe. The range of sensitivity of a T/R-probe is the crossing section of the directional lobes. The transmitter membrane generates a certain sound pressure distribution in the material which is described by the directional pattern. It depends on the shape of the membrane, on its frequency, on the material of sound penetration and on the direction of insonation. Calculated and experimental results show that for point reflectors the directional lobe of the receiver membrane corresponds to the directional lobe of the transmitter arranged in the same way.

For a usable signal-to-noise ratio a limited sensitivity range is necessary. For the testing of thick walled parts therefore several angular beam T/R-probes have to be employed whose sensitivity ranges cover the whole welding area under inspection. The dimension of the sensitivity ranges depends on the smallest reflector that has to be detected safely, that is with a signal-to-noise ratio of at least 10 dB. For defining a registration limit a 3 mm-disc-shaped reflector has been employed as equivalent flaw size. Experiments with T/R-probes of different sensitivity ranges showed that the testing zones should have a dimension of 15 mm in both lateral and azimutal directions. The sensitivity at the zone edges then decreases by not more than 6 dB. A weld seam of 60 mm thick plates has to be divided into four overlapping testing zones. At the same time by this division the scanning pattern is defined.

Since the US-testing with T/R-probes is performed within half the skip distance the incident angle depends mainly on the depth of the testing zone. The incident angle, however, has to be adapted to the preferred orientation of the expected flaws, if possible. According to preliminary investigations in developing an atlas of defects in austenitic welds it is assumed that flat defects (two-dimensional separations of material) in the weld (e. g. lack of side wall fusion) are orientated parallel to the weld side walls and approximately normal to the surface of the plate. Because of the directional lobes of these flaws the application of large incident angles is favourable. For a 60 mm thick weld the following angles are suitable: $\beta = 70^\circ$ for the surface zone, 65° for the second, 60° for the third and 45° for the lowest zone, since in this case the mirror effect is exploited for flaw detection.

The sensitivity range of the probes generated by the crossing beams is placed in the transducer's far field. The required transducer dimensions have to be calculated taking into account a fixed zone width of 15 mm in lateral and azimutal directions and the condition that the sensitivity decrease should be 6 dB at the zone edges.

This can be done using the Kirchhoff diffraction theory in the Fraunhofer approximation which describes the sound pressure distribution in the far field. The transducer surface is treated as a diffracting aperture, which is illuminated normally by waves possessing the eigenfrequency of the transducer. The mathematical solution of the problem of waves penetrating obliquely through the interface between the two media, wedge and specimen, is complicated. Therefore, for simplification, the excited surface of the specimen is treated as a diffracting aperture (fig. 5) [20] which is illuminated with pressure or shear waves under the beam angle in the workpiece.

The Kirchhoff integral [21] gives the sound pressure distributions of longitudinal waves in the Fraunhofer approximation [20]:

$$p_l(\beta,\delta) = \frac{a \cdot b}{\cos\beta_K} \cdot b_l(\beta) \cdot b_l(\delta) \cdot \frac{\sin x}{x} \cdot \frac{\sin y}{y}$$

The meaning of the symbols is as follows:

$$x = \frac{a \cdot \pi \cdot f}{c_{l,St} \cdot \cos\beta_K}\left(\sin\beta - \sin\beta_K \cdot \frac{c_{l,St}}{c_{l,K}}\right)$$

$$y = \frac{b \cdot \pi \cdot f}{c_{l,St}} \cdot \sin\delta$$

Azimutal directional lobe for longitudinal waves:

$$b_l(\beta) = \frac{2 - 4 \cdot \sin^2\beta \cdot \left(\frac{c_{t,St}}{c_{l,St}}\right)^2}{N_l(\beta)}$$

$$N_l(\beta) = \left[1 - 2\left(\frac{c_{t,K}}{c_{l,St}}\right)^2 \sin^2\beta\right]^2 \cdot \frac{\varrho_K}{\varrho_{St}} \cdot \frac{1}{\sqrt{\left(\frac{c_{l,St}}{c_{l,K}}\right)^2 - \sin^2\beta}} +$$

$$+ 4\left(\frac{c_{t,K}}{c_{l,St}}\right)^4 \cdot \frac{\varrho_K}{\varrho_{St}} \cdot \sin^2\beta \cdot \sqrt{\left(\frac{c_{l,St}}{c_{t,K}}\right)^2 - \sin^2\beta} +$$

$$+ 4\left(\frac{c_{t,St}}{c_{l,St}}\right)^4 \cdot \sin^2\beta \sqrt{\left(\frac{c_{l,St}}{c_{t,St}}\right)^2 - \sin^2\beta} +$$

$$+ \frac{1}{\cos\beta}\left[1 - 2\left(\frac{c_{t,St}}{c_{l,St}}\right)^2 \cdot \sin^2\beta\right]^2$$

β = azimutal angle of incidence (plane of incidence)
δ = horizontal angle
c = velocity of sound
ϱ = density

Indexes:

K = probe wedge
St = material (steel)
l = longitudinal wave
t = transversal wave

The expression for the directional lobe $b_l(\delta)$ can be derived by analogy to $b_l(\beta)$.

The pressure distribution $p_l(\beta, \delta)$ corresponds to the diffraction pattern of a rectangular slit in optics with illumination incident from one side of the lit (fig. 6).

The pressure distribution of shear waves in the Fraunhofer approximation is [20]:

$$p_t(\beta,\delta) = \frac{a \cdot b}{\cos\beta_K} \cdot C_t(\beta) \cdot \frac{\sin x}{x} \cdot \frac{\sin y}{y}$$

The meaning of the symbols is as follows:

$$x = \frac{a \cdot \pi \cdot f}{c_{t,St} \cdot \cos\beta_K} \left(\sin\beta - \sin\beta_K \cdot \frac{c_{t,St}}{c_{l,K}} \right)$$

$$y = \frac{b \cdot \pi \cdot f}{c_{t,St}} \cdot \sin\delta$$

Azimutal directional lobe for shear waves:

$$C_t(\beta) = \frac{4 \sin\beta \cdot \cos\beta \cdot \sqrt{\left(\frac{c_{t,St}}{c_{l,St}}\right)^2 - \sin^2\beta}}{N_t(\beta)}$$

$$N_t(\beta) = \left[1 - 2\left(\frac{c_{t,K}}{c_{t,St}}\right)^2 \cdot \sin^2\beta\right]^2 \cdot \frac{\rho_K}{\rho_{St}} \sqrt{\frac{\left(\frac{c_{t,St}}{c_{l,St}}\right)^2 - \sin^2\beta}{\left(\frac{c_{t,St}}{c_{l,K}}\right)^2 - \sin^2\beta}} +$$

$$+ 4\left(\frac{c_{t,K}}{c_{t,St}}\right)^4 \cdot \frac{\rho_K}{\rho_{St}} \cdot \sin^2\beta \sqrt{\left(\frac{c_{t,St}}{c_{t,K}}\right)^2 - \sin^2\beta} \cdot \sqrt{\left(\frac{c_{t,St}}{c_{l,St}}\right)^2 - \sin^2\beta} +$$

$$+ 4 \sin^2\beta \cdot \cos\beta \cdot \sqrt{\left(\frac{c_{t,St}}{c_{l,St}}\right)^2 - \sin^2\beta} + \cos^2\beta$$

The square of the sound pressure p represents rather well the superposition of the pressure distributions of the transmitting and of the receiving transducer membrane in a T/R-probe that is to say the sensitivity distribution of the T/R-probe as a function of the effective angle in the specimen. Fig. 7 shows, as an example, the azimutal sensitivity distribution of the T/R-probe for pressure waves (SEL 2), calculated with the above formulas.

The transducer length, a, and the angle of incidence in the steel specimen, β, together determine the vertical extension of the sensitivity area of the probe. The width of the transducer, b, determines the lateral extension of the sensitivity area and therefore defines the width of the scanning line during testing.

If inversely, the extension of the testing zone is specified by the permissible signal-to-noise ratio one has to calculate the transducer dimensions. Since the set of equations is not solvable in every case one has to use an iterative method to determine a and b.

A first approximation gives for the condition $\frac{a}{\lambda}$; $\frac{b}{\lambda} \gtrsim 4$ a transducer length

$$a \approx 48{,}35 \cdot \frac{c_{St}}{f \cdot \Delta\beta} \cdot \frac{\sqrt{1 - \left(\frac{c_K}{c_{St}}\right)^2 \sin\beta_M}}{\cos\beta_M}$$

and a transducer width

$$b \approx 48{,}35 \cdot \frac{c_{St}}{f \cdot \Delta\delta}$$

The meaning of the symbols is as follows:

β_M = angle of incidence of the main beam = β

$\Delta\beta$ = azimutal aperture angle of the ultrasonic beam defined by a decrease of sensitivity of 6 dB from the maximum

$\Delta\delta$ = horizontal aperture angle

These three values are defined by the position and extension of the testing zone.

When computing $\Delta\beta$ and $\Delta\delta$ one has to consider the whole sound path, s_{total}, made up by the path in the specimen and the equivalent path in the wedge of the probe:

$$S_{total} = S_{St} + \frac{c_K}{c_{St}} S_K$$

Using the transducer dimensions, a and b, approximately determined one has to pass several iterative steps with the aid of the above formulas describing the sound pressure in the far field to match the transducers dimensions to the specified testing zone.

Furthermore the dimensions of the wedge have to be computed (fig. 8). These values result from geometrical considerations:

Wedge angle:

$$\sin\beta_K = \frac{c_K}{c_{St}} \cdot \sin\beta_{St}$$

$$\tan\beta' = \left(1 - \frac{k^2}{t^2 \cdot \tan^2\beta_{St}}\right)^{1/2} \cdot \tan\beta_K$$

$$\sin\beta'' = \frac{k}{t} \frac{\sin\beta_K}{\tan\beta_{St}}$$

$$\tan\beta''^{*} = \frac{k}{t} \frac{\tan\beta_K}{\tan\beta_{St}} ; \qquad k = \frac{b}{2\cos\beta'^{*}} + 1$$

Wedge height:

$$H = h + a \cdot \sin\beta_K$$

Wedge length:

$$L = b \cdot \cos\delta' + \sin\delta'\left(\frac{a}{2}\frac{1}{\cos\beta_K} + \frac{a}{2}\cos\beta_K + h\tan\beta_K\right)$$

Wedge width:

$$B = b \cdot \sin\delta' + \cos\delta'\left(\frac{a}{2}\frac{1}{\cos\beta_K} + \frac{a}{2}\cos\beta_K + h\tan\beta_K\right)$$

Edge heights of the wedge:

$$E_1 = h - b\sin\delta'\cos\delta'\tan\beta_K - \frac{a}{2}\sin\beta_K$$

$$E_2 = h + \frac{a}{2}\sin\beta_K\left(\frac{\cos^2\delta'}{\cos^2\beta_K} - \sin^2\delta'\right) + h\cos^2\delta' \cdot \tan\beta_K$$

The meaning of the symbols is shown in fig. 8. For the calculation of the dimensions of the wedge the height of the membrane will be estimated. By iteration the height of the membrane will be optimized such that the height of the edges E_1 and E_2 will be in the range 2 ... 5 mm.

In the probe both wedges on which the transmitting and the receiving membranes are mounted, are acoustically isolated from each other, e. g. by a layer of cork.

An improved suppression of reflections from coarse grained structure was obtained by the use of short, broad-banded ultrasonic pulses.

Broad-banded ultrasonic pulses can be obtained by mechanically damping the ultrasonic membrane. This is done by gluing a damping mass on to the backside of the membrane. The damping mass consists of an epoxid-tungsten-mixture which has an acoustical impedance similar to that of the membrane material. If both materials have similar acoustical impedances, the membrane will emit ultrasonic shock waves on exitation. Damping of an oscillating system like an ultrasonic membrane means always a loss of sensitivity. This must be compensated for. Provisions must be made to get a high amplitude of the ultrasonic signal, to improve the sensitivity of the whole testing system. This is done by matching the electrical impedances of the parts of the system, which consists of probe, cable, transmitter and receiver.

In fig. 9 the form of ultrasonic pulses obtained from a damped membrane and from the same membrane without any damping are compared.

Transmitter receiver probes which emit pressure waves will according to Snellius' diffraction law always transmit a shear wave into the material too. A characteristic of the directivity pattern of the shear wave in steel is that under an angle of about 33^{o} the shear wave does not exist [e. g. 22]. The problem is to choose the angle, β_k, of the wedges and the length, a, of the membrane in such a way that the shear wave will be transmitted into steel at an angle smaller than 30^{o}.

In fig. 10 it is shown that in this case, outside the very narrow beam only very small amplitudes of sound pressure of the shear wave exist. If the angle between the directional lobes of transmitter and receiver is large enough, it can be obtained that the shear wave lobes of transmitter and receiver cross each other in an area of the workpiece from which interference echoes do not superpose on the reflection signals from the testing zone.

T/R-probes with following specifications have been made:

	SEL 1	SEL 2	SEL 3	SET 4
Testing Zone	0 - 15 mm	15 - 30 mm	30 - 45 mm	45 - 60 mm
Frequency	2 MHz	2 MHz	2 MHz	1 MHz
Angle of Incidence (β)	70^{o}	65^{o}	60^{o}	45^{o}
Dimensions of Transducer Membranes a . b	14 . 7 mm^2	22 . 11 mm^2	24 . 12 mm^2	24 . 12 mm^2

The probe casings are of uniform size (fig. 3): length . width . height = 38 mm . 38 mm . 27 mm, the coupling surface having the dimensions length . width = 32 mm . 34 mm.

2.1.2 Measurement of the characteristics of the probes

The distribution of sensitivity of the transmitter-receiver angular probes can be measured in our house very easily. The experimental apparatus is schematically shown in the upper part of fig. 11. The

lobes of transmitting and receiving membrane are cut through perpendicular to the surface of the test piece to which the probe is coupled, in varying projection distances, $a_{proj.}$ from the probe. This is achieved by varying the distance of the probe from a measuring plane, which is perpendicular to the surface of the test piece. In this plane the distribution of sound pressure will be scanned with the aid of an electrodynamical probe.

The transmitting and receiving membranes will be separately excited with the same electrical pulse. The resulting distributions of sound pressure will be separately registered (fig. 11, second and third line of drawings). After multiplication of both distributions the sensitivity distribution of the probe can be obtained (1st line, fig. 11). In the center row, first line of drawings the sensitivity distribution of the probe is shown. Below, the sound pressure distributions of the two membranes, named A and B, are registered in the crossing area. The first and the last row of drawings show these distributions just in front of and behind the crossing area for the probe SEL 2.

The solid lines in these figures are the isobars of the sound fields. In the center of the concentric rings the highest sound pressure is found. It decreases continuously towards the outer regions of the beam. Considering the specially interesting case of the sensitivity distribution of the probe in the crossing area of the main beams (fig. 11, 1st line, 2nd row) one will find, that the sensitivity from the center to the next isobar decreases by two decibels, to the following by five decibels. This fulfils the requirement, that a testing zone of 15 . 15 mm^2 should be covered by the probe, the decrease of sensitivity to the edges of the testing zone being approx. six decibels.

From fig. 11 (1st line, 1st row) one can see that the highest sensitivity of the probe SEL 2 is already obtained in an area just in front of the crossing point of the main beams. This is due to the natural divergence of the sound beams. The lobes of the transmitting and receiving membranes are inclined towards one another. They begin to overlap already shortly before the crossing point of their main beams. Because of the smaller cross section of the lobes in that area it can be that the maximum sensitivity of the T/R-probe is situated shortly before the crossing point of the two main beams.

At present a computation model is being worked on which should be able to take into account this divergence effect in the computation of the probes.

2.2 Ultrasonic Testing on Transverse Defects

With the probes designed for detection of longitudinal defects the detection of transverse defects is satisfactorily possible in the upper testing zone only (fig. 12). For the lower zones it is necessary to separate the transmitting and the receiving part of the probe and to place them on the two sides of the weld seam to avoid the strong ultrasonic scattering from the weld metal (fig. 13). By this, long sound paths in the scattering weld metal do not occur. The angle between the directional lobes of the transmitting and of the receiving part of the probe is increased, but according to a guide line on testing weld joints with ultrasound by the German Society of Nondestructive Testing [23] it may not exceed the angle of 40°. By this increase of the angle between the lobes the probe width is enlarged up to 60 mm.

2.3 Results of Ultrasonic Testing Using T/R-Probes

Results of longitudinal flaw detection have been reported at various times [12 - 14]. Fig. 12 shows as example screen displays of echoes from cylindrical bore holes (diameter 3 mm) as longitudinal test reflectors in the weld joint. With flat bottom holes as longitudinal test reflectors (diameter 3 mm), orientated normal to the surface to which the probe is coupled, a signal-to-noise ratio of at least 10 dB could also be obtained in all testing zones.

Further, fig. 12 shows as an example a result of the transverse flaw detection in the testing zone 0 - 15 mm. A flat bottom hole (diameter 3 mm) which is placed in the weld joint normal to the surface to which the probe is coupled is taken as test reflector.

3. Ultrasonic Testing at Elevated Temperatures and Radiation Load, First Results of a Materials All-Out Search

In-service inspection of the tank of the sodium cooled fast breeder reactor takes place at 250°C and at a γ-activity of approximately 10^4 rad/h. Ultrasonic probes, media for acoustic coupling, cables and plugs have to withstand these conditions. The technological problem to find proper materials to build up the ultrasonic probes for application in in-service inspection seems to be solvable. This is the result of a preliminary materials all-out search.

Lithiumniobate and leadmetaniobate are eligible as ultrasonic transducer membranes. Lithiumniobate with a transition temperature $T_{Curie} \approx 1200$ °C answers well the testing conditions. But it is much more difficult to damp lithiumniobate mechanically than leadmetaniobate. Therefore for the time being leadmetaniobate is used having a transition temperature $T_{Curie} \approx 520$ °C.

The damping mass which is glued on to the backside of the membranes consists of a casting resin-tungsten mixture which is resistant to γ-radiation and to temperatures up to 260 °C.

For acoustic insulation between the parts of the probe silicon rubber is used.

As for the wedge material the use of plastics or glasses is opportune because of the relatively good matching of the acoustic impedance between these materials and liquid coupling media. Plastics are in advantage of glasses because of their better machining quality. A plastic material with proper temperature and radiation resistivity is polyimid. Using polyimid for the probe wedge the transducer membrane is glued to the wedge by a polyimid casting-resin.

As for the acoustic coupling media the use of silicon oils is provisionally planned. At present some research work is going on to solve the problem of a dry acoustical coupling at elevated temperatures.

For transmission of the electric signals coaxial cables with fiber glass - mica insulation will be used. Insulators and range spacers of the plugs are made of polyimid.

To transfer the concept of T/R angular beam probes to operational ranges at elevated temperatures it is essential to know the temperature dependence of the velocity of longitudinal and transversal waves both within the probe and the tank material, X 6 CrNi 1811. Fig. 14 shows as an example the measured velocity of sound in the steel X 6 CrNi 1811 and in the wedge material polyimid "VESPEL" as a function of temperature [24].

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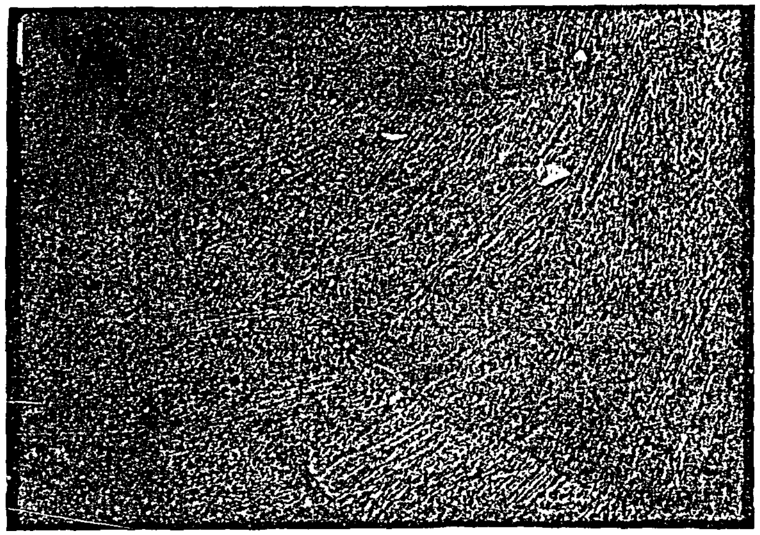


Fig. 1: Optical micrograph of a part of an austenitic weld joint in the steel X6 CrNi 1811

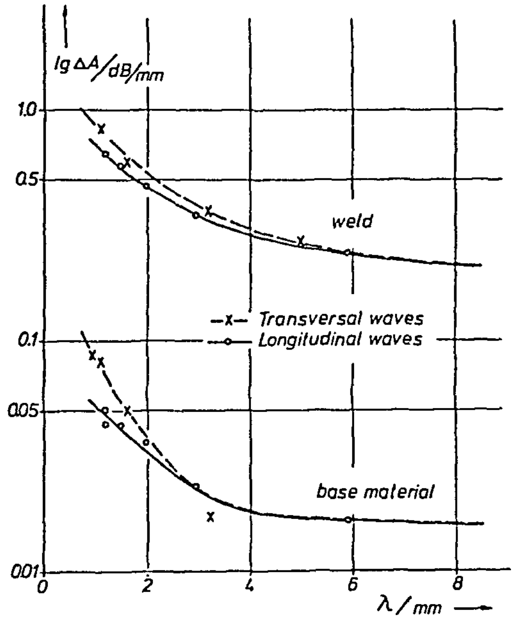


Fig. 2: Ultrasonic attenuation in austenitic base materi:l and in the weld material

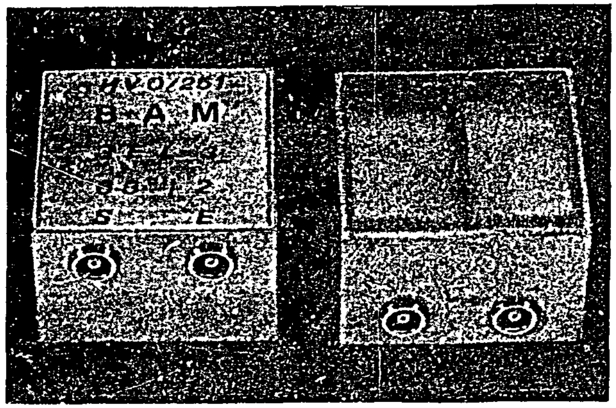


Fig. 3

Transmitter/receiver
ultrasonic probes

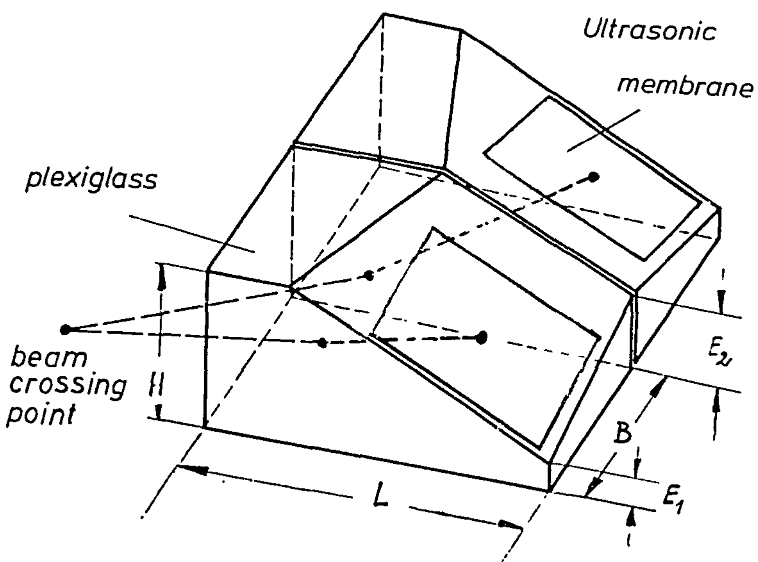


Fig. 4: Design of the transmitter/receiver probe

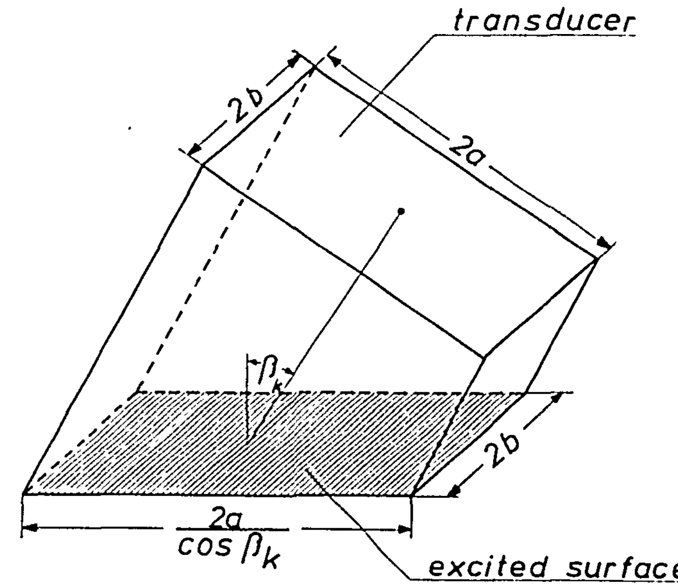


Fig. 5: The excited surface of the workpiece as a diffracting aperture

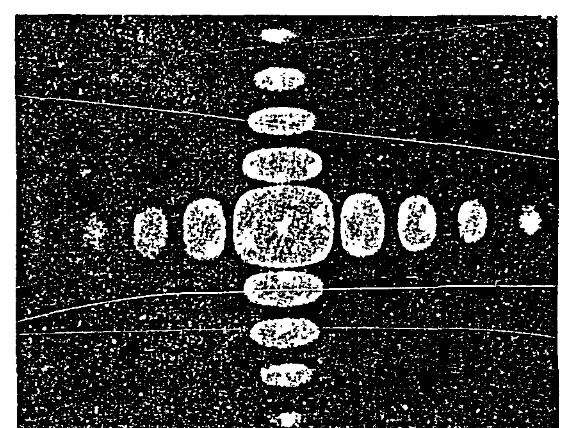


Fig. 6:

Fraunhofer diffraction pattern of a rectangular aperture 8 mm x 7 mm, magnification 5o x, mercury yellow light λ = 5790 Å. To show the existence of the weak secondary maxima the central portion was overexposed. (After H. Lipson, C. A. Taylor, B. J. Thompson /21/)

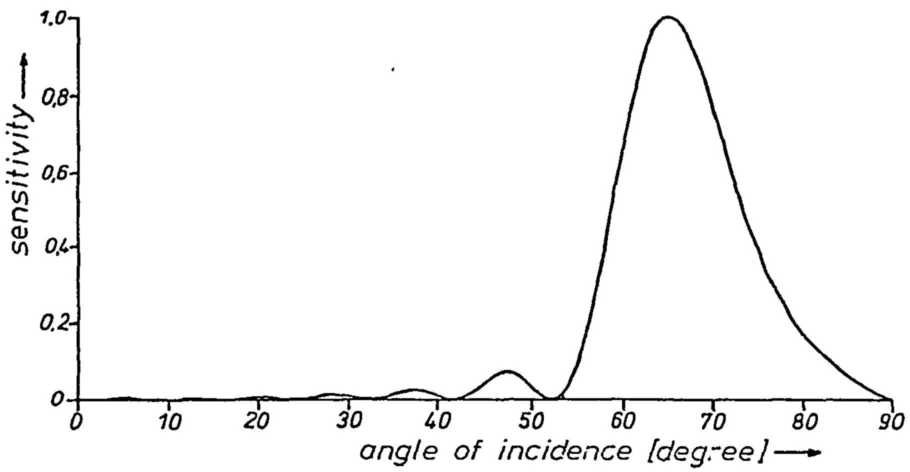


Fig. 7: Calculated azimutal sensitivity distribution $p_1^2(\vartheta)$ (longitudinal waves) of the T/R angular probe SEL 2

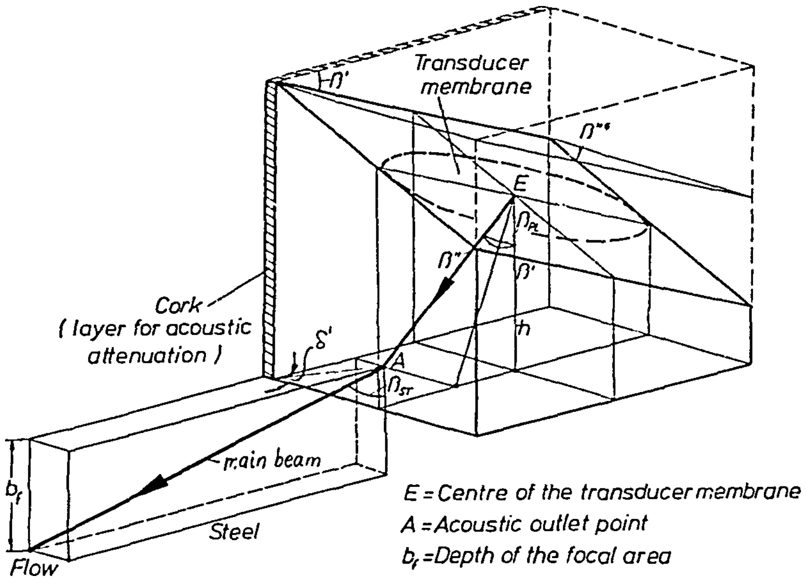


Fig. 8: Probe wedge geometry

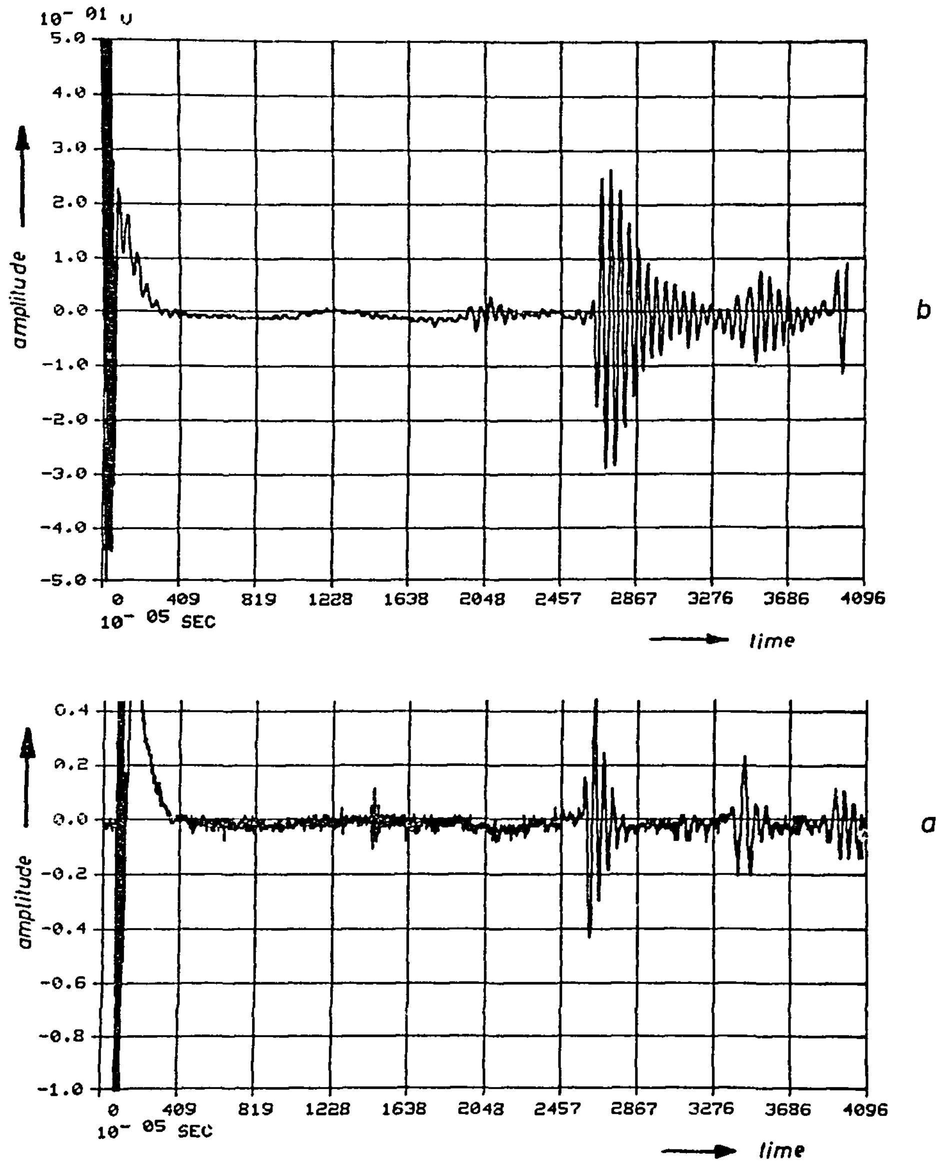


Fig. 9: Comparison between ultrasonic pulses obtained from a damped membrane (fig. 9a) and from the same membrane without any damping (fig. 9b). T/R-probe SEL 2, reflector: Cylindrical bore hole (Ø 3 mm) in a depth of 24 mm

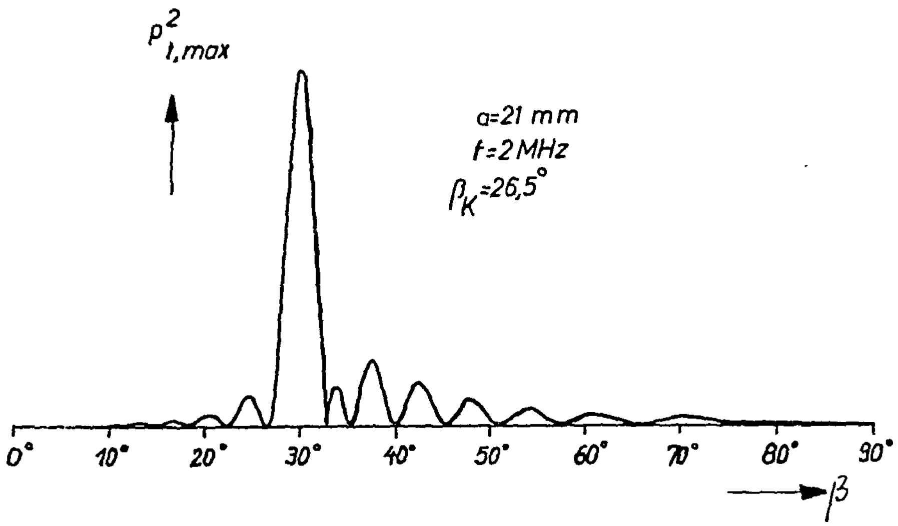


Fig. 10: Calculated sensitivity distribution $p_t(\beta)$ of ultrasonic transversal waves in austenitic steel

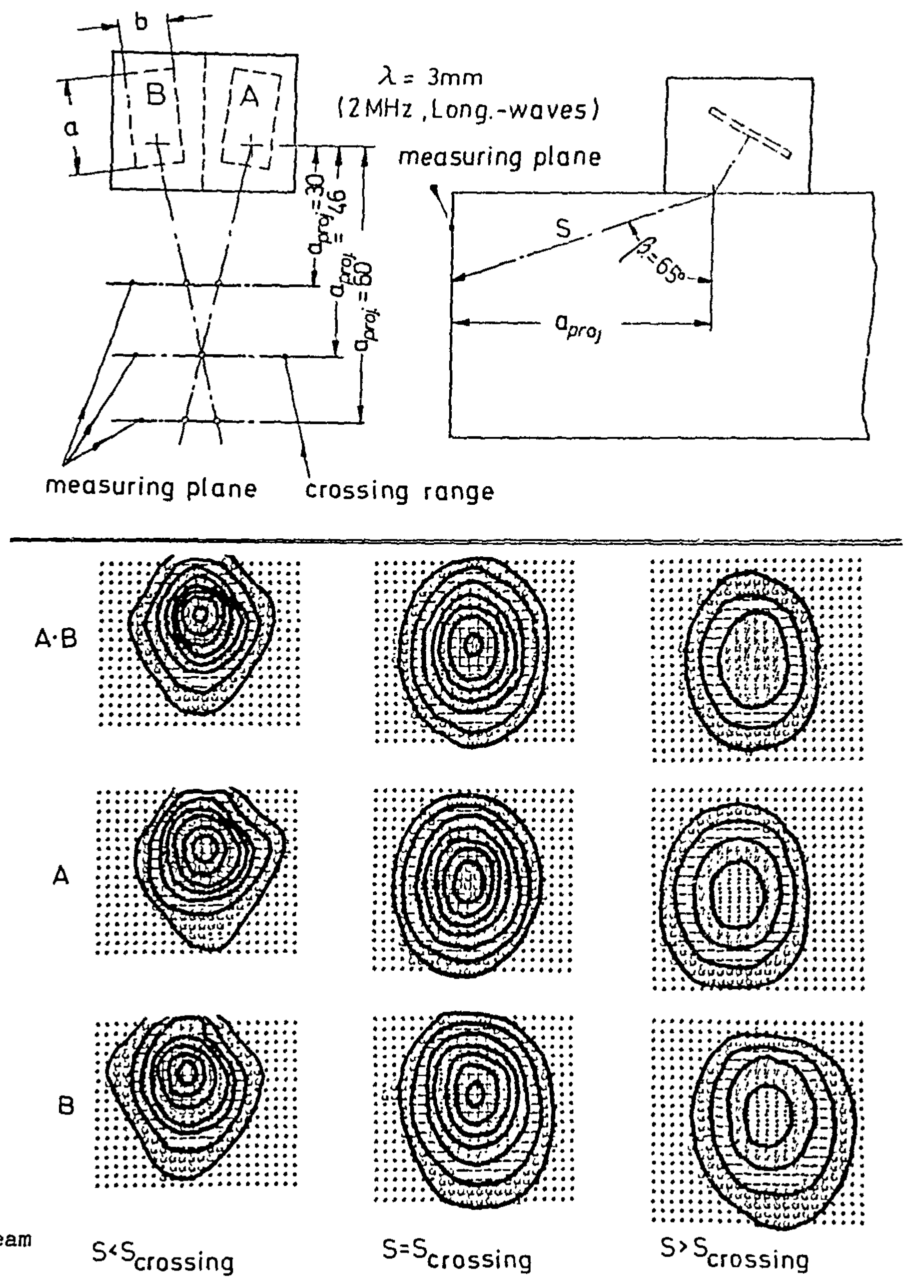
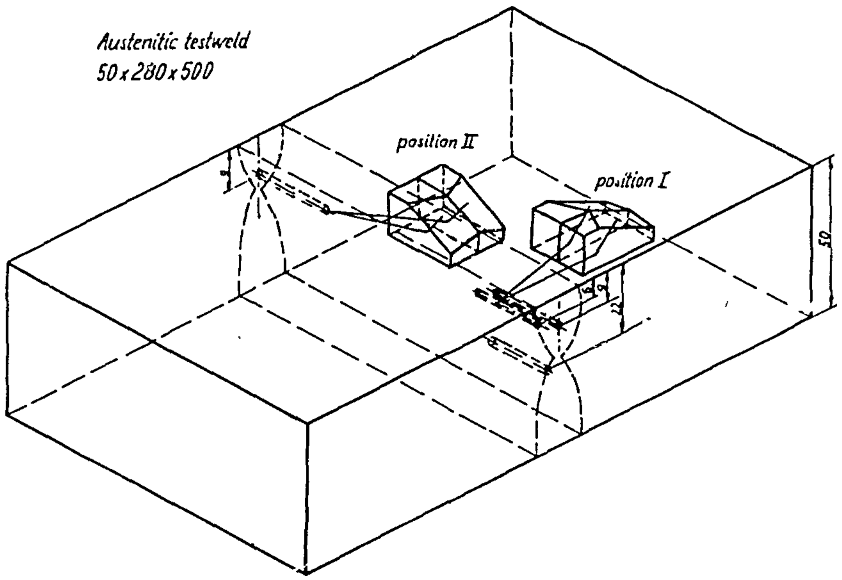


Fig. 11:

Sensitivity and pressure distribution in the beam cross section for the T/R angular probe SEL 2



1. CYLINDRICAL DRILL HOLE, DIAMETER 3 MM, AS ARTIFICIAL LONGITUDINAL FLAW.

   COMPLETE SOUND TRANSMISSION OF THE WELD, DEPTH = 6 MM

   PROBE: SEL 1

   POSITION I

   S/N = 14 DB

2. CYLINDRICAL DRILL HOLE, DIAMETER 3 MM, AS ARTIFICIAL LONGITUDINAL FLAW.

   HOLE IN THE MIDDLE OF THE WELD, DEPTH = 9 MM

   PROBE: SEL 1

   POSITION I

   S/N = 22 DB

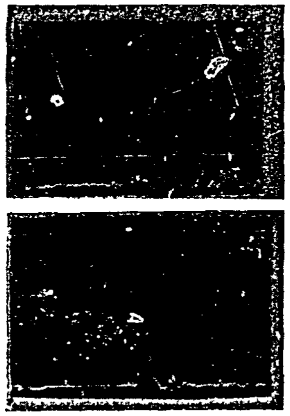


Fig. 12, p.1

3. FLAT BOTTOM HOLE, DIAMETER 3 MM, DEPTH = 9 MM, AS ARTIFICIAL TRANSVERSE FLAW IN THE MIDDLE OF THE WELD

   PROBE: SEL 1

   POSITION II

   S/N = 12 DB

4. CYLINDRICAL DRILL HOLE, DIAMETER 3 MM, AS ARTIFICIAL LONGITUDINAL FLAW.

   COMPLETE SOUND TRANSMISSION OF THE WELD, DEPTH = 22 MM, LOW DAMPING

   PROBE: SEL 3

   POSITION I

   S/N = 14 DB

5. CYLINDRICAL DRILL HOLE, DIAMETER 3 MM, AS ARTIFICIAL LONGITUDINAL FLAW.

   COMPLETE SOUND TRANSMISSION OF THE WELD, DEPTH = 22 MM, HIGH DAMPING

   PROBE: SEL 3

   POSITION I

   S/N = 19 DB

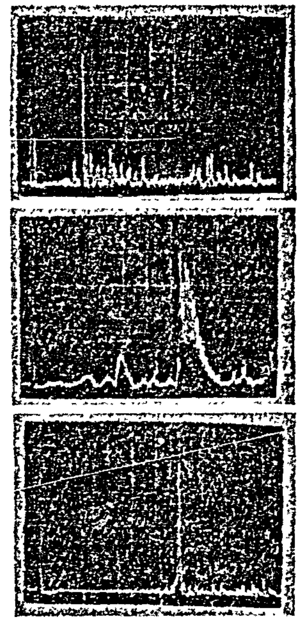


Fig. 12: Results of longitudinal and transversal test flaw detection

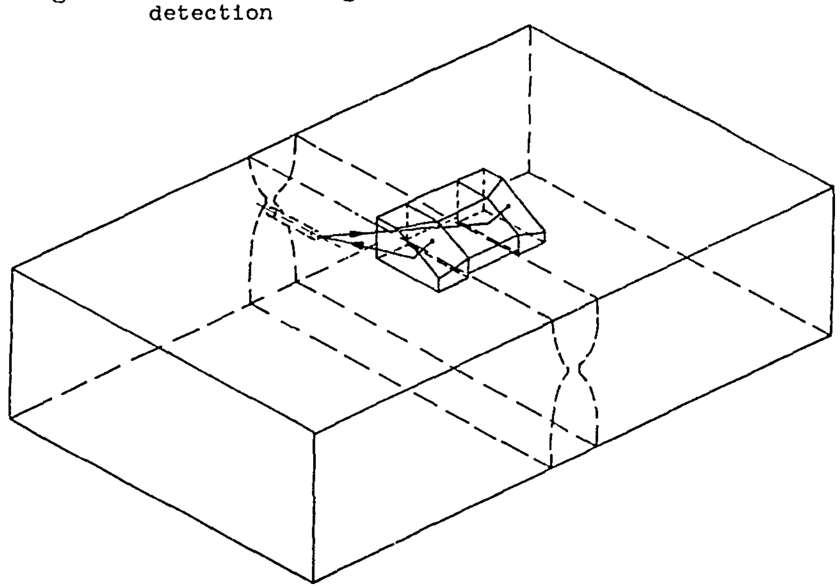


Fig. 13: Draft of a T/R-angular probe for transversal flaw detection

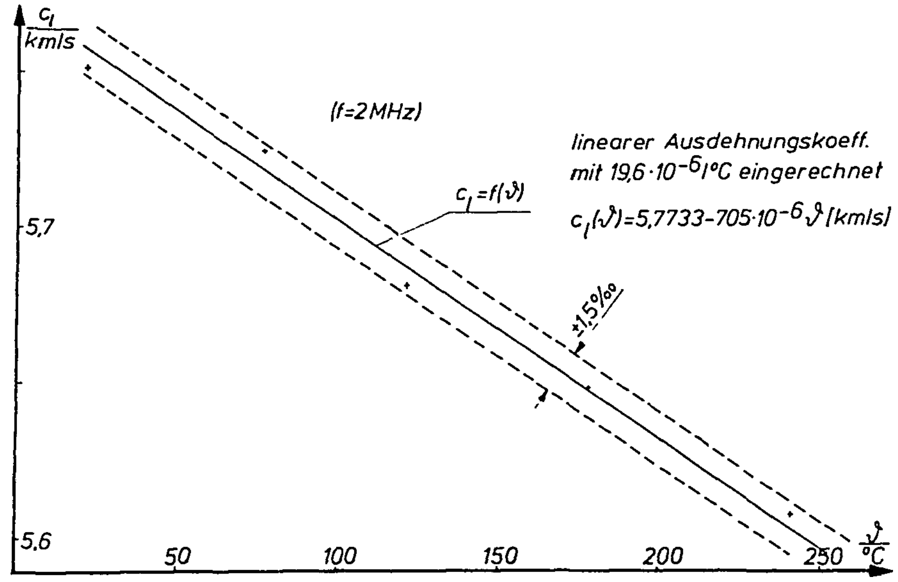


Fig. 14a: Velocity of ultrasonic longitudinal waves in steel X6 CrNi 1811 as a function of temperature

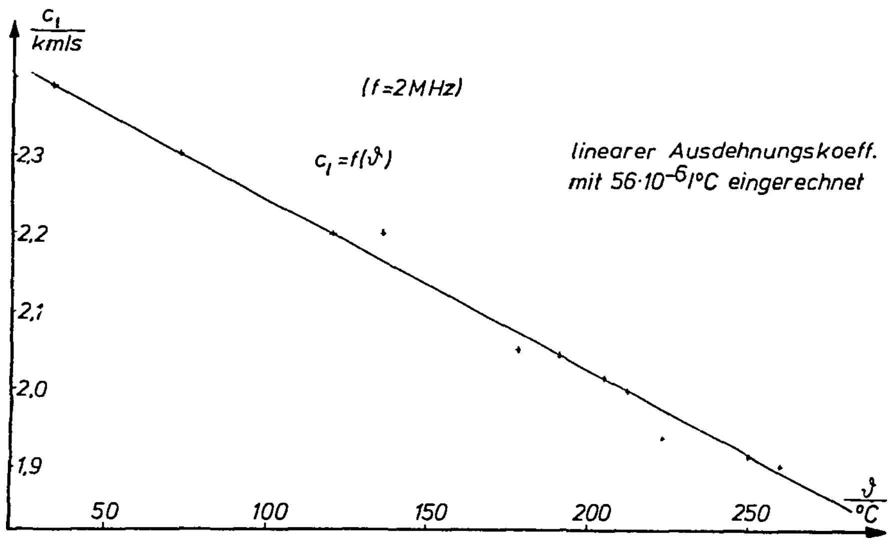


Fig. 14b: Velocity of ultrasonic longitudinal waves in polyimid "VESPEL" as a function of temperature

W. Haesen, Th. J. Tromp, "Ultrasonic Testing, State of the Art and Possible Developments". (The Netherlands)

1. INTRODUCTION

Inspection techniques for periodic testing are of current interest for the SNR-300 components. For periodic testing it is necessary to "fingerprint" the components. Since the pumps and steam generator are under construction it was necessary to asses what the state of the art is at this moment for the time that the "fingerprinting" has to be done is quite near. Because ultrasonic testing is considered an important method we made a survey of what is available to us, as a manufacturer of LMFBR components, at this moment. As a results of this we got a better understanding of what is needed in the future. The problem for the manufacturer of components is that he has probably no experience in all sophisticated NDT-techniques. However he has to use or prescribe these techniques.

2. AVAILABLE TRANSDUCERS

For inservice inspection purposes one has to "fingerprint" the components before they go on stream. The first periodic tests of the SNR-300 may still be some years away however this does not mean that we have these years available for development. Because we assume that the "fingerprinting" will have to be done during manufacturing of the components or in the acceptance test period. This means that we have to rely on the techniques that are presently available.
The best transducers which are operational for the SNR-300 components, which are under construction now, are:

2.1 Transmitter/receiver focused prism transducer operating in the longitunal mode at 2 MC/s.

2.2. The same as 2.1. but operating in the transverse mode.

2.3. Transducers according to 2.2. but designed for near surface flaws.

2.4. Specialised transducers for internal bore welds of the focused single crystal type operating in the transverse mode.

2.5. Custom made transducers for tube/tube welds in steam generators. They consist of a twin arrangement of focused single crystals which can scan the weld in two passes.

3. CAPABILITIES OF THE TRANSDUCERS

3.1. Type 2.1.: designed for austenitic weld material; a flat bottom hole of 3 mm Ø in the direction of the beam axis can be detected with a signal to noise ratio of 10 dB.

3.2. Also designed for austenitic weld material, the application depends on the weld texture. These transducers can have the same detection capability however in most cases only at a signal to noise ratio of 5 dB. Wavetransformation by these transducers are far less than with the longitudinal type.

3.3. Type 2.3. will detect flaws in the upper 2 to 3 mm of a weld. The weld has to be grinded flat for inspection. by means of this transducer.

3.4. Type 2.4.

On the inside and outside of the weld, a hole of 1 mm diameter and a depth of 1 mm is at least detectable. Some preliminary tests showed that detection of holes of 0.2 mm depth is possible.

3.5. Type 2.5.

Since the "double wall" X-ray technique is not capable of finding signs of lack of fusion in tube to tube welds it was necessary to find an alternative. Ultrasonic testing provided an answer.
These transducers were tested and it has been showed that lack of fusion can be detected.

It should be mentioned that the transducers type 2.1. and 2.5. are of recent design and little experience is available to date. Therefore no standards are available for these probes. The probes have actually one specific purpose, which is: to generate statistical data on which future standards may be based.

The flaw detectability in ferritical material, the maximum that can now be obtained under favourable circumstances in production, is:

at 4 MC/s	long.mode	equivalent	flat	bottom	hole	0,8 mm dia.
" 2 "	"	"	"	"	"	" 1,5 mm dia.
" 4 "	transv."	"	"	"	"	" 0,4 mm dia.
" 2 "	"	"	"	"	"	" 0,8 mm dia.

With the present techniques used on laboraty test samples the absorption measured on austenitic weld material can be as low as:

Absorption dB/mm	Operating mode	Frequentie
0,6	longitudinal	2 MC/s
1,4	transversal	2 "
1,5	longitudinal	4 "
1,7	transversal	4 "

All this is probably not new but is where ultrasonic testing for practical purposes now is as far we know.

4. DATAPROCESSING/RECORDING

As a result of our practical experience as users of ultrasonic testing, we feel that the CRT-display is not sufficient. The CRT is excellent for monitoring purposes for the operator. The signal/noise ratio can be such that the actual signal can lead to misinterpretation. Therefore we would like to see a development where correlation techniques are matched to ultrasonic testing. As an aid for interpretation a facsimile recording of signals may be a most useful tool.

With radiographic inspection the photograph is afterwards always available and can be used as a figerprint. The signals obtained by ultrasonic testing are usually not recorded. For inservice inspection however this will become mandatory.
Thus what is needed is recording equipment that is simple to operate, reliable and tnat can be used during production, without the need for highly trained personnel.
Since fingerprinting can probably be conviently done during the manufacture of components.

5. FIELDS for DEVELOPMENT

5.1. Correlation techniques

As mentioned before this may help to improve: signal to noise ratio. Improvements of 6 dB and more are expected which will also enhance interpretation.

5.2. Probe design

Here is a lot that can be developed and improved, to name a few

Efforts to assure correct focus are necessary. The answer may be found in:

5.2.1. bowl crystal probes.

5.2.2. multi crystal probes.

5.2.3. careful selection of the wedge material to which the crystals are fused.

5.3. Coupling

Coupling can be a serious problem in practice due to: weld geometry. In this area improvements are necessary and perhaps a modified and local immersion technique is possible.
This is a solution which may lead to an effective "contactless" coupling method.

5.4. Austenitic material

Austenitic material poses no special problems. The weld material is an area for concern. However this is more a metallurgical problem, to improve texture, than a problem for the ultrasonic testing technique proper.

For practical purposes it is assumed that grain sizes smaller than 0.4 of the wave length are acceptable. Grain sizes of approx. 0,2 are not troublesome, while sizes below 0.1 causes no problems at all.

To improve weld texture one may have to go new welding procedures. Research in this area is required to assure that texture can be improved without sacrifying the required mechanical properties.
For austenitic components now under construction one has to accept that the various welds cannot be improved to facilitate ultrasonic testing.

5.5. Future work

As designer of heatexchangers and pumps we have to make a selection of the possibilities. Future work will be concentrated on at least:

- ultrasonic transducers of improved design for internal bore welds as a convenient back-up method for the micro-focus X-ray equipment. Since the I.B.-welds are not accessible at both sides after heat treatment of the steam generator, ultrasonic testing may well be benificial here.
- Twin crystal probes.
- Focused crystal probes.
- High temperature probes for use in sodium.
  For inservice inspection such transducers may be an asset.
- Research on possibilities of inspection of thick walled austenitic materials has already been started.
- Additional attention will be paid to adequate matching of transducers and ancillary (ultrasonic) equipment.

These points have recently become very important on account of the inservice inspection requirements for the SNR-300.

Although many of the points mentioned are already under investigation however little in way of practical useful results is yet available.

6. CONCLUSIONS

Many improvements are possible and necessary. The problems associated with austenitic weld material should be investigated with high priority.
The quality of testing ferritical material can be called satisfactory for the time being. The points listed in this paper are not new by any means but are presumably an adequate survey of what is possible today.

J. Spanner, "Preliminary development of in-service inspection methods for LMFBRs". (USA)

Introduction

Although firm requirements have not yet been established in the United States for inservice inspection of LMFBR's, some initial development work on potentially applicable nondestructive testing (NDT) methods has been conducted by the Hanford Engineering Development Laboratory. This laboratory is operated by the Westinghouse Hanford Company for the U. S. Energy Research and Development Administration. We have conducted preliminary development programs in three areas that are pertinent to the subject of this IWGFR Specialists' Meeting. These are:

Ultrasonic Examination of Austenitic Stainless Steel Welds

Electro-Thermal NDT Method for Stainless Steel Components

Eddy Current Methods for In-Situ Examination of Heat Exchanger Tubes

A synopsis of the investigations we have conducted in each of these three areas is presented in this paper, along with a discussion of the experimental results that have been obtained.

Ultrasonic Examination of Austenitic Stainless Steel Welds

Ultrasonic (UT) equipment and techniques are widely used for the examination of welds in carbon steel components. However, ultrasonic examination of comparable welds in austenitic stainless steel components using conventional equipment and techniques is generally less effective due to the significant increase in acoustic attenuation exhibited by these materials. Furthermore, large amplitude ultrasonic indications may occur in weld regions that are free of rejectable defects. The acoustic energy attenuation problem, combined with the false indications encountered during the examination of many austenitic stainless steel welds, have emphasized the need to develop more effective ultrasonic methods to supplement the examination processes presently employed during the fabrication of stainless steel components, and for possible use during inservice inspection of LMFBR plants.

We have recently completed the first year's effort on a program that was designed to investigate this problem and develop viable solutions [1][1]. Sixty-eight weld samples were acquired, cataloged, and subjected to a series of conventional ultrasonic and radiographic examination processes. Figure 1 illustrates the variety of weld samples that were accumulated. Most of these samples are remnants from weld process or welding operator qualifications; hence, are typical of the welding processes used during the fabrication of piping for the Fast Flux Test Facility (FFTF). Figure 2 shows three acoustic image photographs that dramatically illustrate the severe acoustic attenuation that may be encountered when attempting to penetrate an austenitic stainless steel weld. These photographs were obtained using a white-light schlieren apparatus, a continuous-wave (CW) ultrasonic system operating at 2.25 MHz, and a welded, 1/4 inch ($\sim$ 1/2 cm) thick test block made from Type 304 stainless steel.

Following the initial examination, selected samples were machined to provide coupons with flat, parallel surfaces, and these coupons were subjected to additional, and more detailed, radiographic and laboratory ultrasonic procedures. Numerous sites that produced ultrasonic indications were detected in these coupons, and these noise sites were precisely located, ultrasonically characterized, and metallographically examined along planes in front of, through, and behind the noise site. In addition, montages of photomicrographs from the metallographic examination were assembled in the vicinity of 13 suspected noise sites to provide a broader pictorial perspective of the areas being analyzed. The most prevelant microstructures visible on the photomicrographic montages were: (1) weld-metal/base-metal interfaces, (2) homogenous-dendritic structure interfaces, and (3) parallel dendritic growth patterns located at, or adjacent to, suspected noise sites. It was determined that although the ultrasonic noise signals could usually be associated with major dendritic growth patterns, the existence and magnitude of some of the observed signals could not be explained simply on the basis of a dendritic microstructure.

Examples to illustrate the preceeding discussion are shown in Figures 3, 4, and 5. Figures 3 and 4 are photomicrographs of two noise sites in the same coupon that produced ultrasonic signals of significant amplitude. These montages cover an area that contains some base metal and successive weld passes. The montage shown in Figure 5 covers a similar area in a noise free coupon. The apparent differences between the "noisy" weld and the noise-free weld appear to be restricted to the minor dendritic growth patterns present in the weld metal (upper) regions shown in Figures 3 and 4. Furthermore, the area shown in Figure 3 produced a greater reflected signal amplitude (45 percent) than the region shown in Figure 4 (35 percent), although the dendritic pattern is far more pronounced in Figure 4. This indicates that, although dendritic growth patterns may act as reflecting surfaces to produce ultrasonic indications, the levels and severity of the observed noise signals cannot be directly corre-

1 Numbers in brackets refer to references at the end of this paper.

lated with relative quantities of dendritic microstructure.

Based on the experimental results obtained to date on this program, combined with our knowledge of work performed by other investigators on this and similar problems, we conclude that the difficulties that are presently encountered during ultrasonic examination of austenitic steel welds are generally attributable to the following conditions, which may occur singly or in combination:

Unpredictable and potentially severe attenuation of acoustic energy within the cast microstructures found in weldments.

Sound beam refraction occurring at the weld/parent interface, within the weld, or both; and attributable to variations in acoustic velocities, internal stresses, etc. Such refraction effects cause the sound beam to "bend"; hence, the UT operator provides incorrect defect location data based on an assumption of straight beam paths. The consequences are that destructive exploration fails to reveal a defect at the predicted location, and the existence of an actual defect is not disclosed. Furthermore, the signal from an actual defect is incorrectly evaluated as a spurious noise signal which further errodes confidence in the reliability of ultrasonics as an effective examination method.

Reflections from microstructural discontinuities such as dendritic crystal growth, segregation of impurities at grain boundaries, etc.

Reflections from geometric discontinuities. These may be due to weld design configuration, weld root configuration, weld reinforcement, or ripple and shrinkage on the final weld surfaces.

Other as yet undefined reflection and diffraction sources such as stress distributions or crystallographic orientations that produce wave front interferences.

Although we consider the problems that are presently encountered in examining austenitic stainless steel welds to be significant and difficult, we are confident that improvements can be achieved toward providing more effective methods for ultrasonically examining this type of weld. Future efforts on this program will emphasize investigations of electronic signal enhancement processes and computerized noise discrimination techniques, in conjunction with the development and evaluation of equipment, techniques, and procedures that are tailored to the examination of austenitic stainless steel weldments.

Electro-Thermal NDT Method for Stainless Steel Components

The infrared electro-thermal concept offers attractive potential as an alternate method for examining austenitic stainless steel components. In principle, this method consists of passing a short, high-amplitude electrical current pulse through a test object, and monitoring the resulting surface temperature profiles using a scanning infrared camera or similar sensing device. This relatively new NDT method responds to, hence is affected by, a somewhat different set of material characteristics than are the more common NDT methods. Thus, the electro-thermal method offers a possible alternative for examining stainless steel welds where microstructural or surface condition variations inhibit the effectiveness of the eddy current (ET) and ultrasonic (UT) methods. The electro-thermal method also appears potentially applicable for inservice inspection of LMFBR components.

We have recently completed a preliminary feasibility study and laboratory demonstration to evaluate the sensitivity of the electro-thermal method by detecting artificial discontinuities in stainless steel test plates [2]. An experimental system, assembled from available laboratory components, was used to conduct this demonstration study. The plates used as test specimens were 2 x 4 x 0.2 inch (5 x 10 x 0.5 cm), had smooth surfaces, and were made of Type 304 stainless steel. Each plate contained one 0.005 inch (0.013 cm) wide Electrical Discharge Machined (EDM) notch, and a series of 13 plates were used to evaluate the response to notches with different lengths and depths. Figure 6 shows a close-up of one of the plate specimens and the electrode configuration. Our laboratory tests demonstrated that this experimental system was capable of detecting notches cut into either the front or back surfaces of the test plates.

Experiments were conducted using different combinations of electrode contact and notch placement to evaluate the sensitivity to surface and subsurface discontinuities. Figure 7 illustrates the response obtained from three different sized notches on the front surface of the plates (i.e. side facing the infrared camera). The dark regions are low temperature zones corresponding to areas with low electrical current flow, and the bright lines are due to a type of cavity effect. The cavity effect occurs because the infrared camera "sees" the notch as a small, high emissivity area. Notice that a notch as small as 0.06 inch (0.16 cm) long x 0.06 inch (0.16 cm) deep was detected.

Figure 8 illustrates the response that was obtained from three different sized notches that were located on the back surface of the plates (i.e. side away from the camera). This figure illustrates typical sensitivities to subsurface discontinuities; or to discontinuities on the inner surface of a component when an examination is performed from the outer (accessible) surface. Although the response data are not included in this paper, our laboratory system was able to detect notches on the back surfaces as small as 0.03 inch (0.08 cm) deep x 0.50

inch (1.28 cm) long, and also 0.12 inch (0.32 cm) deep x 0.12 (0.32 cm) long when the electrical current was applied only to the front surfaces of the test plates. In other words, we could detect 1/8 inch long notches that penetrated about 60% through the plate, and 1/2 inch long notches that penetrated only about 15% through the plate.

The results obtained during this study have shown that the significant infrared (surface temperature) features of the electro-thermal indications from front surface notches are two adjacent dark (low temperature) regions. The infrared pattern obtained from back surface and subsurface notches is a single bright (high temperature) region. Thus, qualitative interpretation of the results from and electro-thermal examination appears to be relatively straightforward.

Our investigation provided a conclusive demonstration of the potential sensitivity of this method for examining stainless steel components, and indicated that the method offers potential for inservice inspection applications. Evaluation of the electro-thermal method on components with rough surfaces (such as welds) was not performed during this study, but future work is planned in this area using a high frequency current source to limit the current penetration depth and minimize the effect of surface roughness.

Eddy Current Methods for In-Situ Examination of Heat Exchanger Tubes

Single and multiple frequency eddy current (ET) techniques have been evaluated for applicability to inservice inspection of the tubes in sodium/sodium heat exchangers. This investigation was conducted in two phases using laboratory equipment, mock-up fixtures to simulate the configuration of tubes in the FFTF intermediate heat exchangers (IHX's), and test samples cut from typical IHX tubes.

The Phase I tests were conducted using a four-tube mock-up that had been immersed in hot sodium (Figure 9). Drilled holes and EDM notches were used to simulate defects in the tube walls, and baseline eddy current examinations were conducted before the tubes were exposed to sodium. After exposure for about 30 hours at 1100°F, the sodium was drained and the tubes were periodically reexamined during removal of residual sodium deposits using a sequential cleaning process. During many of the Phase II tests, solder was used to simulate sodium deposits on the tubes. The experimental arrangement used during these studies is schematically depicted in Figure 10.

On the basis of these initial investigations, we concluded that conventional, single frequency, eddy current equipment (operating at approximately 100 kHz) generally provides an effective examination on Type 304 stainless steel tubes that are 0.875 inch OD x 0.049 inch wall thickness and have not been exposed to sodium [3]. The conventional single frequency method did not provide an effective examination on sodium contaminated tubing because sodium deposits produced signals that could interfere with the detection of significant discontinuities. If the sodium can be thoroughly removed from the inner surfaces of the tubes and detection of outer surface discontinuities is not intended, a conventional single frequency test (operating at about 1 MHz) can provide an effective examination for inner surface discontinuities.

The second phase of this program involved an investigation of multi-frequency (multi-parameter) techniques in search of a successful method for inservice examination of sodium-contaminated IHX tubing [4]. A four-frequency laboratory system was assembled and evaluated. It was found that this system could detect discontinuities on the outer tube surfaces while effectively discriminating against the interfering signals caused by probe motion, tube supports, and residual sodium on the outer surfaces of the tubes. However, we were not able to discriminate against the large signals which resulted from residual sodium on the inner surfaces of the tubes, because these signals exhibited characteristics that were inseparable from the signals from discontinuities on the inner tube surfaces. In addition, when sodium was retained within a discontinuity on either tube surface, its effect was to reduce or otherwise modify the shape of the signal from the discontinuity alone.

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FIGURE 1. Photographs Showing Typical Weld Samples Employed During Ultrasonic Investigation.

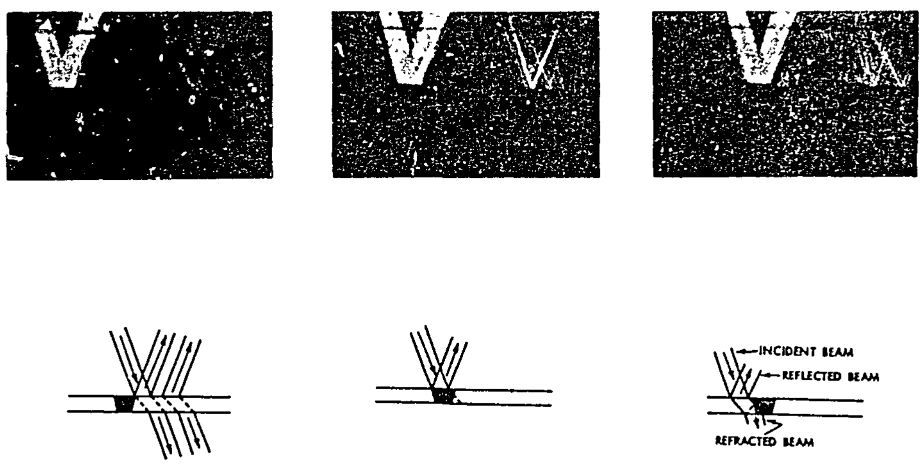


FIGURE 2. Schlieren Images Comparing 2.25 MHz Ultrasonic Beam Transmitted Through Base Metal and Weld Metal.

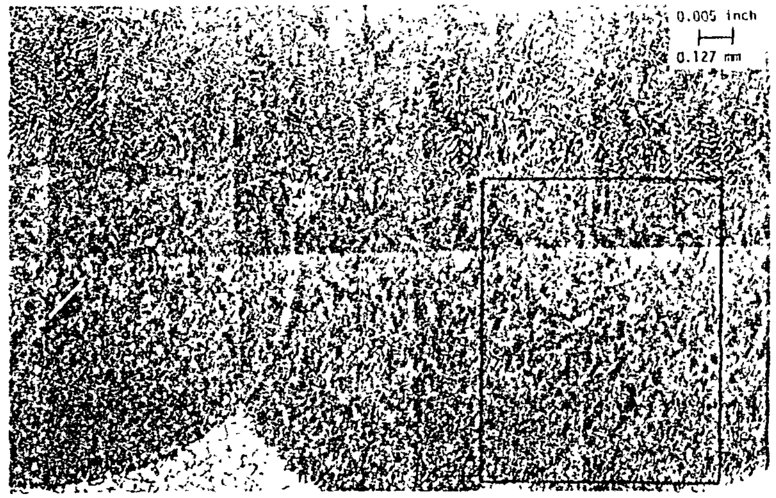


FIGURE 3. Montage of Photomicrographs Taken at Noise Site 1 in Weld Sample WS-27-2.

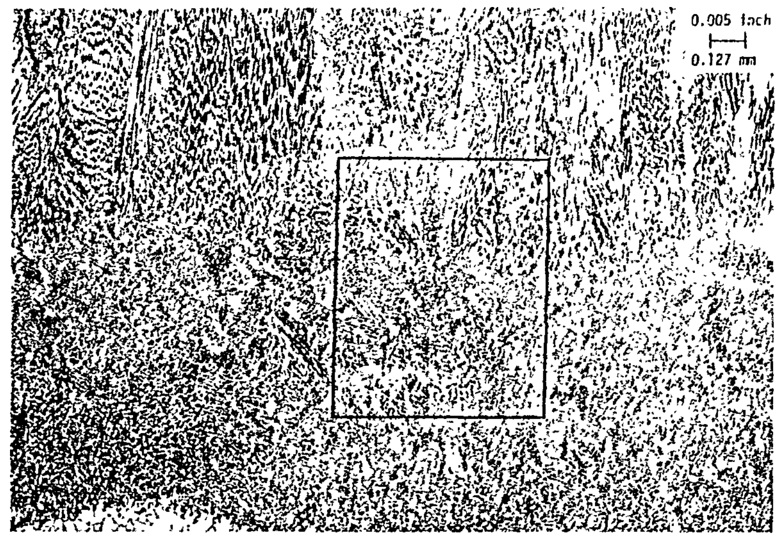


FIGURE 4. Montage of Photomicrographs Taken at Noise Site 2 in Weld Sample WS-27-2.

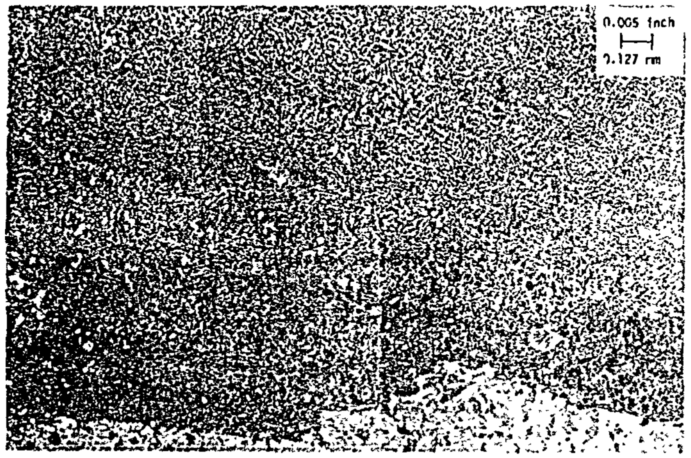


FIGURE 5. Montage of Photomicrographs Taken at Site D1 in Weld Sample WS-12.

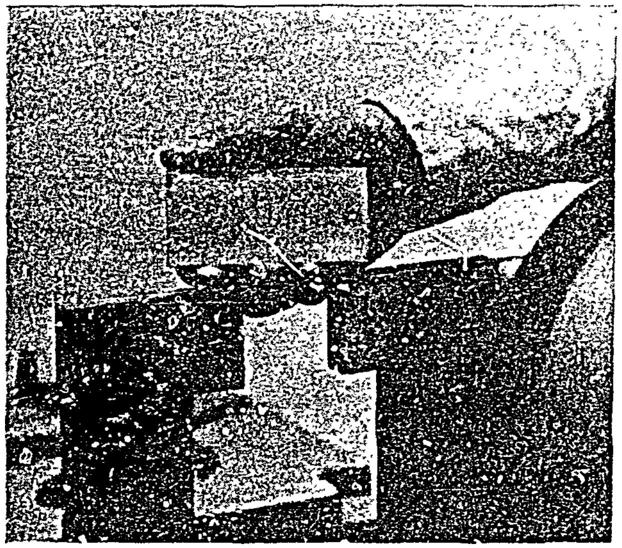
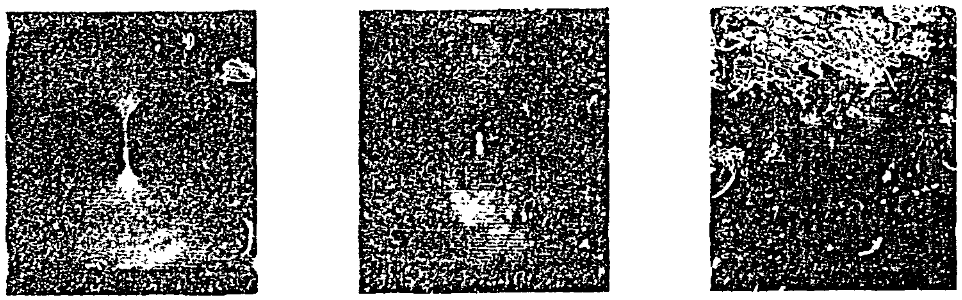
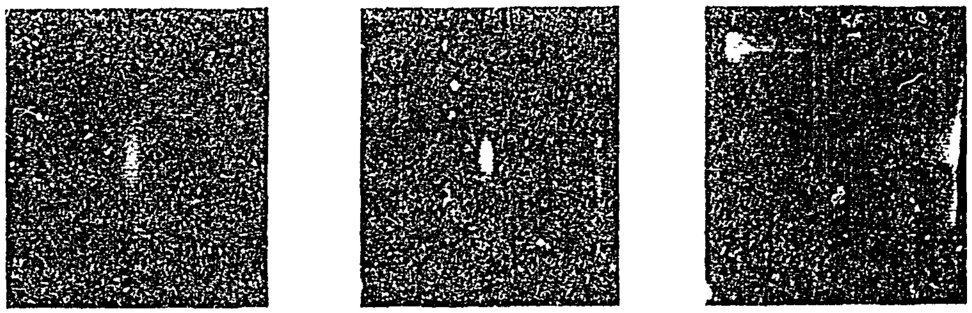


FIGURE 6. Closeup of Test Specimen and Holding Fixture (Electrodes) Used to Demonstrate the Electro-Thermal Method.



0.5 in long x 0.12 in deep   0.12 in long x 0.06 in deep   0.06 in long x 0.06 in deep

FIGURE 7. Electro-Thermal Indications from EDM Notches on the Front Surface of Test Specimens.



0.5 in long x 0.12 in deep   0.25 in long x 0.12 in deep   0.5 in long x 0.03 in deep

FIGURE 8. Electro-Thermal Indications from EDM Notches on the Back Surface of Test Specimens.

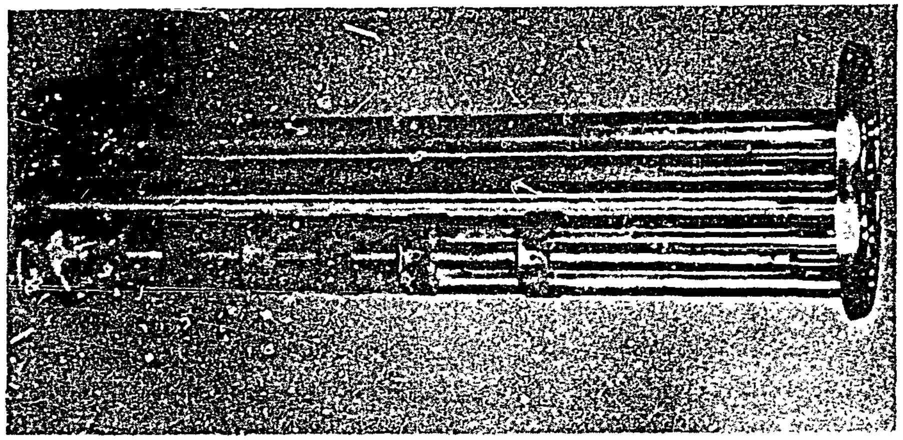


FIGURE 9. Four-Tube Mock-Up Used to Investigate Sodium Effects on Eddy Current Examination.

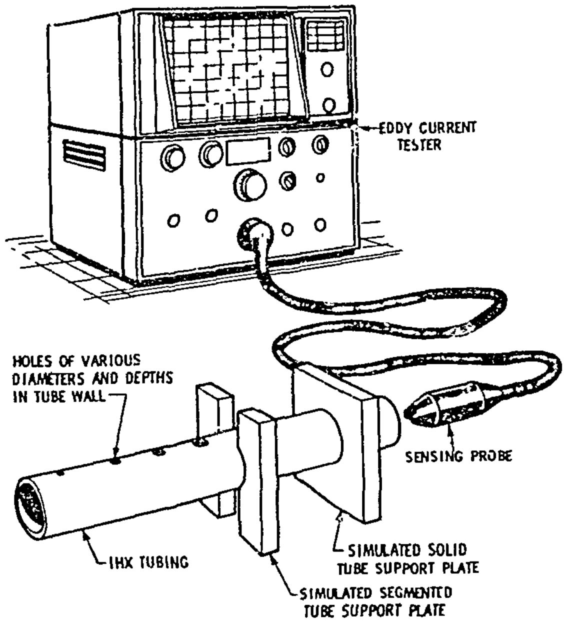


FIGURE 10. Schematic Arrangement of Equipment Used to Investigate Sodium Effects on Eddy Current Examination.

R. W. McClung, "Studies in Non-destructive Testing with potential for In-Service Inspection of LMFBRS". (USA)

INTRODUCTION

Firm detailed requirements have not been established in the United States for the in-service inspection (ISI) of Liquid-Metal Fast Breeder Reactors (LMFBRs). However, although not directed specifically toward such applications, several development programs in nondestructive testing at the Oak Ridge National Laboratory (ORNL) have shown probable benefit. The technology includes work in radiography, ultrasonics, and eddy currents.

RADIOGRAPHIC METHODS

Although radiography is normally not considered as a major contributor for nuclear ISI because of problems with the radiation background, limited applications have been made. These include special work in hot cells and radiography of reactor components in low-radiation-level environments. A development study[1] at ORNL, which led to the installation of an x-ray unit in a hot cell, demonstrated the feasibility of performing radiography despite rather high radiation background. A comparison was made of the relative radiographic quality on a radiographed specimen as successively greater amounts of background radiation (from a ^{60}Co source) were superimposed on the initial exposure. We demonstrated that up to 32 R of radiation could be tolerated without severe loss of sensitivity (as measured by a plaque-type penetrameter). For even greater levels of background radiation, experiments were conducted with chemical reduction using Farmer's reducer as a bleaching agent on the overexposed film. We showed that the tolerance to radiation could be increased up to more than 300 R. For example, Fig. 1 is a reproduction of an x-radiograph made of a highly radioactive ^{60}Co gamma-ray source. This source produced a radiation field at the plane of the film of about 12,000 R/hr. During the short exposure, the film was subjected to about 200 R of background gamma rays from the source.

Another area of development in radiography with potential benefit for ISI is radiographic image enhancement. Because of the inherent difficulties in performing radiography in a reactor system, the quality

*Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

of the as-processed image may not be optimum for best interpretation. Many organizations have conducted developmental studies of techniques and equipment for image enhancement, including sophisticated computer systems, television circuitry, and optical approaches. The work at ORNL *emphasized video techniques*[2] using magnification and contrast enhancement.

Significant benefits were demonstrated in both visibility of image detail and quantitative dimensional measurements in radiographs that had unavoidable poor image quality.

Fig. 1. Radiograph of a 5-Ci ^{60}Co Capsule.

EDDY-CURRENT METHODS

With the exception of ISI of steam generator tubing, eddy currents have not been utilized heavily in postoperation reactor examination. However, with appropriate advances, there are many areas of application wherein eddy currents should be useful. Among the problems that must be overcome for application to LMFBRs are variations in signal due to coil-to-specimen spacing (lift-off), effects of temperature [200°C (400°F) and higher] on the coils and specimens, and the effect of variations in magnetic permeability in some alloys. Developmental programs at ORNL have addressed these needs.

Theory

Significant advances in the theory of electromagnetic induction of eddy currents and the development of mathematical models to simulate inspection conditions have increased the basic understanding of the inspection method.[3–5] (The cited references are typical and not exhaustive.) Many of these models have been programmed for computer solution. The models and programs contain all the significant variables in an eddy-current examination [e.g., the electrical, magnetic, and dimensional properties of the specimen; the configuration of the inspection coil(s); and the operating parameters of the instrumentation]. Therefore, the programs can be used to design optimum eddy-current techniques and probes and to accurately predict the attainable results before experiments. Supplementary computer programs for instrumentation allow optimum design of the circuitry with improved stability and accuracy. Application of the techniques at ORNL for solution of new problems has demonstrated significant savings in time and cost and improved performance, with excellent correlation between the design predictions and experimental results.

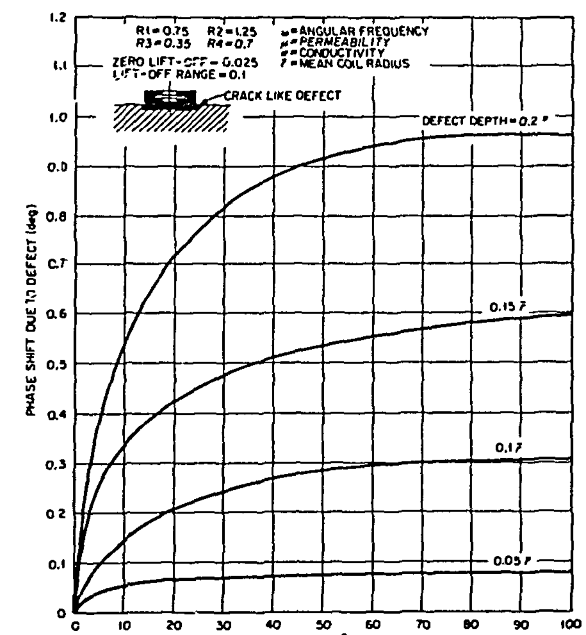


Fig. 2. Calculated Curves for Optimized Eddy-Current Technique and Predicted Performance for Flaw Detection on the Surface of Thick Specimens.

Figure 2 is an example of some of the typical design results for technique development and prediction of results. These curves for the detection of flaws on the near surface of thick specimens (e.g., for cracking in pipe or vessel walls) allow determination of the optimum conditions of coil size and operating frequency and predict the instrument response to flaws having different depths.

Instrumentation

The computer programs cited above have provided beneficial input to optimized design of several phase-sensitive eddy-current instruments that feature excellent stability and sensitivity and relative insensitivity to changes in lift-off (coil-to-specimen spacing). Lift-off sensitivity can be particularly troublesome in automatic or remote scanning systems that may be necessary for ISI. Two typical applications of the instrumentation will be briefly described.

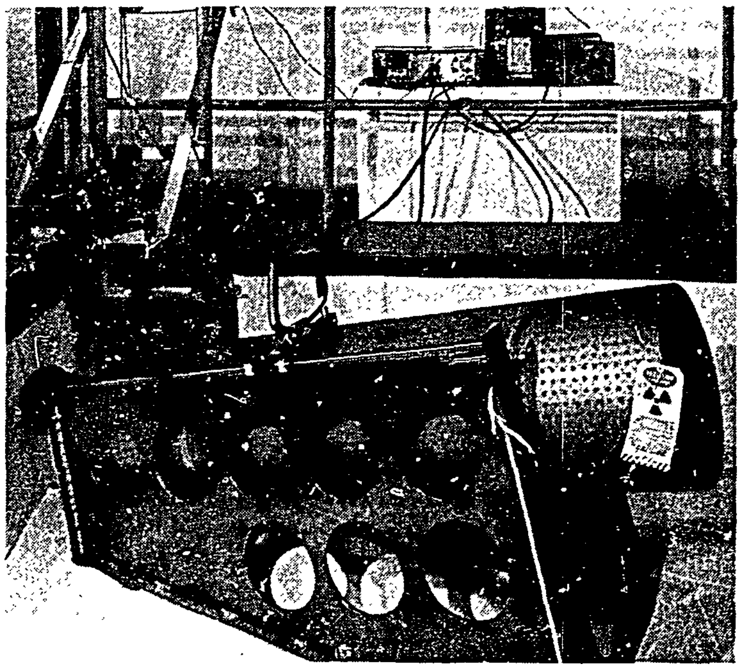


Fig. 3. Phase-Sensitive Eddy-Current Instrument and Scanner for Inspection of Reactor Control Rod (Cylinder).

One application was for the remote postoperation inspection[6] of control rods (actually thin-wall cylinders) for the High Flux Isotope Reactor (HFIR) at ORNL. The neutron-absorbing materials were tantalum and Eu_2O_3 clad with 0.38 mm (0.015 in.) aluminum. The inspection was performed to measure the thicknesses of both the residual cladding and an oxide layer on the cladding and to detect cracks as shallow as 25 μm (0.001 in.) in the cladding. Figure 3 is a photograph of the instrument, a simple mechanical scanning system, and the inspection probe on an unirradiated control rod used during calibration. Figure 4 is a photograph of the inspection being performed at the bottom of the deep

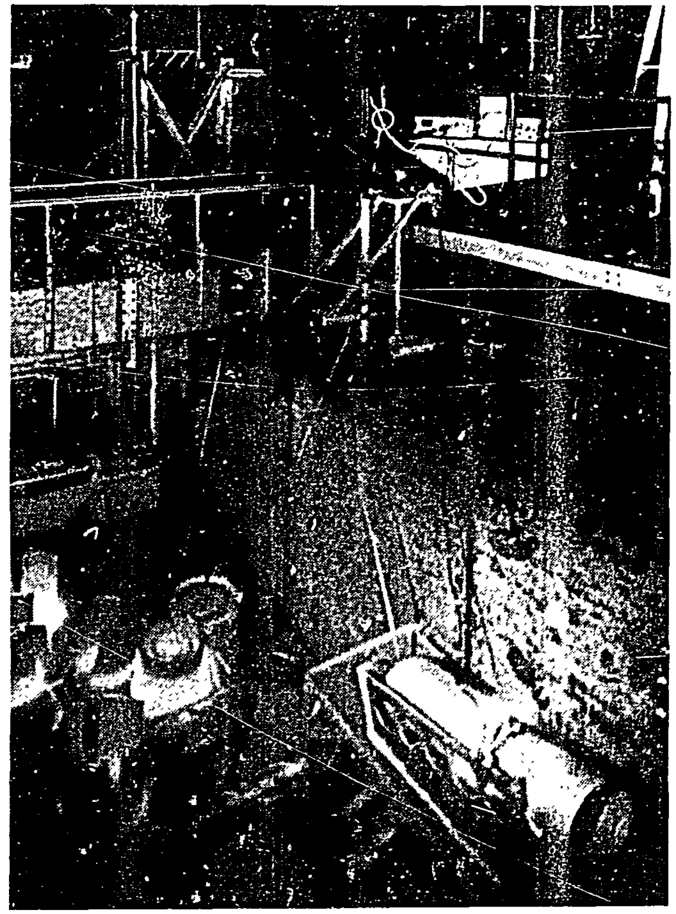


Fig. 4. Eddy-Current Inspection Being Performed on Highly Radioactive Reactor Control Rod (Cylinder).

pool of water. The glow is caused by the Cerenkov effect and is an indication of the very high levels of radiation. All desired inspections were successfully accomplished.

Another application is currently being developed for the ISI of steam generator tubing for an LMFBR.[7] The tubing is 2 1/4 Cr-1 Mo alloy, a ferromagnetic material. Except for the production inspection of ferromagnetic tubing, eddy-current techniques are not generally considered to be beneficially applicable to such alloys. A significant problem is the fact that the inspection must be performed from the bore of the tube which has an inner diameter of 10.16 mm (0.400 in.) and a wall thickness of 2.77 mm (0.109 in.). However, we have demonstrated that, with computer-designed coils such as conceptually shown in Fig. 5, the tubing can be adequately magnetically saturated to allow eddy-current inspection of the entire wall thickness. To overcome potential ambiguities due to variations in different properties such as conductivity, permeability, thickness, diameter, and the presence of flaws will require multifrequency, multiparameter techniques. This advanced instrumentation is being developed.

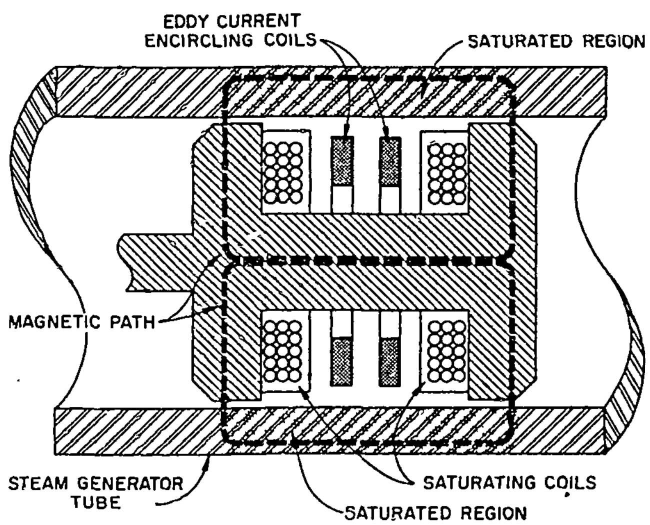


Fig. 5. Conceptual Drawing of Bore-Side Magnetic-Saturation Eddy-Current Probe for In-Service Inspection of Steam Generator Tubing.

For ISI of light-water reactors, ultrasonics has been the prime nondestructive testing method for volumetric examination in the radioactive environment. Although the method has proved to be very beneficial as a qualitative detection tool, there are needs for improvement to obtain more quantitative data on the dimensions of flaws for better determination of significance based on fracture mechanics. Studies at ORNL in ultrasonic-frequency analysis[8–11] (again the cited references are typical and not exhaustive) have demonstrated the feasibility of making quantitative measurements of both flaw size and orientation without regard to the overall amplitude of the reflected signal. For example, Fig. 6 shows ultrasonic spectra in reflections obtained from a 3.18-mm-diam (0.125-in.) reflector at several different angular orientations from normal with the incident beam. The spectrum at normal incidence is quite similar to that of the transmitted pulse. Note the changes in maxima and minima at various frequencies in the spectra as the angle changes. Since two unknown properties of a flaw (a dimension and an orientation) affect the observed frequency spectrum, at least

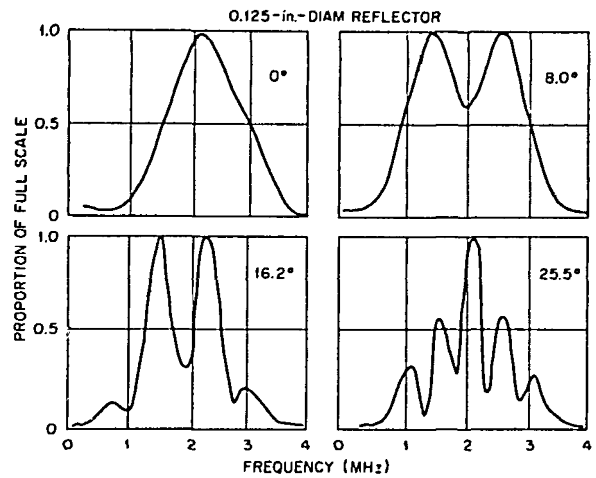


Fig. 6. Ultrasonic Spectra from 3.2-mm-diam (1/8-in.) Reflector at Different Angles of Incidence.

two interrogations are required to isolate each. One-, two-, and three-transducer techniques have been studied for simplified multiple evaluations, and Fig. 7 is a sketch of one of the two-transducer arrangements. Figure 8 is a special test block of steel containing flat-bottomed drill holes with different diameters and orientations. A rubber replica of the holes is also in the photograph. With the frequency-analysis technique, we were able to accurately determine both size and orientation of each reflector, using only the reflection spectra with the ultrasound introduced from the top surface of the block. Further developments are expected to produce inspection techniques that can be applied for ISI.

Another ultrasonic technique that is currently being developed[7] for the bore-side inspection of tube-to-tubesheet joints for steam generators should also be applicable for the ISI of steam generator tubing. As noted in the section on eddy currents, the reference tubing is 2 1/4 Cr-1 Mo with an inner diameter of 10.16 mm (0.400 in.) and a wall thickness of 2.77 mm (0.109 in.). Figure 9 is a photograph of a prototype probe being studied for the ultrasonic inspection. The small-diameter [≈3 mm (1/8 in.)] ultrasonic beam is transmitted parallel to the bore to impinge on a reflector that diverts the sound into the tube wall at

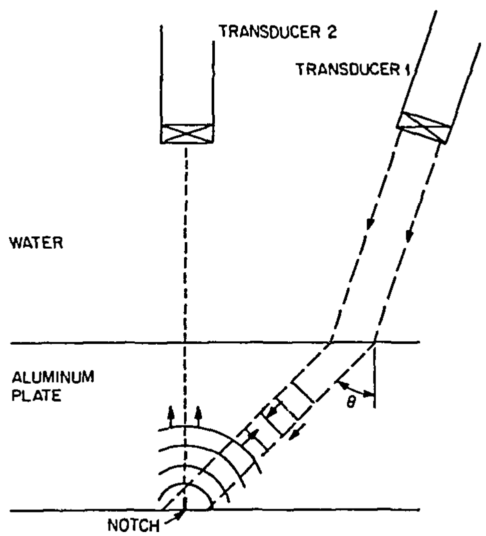


Fig. 7. Two-Transducer Arrangement for Flaw Characterization Using Frequency Analysis.

the desired angle. Reflections from discontinuities may be detected by the initial transmitting transducer or by a secondary receiver. Figure 10 is a schlieren photograph of the output of an experimental probe. The schlieren technique is used to confirm the design and performance of new transducers. The bore-side ultrasonic probes have been shown to have sensitivity adequate to detect a flaw 50 μm (0.002 in.) deep in the 2.77-mm (0.109-in.) wall.

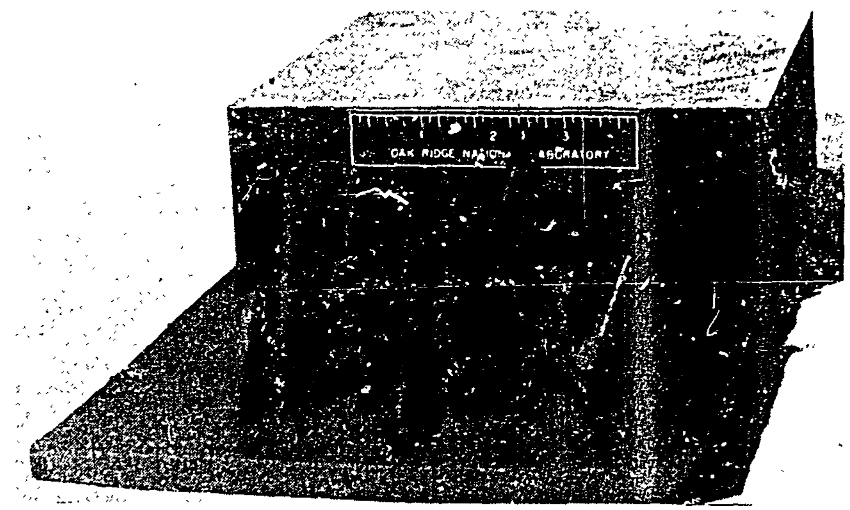


Fig. 8. Steel Block with Rubber Replica of Machine Flaws used for Frequency Analysis Studies.

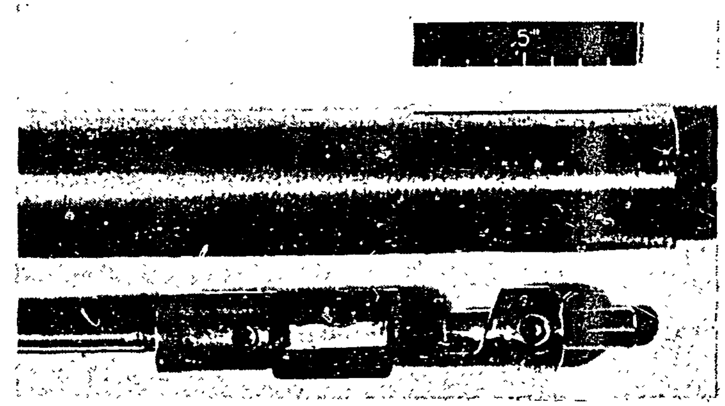


Fig. 9. Modular Ultrasonic Probe Being Studied for Inspection of Tube-to-Tubesheet Joints for Steam Generators.

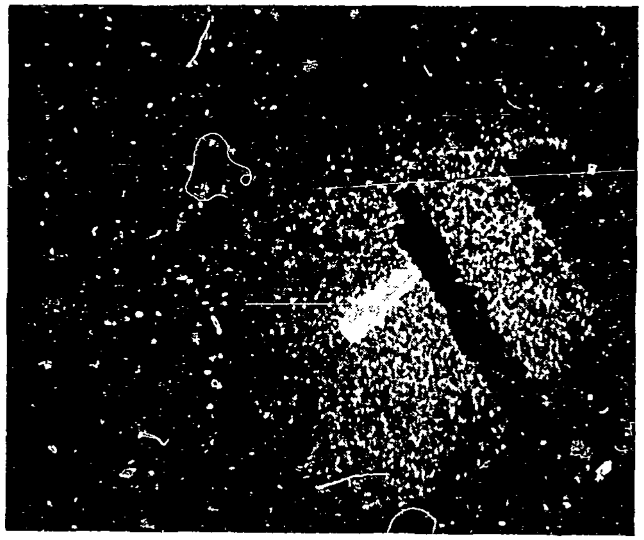


Fig. 10. Schlieren Photograph of Output of Experimental Ultrasonic Probe for Steam Generator Tube-to-Tubesheet Joints.

SUMMARY

A variety of nondestructive examination techniques have been and are being developed at ORNL with potential for ISI in LMFBRs. Among these are radiographic techniques for radiation environment and image enhancement, advanced eddy-current techniques and equipment for flaw detection and thickness measurement and ISI of steam generator tubing, and ultrasonic methods for quantitative flaw evaluation using frequency-analysis and bore-side ultrasonic techniques for steam generator tubing. Further developments should result in positive application to ISI.

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E. G. Tomachevsky, "In-Service Inspection of Rapsodie's Safety Containment". (France)

OBJECT OF THE INSPECTION

Safety containment in carbon steel has been considered as a means to avoid core voiding in the event of sodium leakage through the primary vessel and its double containment. In case of accident, core voiding is prevented by introduction of 50 m3 of sodium from an auxiliary tank. The safety containment must be able to bear this load.

During the concrete-drying period of Rapsodie construction in 1967 it was discovered that some fluor had discharged from the product being used for joining the bored concrete blocks of the biological protection. It was noticed later that the discharging gas was pursued under neutronic flux. It was therefore necessary to inspect the safety containment in case it might have corroded and would not perform its safety function properly.

DIFFICULTY OF INSPECTION

The high radiation level forbade all manual approach, and it would have required shut down and more than six months to study, manufacture, and adjust automatic remote control equipment. Therefore, it was only possible to use manually operated equipment, simple enough to be trusted, rapidly manufactured, and well designed, to reach the safety containment through a complicated way to secure efficient protection for the inspectors.

INSPECTION EQUIPMENT

Biological Protection

1 - The protectional plug, which is part of the reactor, had to be unseated and lifted sufficiently to clear a cressent-shaped opening for introduction of the inspection device. The take out and lift devices, which had not been considered in the reactor design, required a special mechanical tool.

2 - A lead wall with a horizontal and rectangular opening for passage of the inspection devices had to be built to replace the normal vertical handling procedure which had been protected by a lead curtain.

3 - A roller-truck-mounted movable lead shield, fitted with guides for holding the control instrument perches, was necessary.

Control Instruments

There are three control instruments :

1 - a palping perch for checking gaps to verify free passage of the inspecting perches and to eventually determine the right setting of the truck.

2 - a 3-m-long periscope with a 0.2-m and 0.6-m long objective and occular, respectively, equipped with a camera support ring and lighting.

3 - a 3-m-long perch with an articulated 0.4-m-long arm carrying an ultrasonic head. This ultrasonic head, which was specially made for this inspection, consists of :

a) ultrasonic transducer coupling

b) a coupling cupel with water supply

c) a contact electromagnet

The articulated arm allows following the cylindrical containment shape independent of the arm position.

INSPECTION

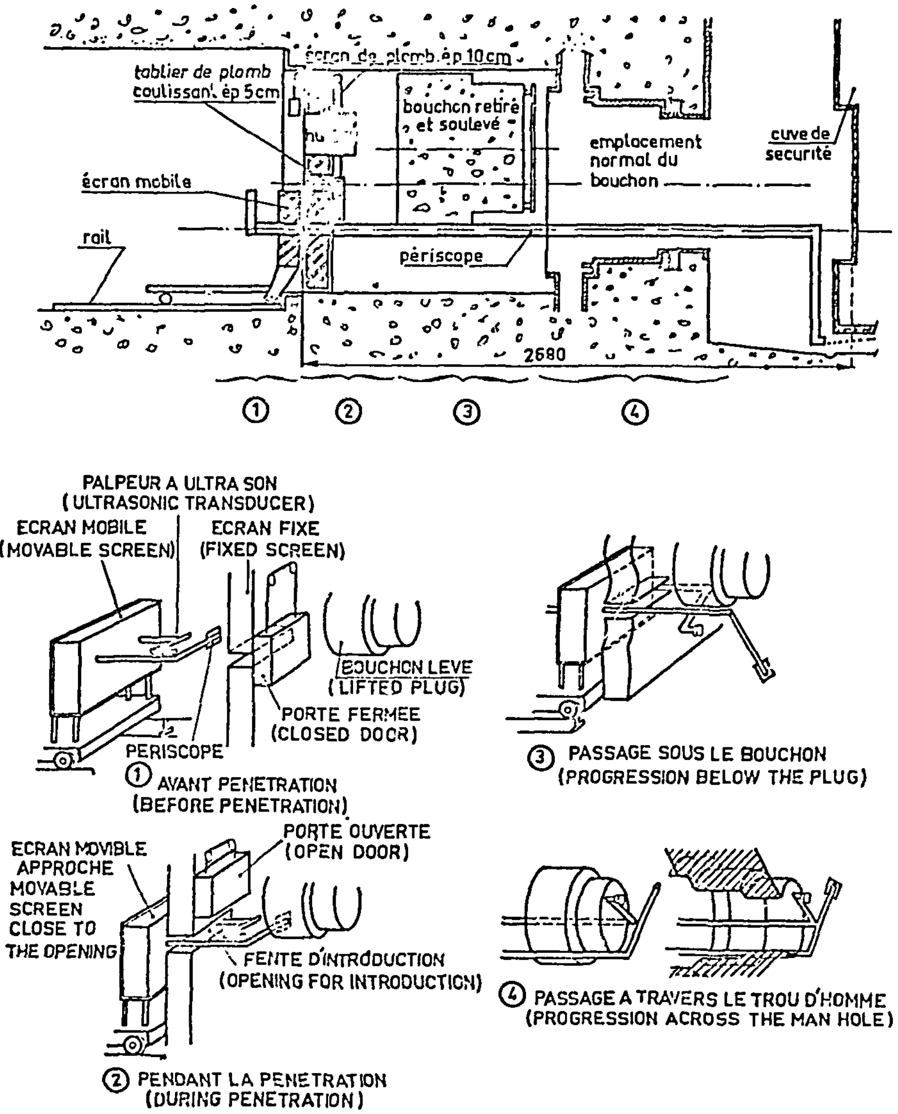
Due to preliminary tests made on a wood mockup, operating time was extremely short.

Visual inspection showed the presence of a few corrosion points which did not appear to be dangerous. This inspection was corroborated by thickness measurements which showed that the measured values were in reasonable agreement with design dimensions.

Part of the containment bottom, lighted with flanking light, was seen to be sound.

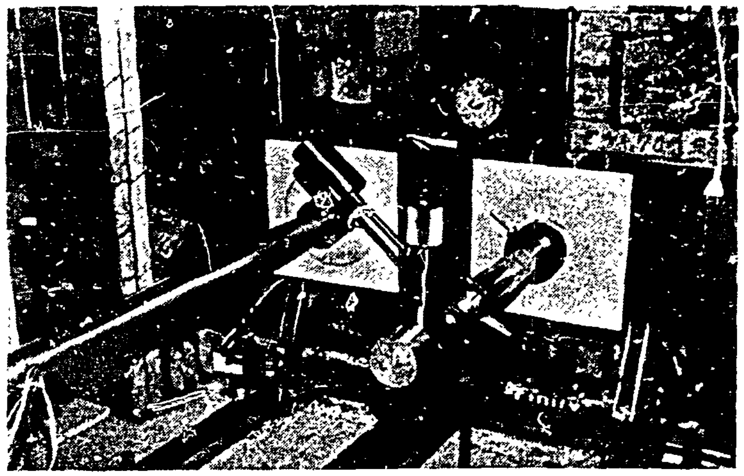
Finally, black and white and color photos were made to attest the containment state on the inspection date (March 13 to 15, 1974).

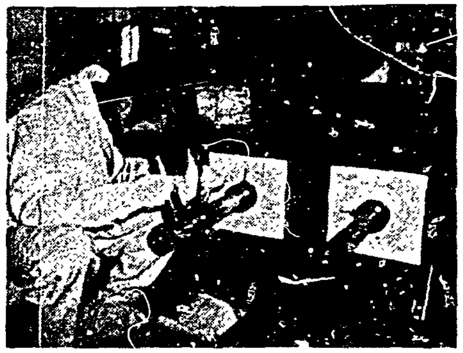
The calculated radioactivity values were confirmed by the measured values.

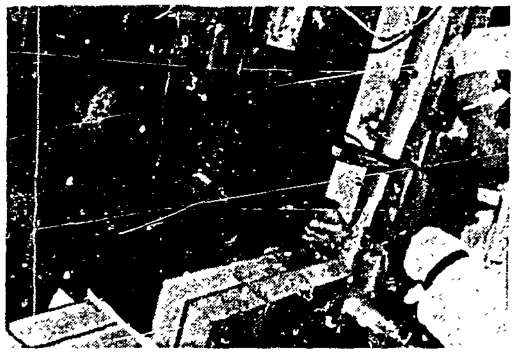


INSPECTION EN SERVICE DE LA CUVE DE SECURITE
DU REACTEUR RAPSODIE

Phases d'introduction de l'appareillage d'inspection







- CHARIOT MOBILE EQUIPE ET PROTECTION FIXE
- OBSERVATIONS VISUELLE
- PRISE DE PHOTO
- PREPARATION AVANT INTRODUCTION

G. Hughes, P. McBane, "A Television/Still Camera with Common Optical System for Reactor Inspection". (United Kingdom)

PFR Above Core Photography

Presented by M.J. Whittle

Summary: (Full details are given in the attached CEGB Reports RD/B/N2646 and RD/B/N2902)

A remotely operated camera system giving continuous television viewing together with the facility to take still photographs for high resolution records was designed (Hughes and McBane 1973) for inspection of the P.F.R. core region. This system performed a survey prior to sodium fill (Hughes et al 1974) and was used extensively to inspect and assist with the removal of a damaged above core orientation mechanism. During the latter operation the camera system, which was argon cooled, operated above sodium in an ambient temperature of 250°C continuously for an 8 hour period. The highly reflective sodium surface and changes in refractive index of the surrounding hot blanket gas did not cause significant degradation of the television pictures.

A Television/Still Camera, with Common Optical System, for Reactor Inspection

SUMMARY

The design of a remotely operated camera system is described. Continuous television viewing is provided, together with the facility to take still photographs to provide high resolution records. Control of shutter, focus and iris together with measurement of light level can all be achieved remotely. Indication of the film frames used and permanent identification of each frame is also provided. The application of the camera to the inspection of the PFR core region is described to illustrate a typical use.

1. INTRODUCTION

The continued need for inspection of reactor components has lead in recent years to the development of a large variety of remote television and still camera viewing systems. In nearly all cases each system was developed for a particular application. Similarly, the present system was designed as part of a rig to inspect the PFR primary circuit, however the camera was designed with the versitility for general reactor inspection. The salient features are:-

1. Continuous television viewing.
2. Still photographs (50 frames) giving the same field of view as the T.V. can be taken permitting high resolution records to be made.
3. Remote focus control, using the T.V., is available, giving simultaneous focus in the film plane.
4. Light level readout and remote iris control.
5. Remote shutter control and automatic frame advance.
6. Frame number indication.

2. MECHANICAL AND OPTICAL DESIGN

Detailed line drawings of the camera assembly are shown in fig.1. The system has been designed to fit into a cylinder of internal dimension 6½" diameter by 11" length. In practice a housing may have to be longer than this to enable cable routing (particularly the T.V. cable) if the access hole is not in line with the Vidicon tube. All the non-proprietry mounting and optical components were designed and manufactured by Applied Optics Ltd., Coulsdon, Surrey. The numbers given in the following description are shown on the line drawing to indicate the individual components.

2.1 Principle of Operation

The objective (of 40 mm focal length) is mounted in a tube (1) which is free to slide in a concentric guide tube (2), the direction of viewing being radially outwards from the main axis of the containment cylinder. Light coming through the objective is directed by a movable prism (3). With this prism in the position shown an image is formed on the vidicon tube of a VE12G* television camera (4). A supplementary lens (5) is fitted in front of the vidicon to obtain the desired field of view. The movable prism which is attached to an arm can be rotated about a pivot (6) to enable the light to pass via prisms (7) and (8) into a Robot Star 50ES® film camera body (9), with a solenoid operated shutter. The amountof light entering the film camera can be adjusted by an iris (10) in the main light tube. A double window (11) for mounting in an insulated cover is shown on the drawing. It is possible to change the front element of this window for a supplementary lens to increase the field of view.

An additional light tube (12) is provided to enable frame numbers to be superimposed on the film. The numbers are generated by two light emitting diode displays (13) positioned at the end of the tube in a mounting which can be moved axially to enable an image to be formed at the film plane. The light from the diodes is reflected by a mirror (14), passes through a focussing lens (15) and enters the main light tube via a small prism (16).

2.2 Construction of Main Frame

All components have been manufactured from 'Dural' and finished by black dye anodising. The base plate (17) supports all the main components and attached to this are two end plates, one circular (18) and the other semi-circular (19). The end plates are further supported by a tie rod (20) between the edges of the plates. The circular end plate is used to attach the camera to its in-reactor positioning equipment and holes are provided to accept mounting studs. The television camera clamps firmly to the base plate, whereas the film camera is located with a knurled, captive, bush (21) which is accepted by the normal lens fitting of the camera. This makes the Robot camera easily removable for film loading. Alignment of the optical components is achieved by grub screws (see for example (22), which adjusts the main prism in front of the still camera) or by sliding tubes with individual locking screws.

2.3 Prism Actuator

The movable prism (3) is driven by a D.C. motor (23) (Vactric type 08P601/28V)† via a gearbox (24) (Weyers type 08/S40:1)** which operates on a gear wheel (25) attached to the supporting arm. A cam (26) mounted above this gear, on the same shaft, operates the two microswitches (27) and (28) which enable the prism to be driven to two fixed positions, i.e. one directing light to the T.V. camera and the other to the film camera.

2.4 Focussing Mechanism

Focussing is performed with a closed loop servo system. A D.C. motor (29) (Vactric Type 08P601/28V) drives a gearwheel with an eccentric roller (30) through a gearbox (31) (Weyers type 08/S 600:1). This gearwheel meshes with an adjacent wheel to drive a 500 Ω potentiometer (32), which provides the position feedback signal. The offset roller moves against a spring loaded arm (33) which is pivoted at one end. The other end of this arm is connected to the tube holding the main objective (1) and is thus capable of sliding it up and down the guide tube (2).

---

* Manufactured by Rees Instruments Ltd., Old Woking, Surrey, England.
® Supplied by S. Davall & Sons, Greenford, Middlesex, England.

† Manufactured by Vactric Control Ltd., Morden, Surrey, England.
** Manufactured by Weyers Bros. Ltd., Loughton, Essex, England.

2.5 Iris Drive

The iris is controlled by a closed loop servo system using the same basic components as in 2.3 above. The motor (34), gearbox (35), potentiometer (36), used in this context are shown in the drawing. The drive spindle, potentiometer gear and iris ring (10) are linked by a double gear wheel (37) mounted on a separate pivot.

3. ELECTRONIC CONTROL SYSTEM

This has been designed to operate over cabling distances of the order of 60 ft., between camera and control panel.

3.1 Shutter and Prism Actuation

The circuit diagram (fig.2) is shown with the prism in the 'still' camera position. In this position the contacts of the microswitch MS2, transfer the supply from the drive motor to the shutter switch, enabling the shutter to be operated.

If SW1 is now changed to the T.V. position the supply is reconnected to the prism motor in the reverse direction, its supply finally being broken when the cam operates MS1. In this position there is no supply to the shutter switch, thus preventing operation of the film camera when the prism is in the T.V. position.

3.2 Focus and Iris Servos

The D.C. closed loop servo system designed to control both focussing and iris opening is shown in fig.3. A type 40PI* differential amplifier provides good noise immunity. The maximum output of the amplifier is limited to ±27 V by zener diodes ZD1 and ZD2.

Stability is improved by the use of phase advance networks on both inputs to the amplifier. The gain can be adjusted to a maximum, consistent with stability, for best response by using the 2M Ω preset potentiometer.

A ten turn potentiometer is used as the command element, the dial of which can be pre-calibrated in terms of focus distance or iris position. It is useful to have a digital voltmeter in the system to monitor the voltage on the feedback potentiometer. This provides a check on system function and gives a more accurate positional calibration.

* Supplied by Ancom Ltd., Cheltenham, Gloucestershire, England.

3.3 Light Level

A direct indication of the light entering the camera objective is obtained by measuring the output of the first stage of the automatic gain control circuit in the television camera control box. This is a feedback voltage proportional to the light incident on the vidicon and enables a T.V. picture of uniform brightness to be maintained automatically during variations in external light level. This voltage is best measured with a digital voltmeter, varying over a range of 0.5-3.0 V.

3.4 Frame Identification

The seven segment numeric displays (Texas type TIXL301*), formed by miniature light emitting diodes, and used to generate the frame number are driven by the circuit shown in fig.4. The contacts of the frame advance relay (fig.2) change over when the shutter operates and triggers a bistable, which eliminates spurious pulses due to switch bounce. The output of the bistable is fed into a decade counter (Type SN7490*), the B.C.D. output of which drives a B.C.D. - 7 segment decoder/driver (Type SN7448*) which is designed to power the display. An output is taken from pin 11 of the 7490 to provide a drive signal for the second decoder and display. The overall circuit provides a 0-99 counter system. This circuit is repeated in the control cabinet to provide a readout of the number of frames exposed. A common reset facility is provided on the control panel. It proved necessary to stabilise the +5V line at the camera because interference caused spurious counts.

4. PERFORMANCE

The focussing and field of view measurements are given in table 1. Potentiometer readings and feedback voltages (monitored by digital voltmeter) are recorded against subject distance. It is possible to estimate the distance of an object from the camera using this calibration (to approximately 0.1" at near focus position and to 1' at 10-15' distance). Accurate focus at the film plane is obtained using the T.V. picture as the guide. The decrease in total aperture in the still camera optics and consequent increase in the depth of focus assists in this respect. Initial adjustment is performed with a ground glass screen in place of the film, the tube holding the iris and additional lens being moved through the position of focus and finally locked with a grub screw.

* Supplied by Texas Instruments Ltd., Morton Lane, Bedford, England.

The iris control and light level calibrations are given in table 2. The effective aperture varies from f5-6 to f32 over the total control range. Calibration was performed with film exposure tests, comparing indications with a standard exposure meter. The light level voltage obtained from the television control unit behaved consistently, beam and target voltages being turned to the same level (maximum) each time a reading was taken. The calibration given is for one film at a fixed shutter speed, but if necessary these can be generalised by calculating light level factors given by the formula (Jones, 1973)

$$L = \frac{N\,S\,\ell^2}{F^2}$$

where N = ASA number

S = Shutter speed (s)

ℓ = Focal length (cm)

F = f-number (aperture)

Resolution tests have been performed with a standard lens testing chart. Using HP4 film with normal processing in Microphen developer resolutions of 80-88 lines per mm in the film plane have been obtained.

The light level emitted by the frame number diodes has been found to produce satisfactory images at shutter speeds of $\frac{1}{4}$ s and below. This is restricting for general work, where possible because of vibration, it may be necessary to use much higher shutter speeds. It is hoped for future applications to pulse the diode supply voltage to a higher level as the shutter is fired.

5. APPLICATION TO THE INSPECTION OF THE P.F.R. CORE REGION

This camera was initally designed for an optical inspection of the above core region of PFR, and this application illustrates its possible use. An installation assembly of a concentric tube design, having appropriate seals, has been made to enable the camera to be lowered down a control rod guide tube, or into the charge machine hole (fitted with a suitable top plate). The camera is shown mounted at the lower end of the reactor assembly in the photographs of fig.5, with the individual components numbered. The camera (1) is mounted with studs to a base plate (2). The base plate is driven by a rack (3) and pinion (4) arrangement operated by a pneumatic cylinder in the housing above. The angular position of the camera is indicated by a potentiometer (5) directly geared to the main shaft. High temperature teflon insulated cable*, glass sheathed, has been used for the television and control cables in the rig. These are fed through a rotating gland (6) and in the case of the control cables wired directly to tag boards mounted on the camera base plate. A double skinned, insulant filled, housing (7) holds the double window/lens arrangement (8) and lighting unit (9). In this application the housing is cooled by argon passed through insulated tubes and entering the housing via a separate coupling (10). Temperatures at different parts of the camera assembly are monitored with glass sheathed thermocouples. The system maintains an internal temperature of less than 40°C with an external temperature in excess of 150°C.

* Supplied By Boston Insulated Wire (U.K.) Ltd., Kinston-upon-Thames, Surrey, England.

The complete control and monitoring system to be used on this experiment is shown in fig.6. Position potentiometers enable the camera height and azimuth to be measured and recorded. The main readout and selector permit the switching of a digital voltmeter to important points in the system. Each time a frame is taken all parameters are recorded with a data logger.

6. CONCLUSIONS

A camera system has been constructed suitable for remote use, incorporating features which should give it fairly wide application. Operational experience with the system will be gained initially with the inspection of a reactor core at its commissioning phase. It is hoped that this work will reveal any weaknesses in design, the only problem existing, at present, being inadequate framemarkings on the still camera at the higher shutter speeds. Variations in the mounting, housing and lighting arrangement for a particular application should be easily accommodated.

REFERENCE

Jones, A., 1973 - Private communication.

Table 1

Focus/Field of View Calibration

	Distance from Objective ft.	Potentiometer Reading	DVM Level V x 100	Field of View in.	Depth of Focus ft.
	12	7.6	-410	27 x 21	-6 to +6
Normal Objective	10	7.5	-397	22.5 x 16.9	
	8	7.4	-383	18.5 x 13.8	
	6	7.27	-370	14.5 x 10.5	-1.5 to +2
Minimum Focus Distance	4	7.10	-334	11.0 x 8.25	
	3	6.90	-311	8.25 x 6.18	
0.25 - 0.5 inch	2	6.60	-252	6.0 x 4.5	-0.5 to +0.6
	1	5.47	-085	3.25 x 2.4	
	0.75	4.83	+011		
	0.5	2.20	+458	1.875 x 1.4	
	∞ →12	4.90	+000	36 x 27	-6 to +∞
	10	4.90	+000	32.5 x 24.2	
Supplementary Lens	8	4.89	+001	26.5 x 20	
	6	4.86	+005	15.5 x 13.8	-2 to +2
Minimum Focus Distance	4	4.76	+029	14.25 x 11.32	
	3	4.75	+032	11.0 x 8.25	
1.25 inch	2	4.55	+061	8.0 x 6.00	-0.5 to +1
	1	3.70	+194	4.25 x 3.2	
	0.75	3.00	+294		
	0.5	0.80	+650	2.25 x 1.68	

Table 2

Exposure Calibrations

Potentiometer Reading	DVM Level V x 100	Effective Aperture f No.
10	-701	5.6
6	-168	8
4	+093	16
3	+215	18
2	+349	22
0	+619	32

Light Level Voltage T.V. Camera V x 100	Aperture for HP4 400 ASA @ ¼ sec.
+281	f 32
+261	f 22
+220	f 16
+182	f 11
+094	f 8
+088	f 5.6

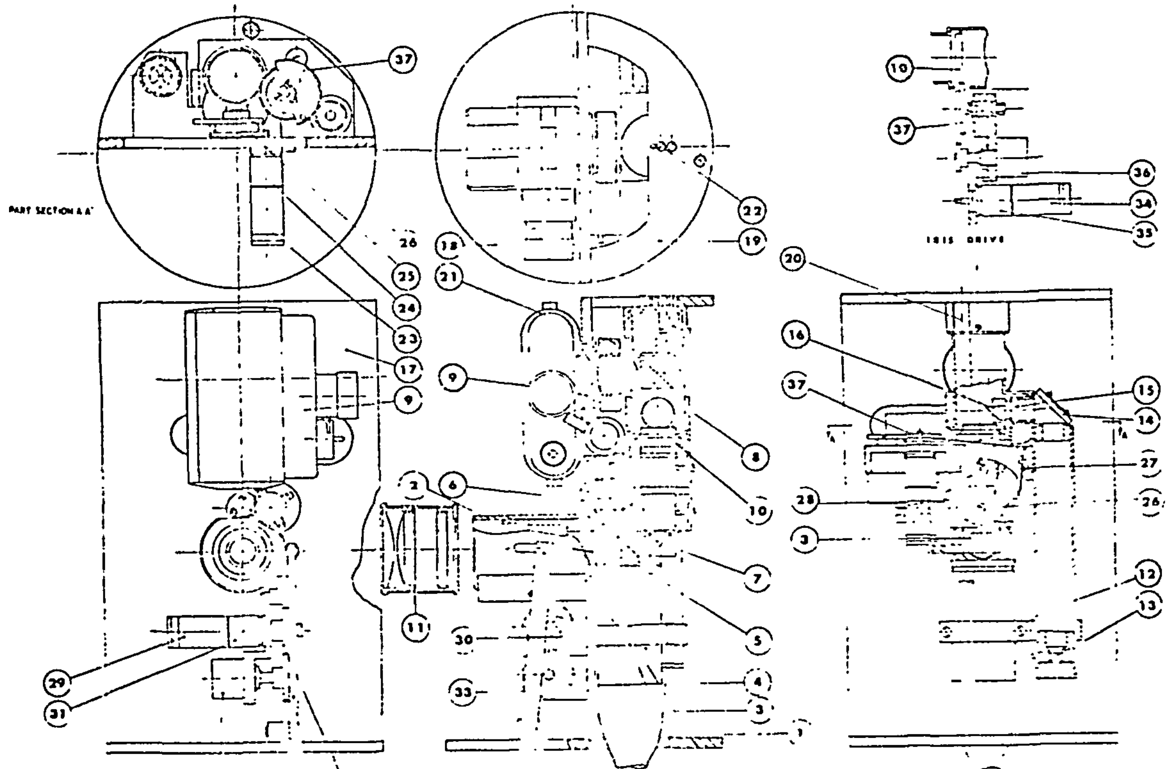


FIG.1 CAMERA DETAILS

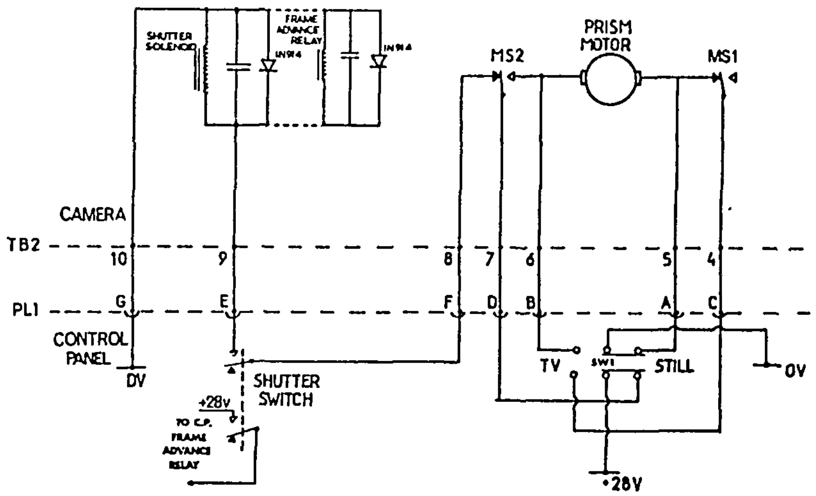


FIG.2 SHUTTER AND STILL / TV OPERATION

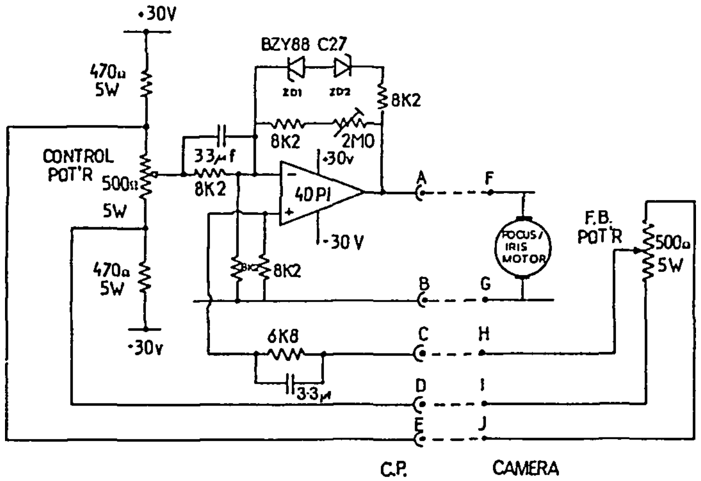


FIG.3 FOCUS AND RIS SERVO CONTROL

CABLE DETAILS

	FOCUS	IRIS
A	PL 2 C	PL 2 B
B	PL 2 A	PL 2 A
C	PL 3 F	PL 3 C
D	PL 3 G	PL 3 D
E	PL 3 E	PL 3 B
F	TB1. 1	TB1. 9
G	TB1. 2	TB1. 2
H	TB1. 7	TB2. 2
I	TB1. 6	TB2. 3
J	TB1. 8	TB2. 1

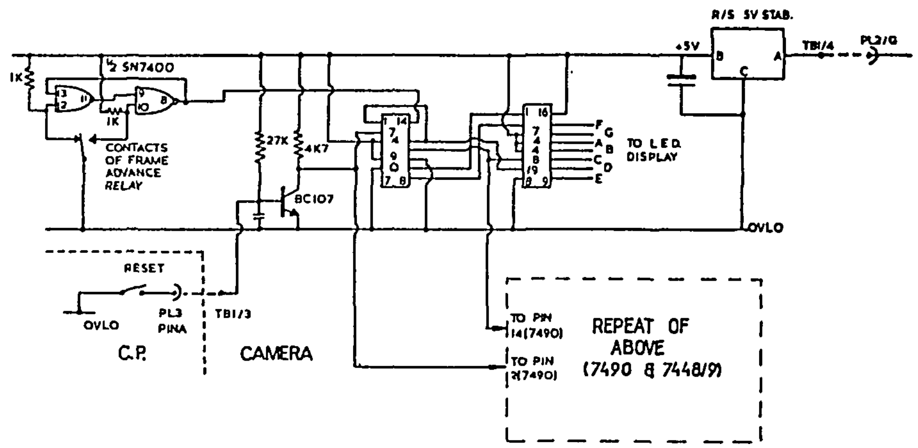


FIG.4 CCT DIAGRAM OF FRAME Nº DISPLAY UNIT

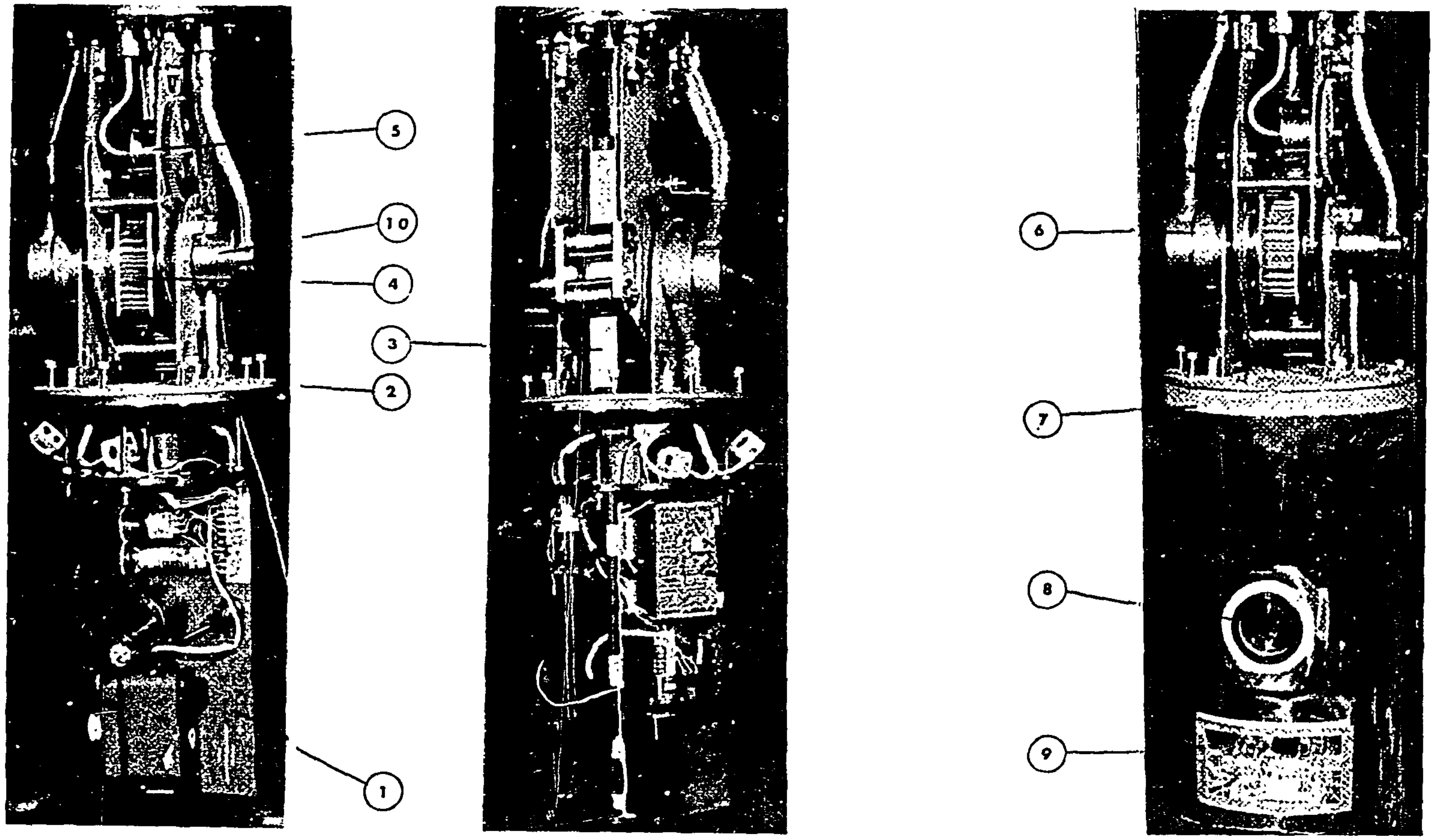
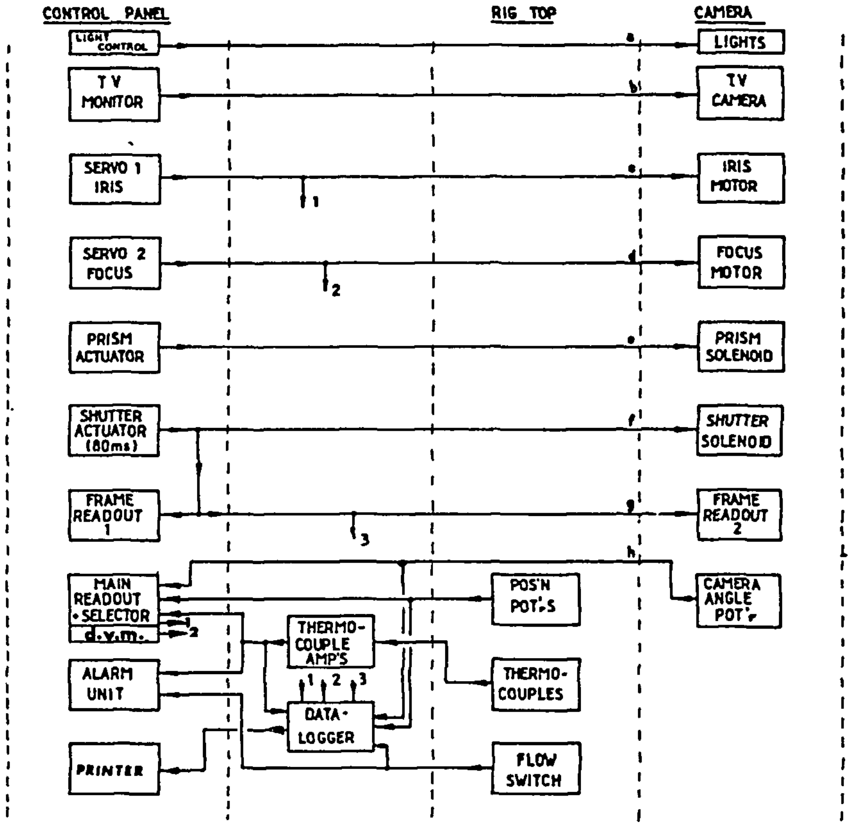


FIG.5 CAMERA MOUNTED FOR P.F.R. INSPECTION



CABLE	No OF CORES	
a	2 CORE (¼" OD)	
b	24	SPECIAL HIGH TEMP CABLE
c	5	
d	3	
e	3	3 x 7 CORE HIGH TEMP
f	2	
g	3	
h	3	

FIG. 6 P.F.R. INSPECTION EQUIPMENT
CONTROL AND MONITORING SYSTEM BLOCK DIAGRAM

REPORT SUMMARY SHEET

Central Electricity Generating Board
Berkeley Nuclear Laboratories

UNCLASSIFIED

RD/B/N2646
Job No. XJ 065

A Television/Still Camera, with Common Optical System, for Reactor Inspection

- by -
G. Hughes and P. McBane

March 1973

SUMMARY

One of the problems of reactor inspection is to obtain permanent high quality records. Video recordings provide a record of poor quality but known content. Still cameras can be used but the frame content is not predictable. Efforts have been made to combine T.V. viewing to align a still camera but a simple combination does not provide the same frame size. The necessity to preset the still camera controls severely restricts the flexibility of operation. A camera has, therefore, been designed which allows a search operation using the T.V. system. When an anomaly is found the still camera controls can be remotely set, an exact record obtained and the search operation continued without removal from the reactor.

An application of this camera in the environment of the blanket gas region above the sodium region in PFR at 150°C is described.

D. B. Friend, A. Jones, "Closed Circuit Television Equipment Developed by Berkeley Nuclear Laboratory for Use on the Dounreay Prototype Fast Reactor". (United Kingdom)

1. INTRODUCTION

Visual inspection by means of closed circuit television has been used in PFR on a number of occasions. Equipment used in two recent inspections will be described, together with a further camera which is at the development stage.

2. *SUPERHEATER INSPECTION*

There is a penetration in the tube plate of PFR superheaters which is normally occupied by a sodium level gauge, (see figure 1). If the gauge is replaced by a t.v. camera, the innermost tubes in the region of the tube plate can be inspected. A suitable camera assembly was constructed to meet the following requirements:

(1) The camera, including necessary lighting, must pass through an 1½" diameter hole to a depth of approximately 3ft.

(2) The focus must be adjustable from 4" to infinity, since the access hole is not on the superheater axis.

(3) The equipment must operate in an ambient temperature of approximately 100°C.

The assembly shown in figure 2 fulfills these requirements. It comprises a 0.75" diameter monochrome camera fitted with a 15mm F/2.9 lens, giving an angular field of view of approximately 20° . Figure 3 shows the component parts and figure 4 the detailed arrangement of the optical assembly. This is fixed inside the lower end of the 1¾" diameter outer tube by an end plug. The t.v. camera is rigidly attached to the lower end of the inner tube. In order to focus, the camera is moved with respect to the optical unit by driving the inner tube with a screw thread. Cables pass within the inner tube and are sealed at the cable entrance by a PTFE plug. Cooling gas enters the space between inner and outer tubes, flows downwards over the camera and bulb and out into the vessel.

In operation, the height of the viewing port in the vessel is set by an adjustable collar on the outer tube and the direction of view may be panned manually.

The equipment performed satisfactorily during trials and was convenient to use. In an ambient temperature of approximately 85°C the camera temperature was held below 28°C by a flow of argon. Figure 5 shows a photograph, taken from the monitor screen during laboratory tests from which picture quality can be assessed. Although there is some obvious distortion, the picture quality was adequate for this inspection. The camera manufacturers claim to have improved later model cameras to reduce these effects.

3. EVAPORATOR INSPECTION

The 0.75" diameter camera is small enough to be inserted into PFR evaporator tubes. These U tubes are approximately 17' long with a bend radius between 2" and 30" as shown in figure 6. The camera is fitted with a lens, 45° mirror and ½ watt prefocus bulb to observe the tube wall (see figure 7). A 15mm focal length lens gives a field of view of approximately 0.25 x 0.19". With this equipment only the straight arms could be inspected and consequently a similar camera fitted with a ¼" diameter, 3ft long, coherent fibre-optic bundle was used to observe the bends (see figure 8). In this case, the wall is illuminated by a ring of seven 1 watt filament bulbs giving a similar field of view.

In each case the lighting cable is loaded into the tube to be inspected first. The equipment is then passed through the tube by pushing on the camera cable whilst tensioning the lighting cable. The picture quality obtained was adequate in both cases, but the resolution is considerably degraded by the use of a fibre-optic system. The discrete nature of the bundle is one cause of this degredation which can be lessened by increasing the number of fibres in the image, (in this case there were approximately 7×10^4). Another cause is the lowering of the faceplate illumination. Since, within the space available, the scene brightness could not readily be increased, the situation could be improved by redesigning the image transfer optics where the largest loss of light occurs.

In both systems, the field of view is such that small detail can be readily seen. If the overall surface condition is to be observed, a shorter focal length objective lens is desirable.

4. EQUIPMENT AT THE DEVELOPMENT STAGE

For situations in which space restrictions are less stringent, equipment is being developed using a 1" vidicon tube which produces better picture quality. The prototype is shown in figure 9 and measures 18" long with a maximum diameter of 4¼". It incorporates a miniature zoom lens giving a wide angle view combined with the ability to examine fine detail. The direction of view is varied by rotating the camera about the y axis and independantly tilting the mirror about the z axis. These functions, together with focus and zoom setting, are remotely controlled by electric motors.

Figure 10 shows a wide angle view (40^o) obtained with this equipment and figure 11 the narrow angle view (8^o) at a range of 3½ft. The camera can be focused over the range 3½ft to infinity. However, a close-up attachment is available to cover the range 3½ft to 1½ft.

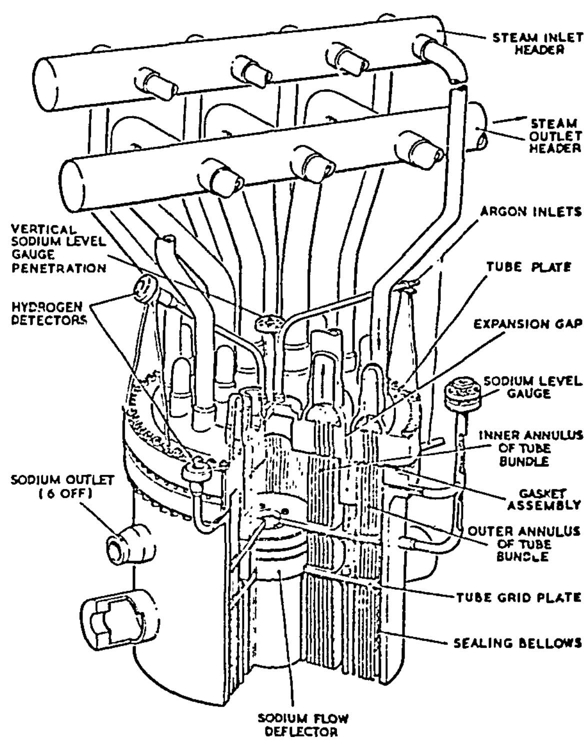


FIG. 1. Upper Region of PFR Superheater

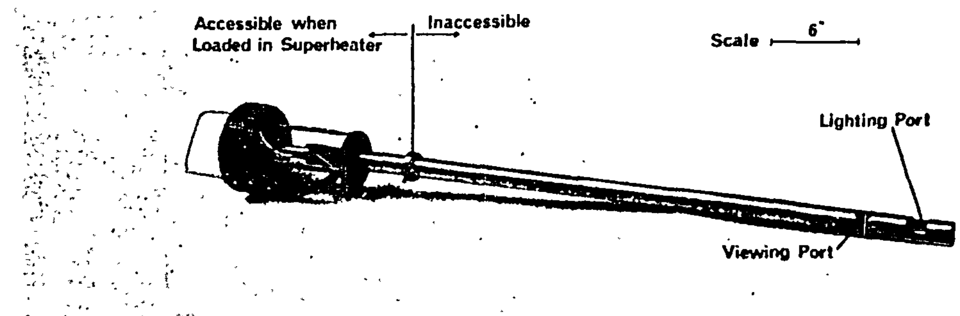


FIG.2 The Assembled Camera

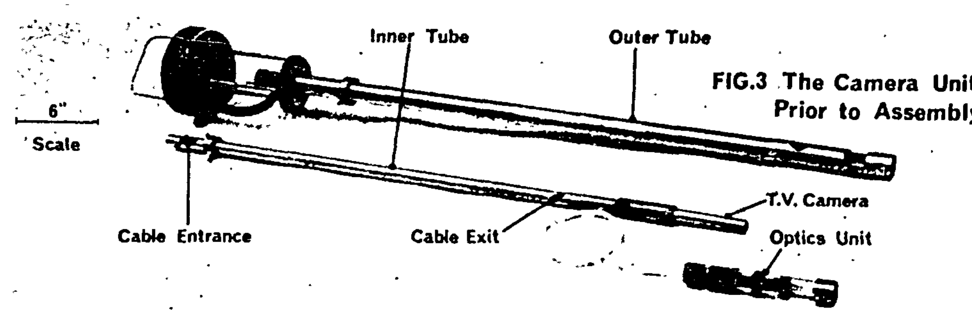


FIG.3 The Camera Unit Prior to Assembly

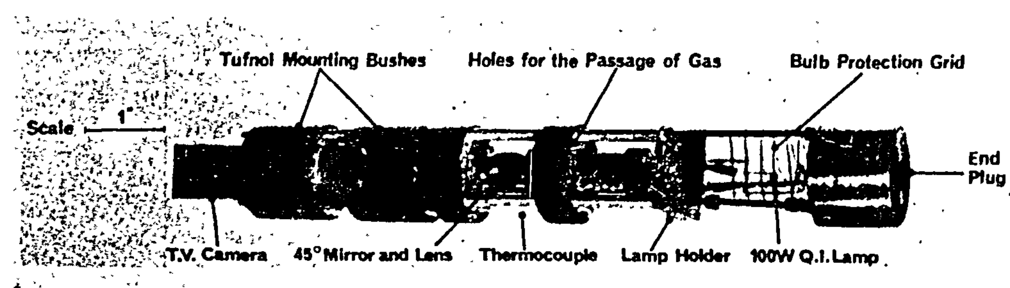
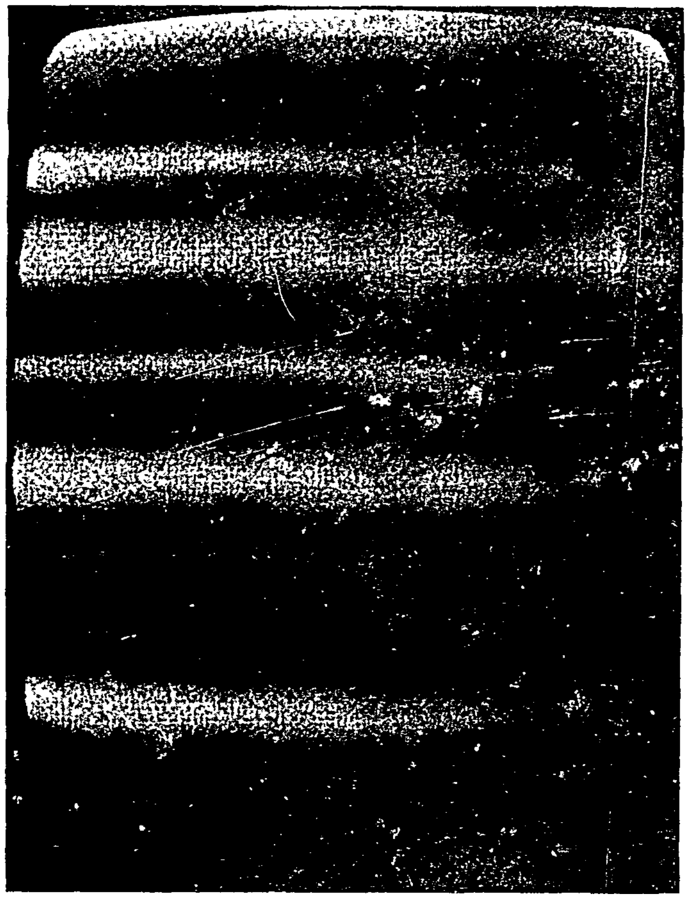
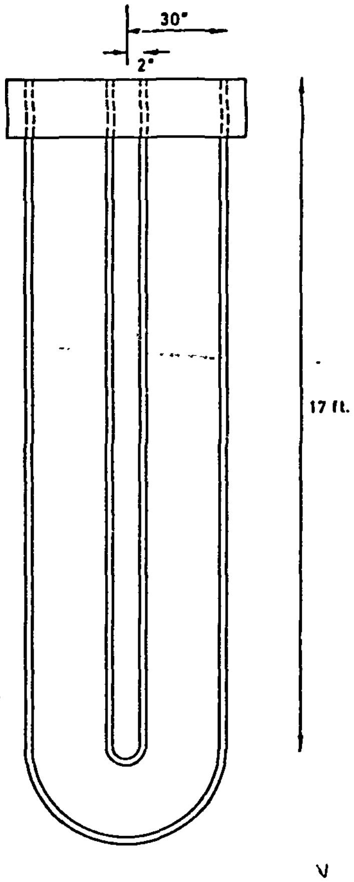


FIG.4 The Optics Assembly



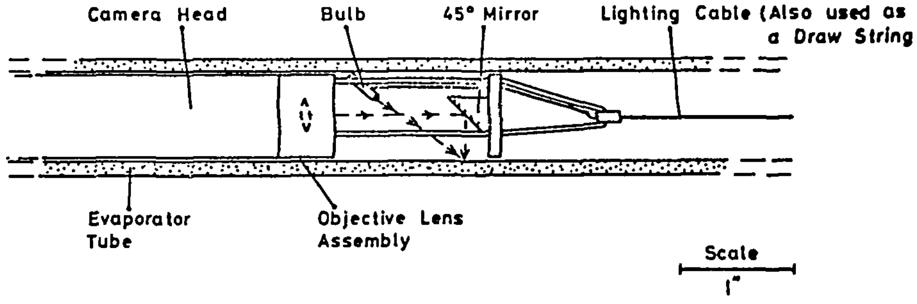
T.V. Picture of Model Superheater Tubes.

FIG. 5.



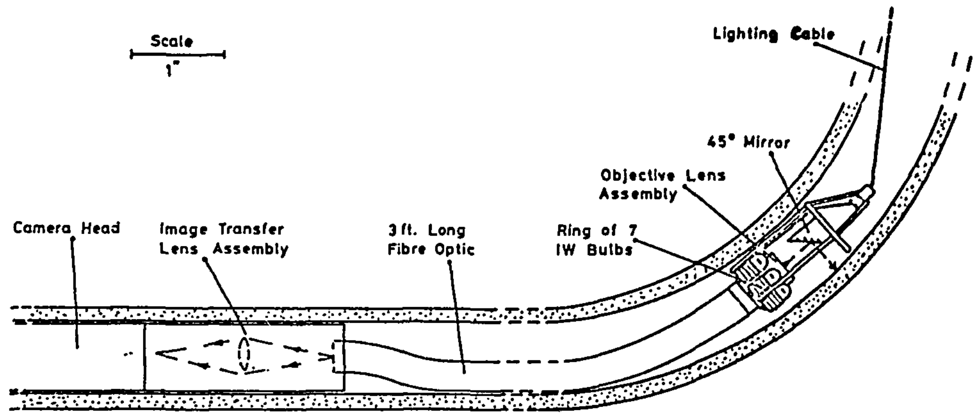
Schematic Representation of Evaporator

FIG. 6.



Equipment for the Internal Inspection of Evaporator Tubes (Straight Portions).

FIG. 7.



Equipment for the Internal Inspection of Evaporator Tubes (Bends).

FIG. 8.

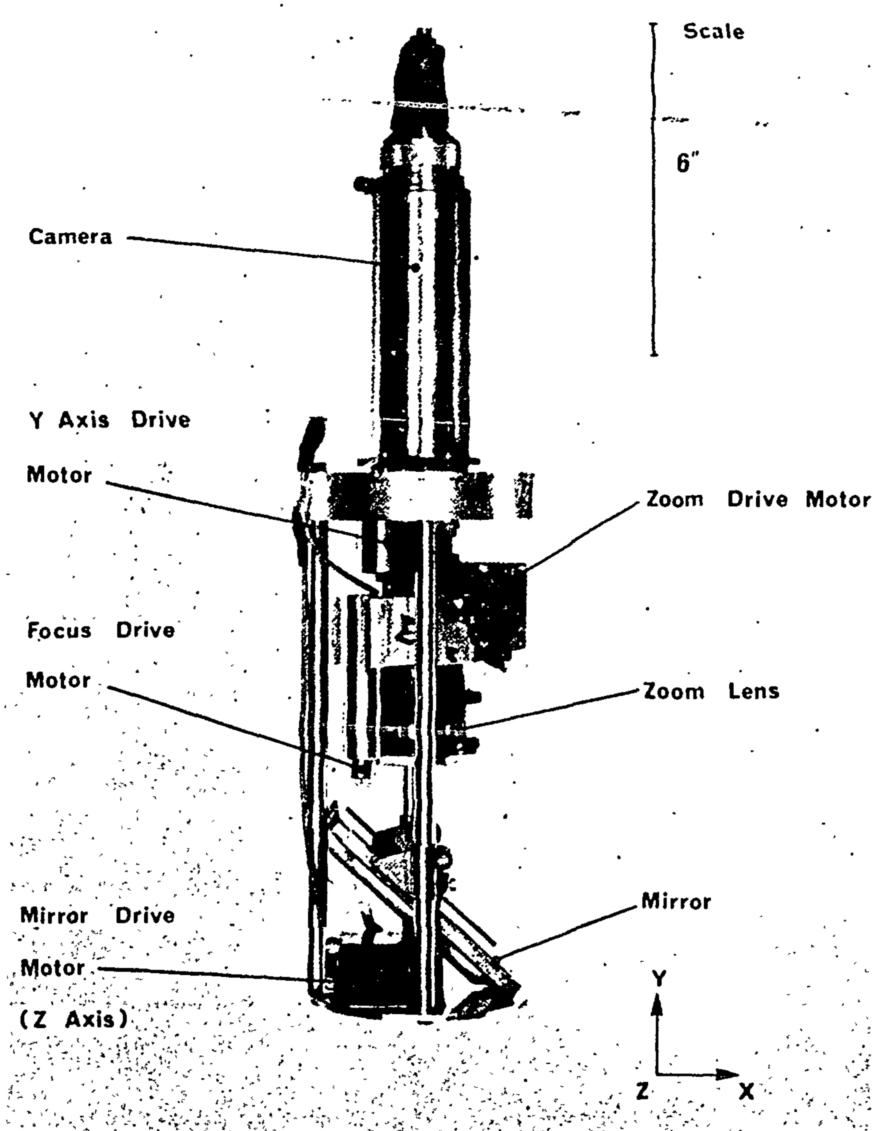


FIG. 9. Prototype Equipment Using a 1" Vidicon Camera

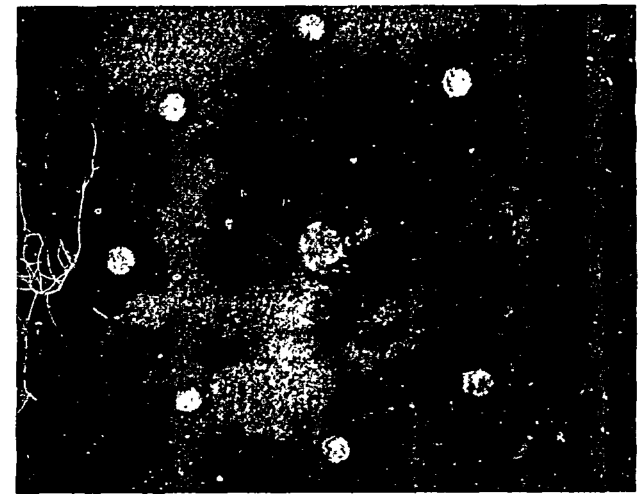


FIG. 10. Zoom Lens Field of View (Wide angle)

FIG. 11. Zoom Lens Field of View (Narrow angle)

K. J. Cowburn, "Inspection of PFR Steam Generators". (United Kingdom)

The PFR Steam Generators are arranged in three circuits, each containing an evaporator, superheater and reheater. Commercial introscopes have been used for the inspection of the straight portions of the tubes with television and fibre optics to examine the bends. Eddy current equipment has been developed for the measurement of bore defects in ferritic and austenitic tubes and for wall thinning in austenitic tubes. Ultrasonic devices are in the final development stages for the tube outer surface (OD) examination.

The inspection requirement for each tube bundle is for systems capable of detecting defects in both the bore and outer surface of the tubes; specifically, pitting and cracking in the bore surface and fretting and thinning on the outer. Full 100% inspection of bend and straight portions is required together with an examination of the tube plate and in particular the tube-tube plate weld region.

EVAPORATOR TUBING

The evaporator units each contain 498 'U' tubes of $2\frac{1}{4}$Cr 1Mo Nb stabilised ferritic steel, 25mm OD, 2.3mm wall welded by internal bore fusion into a tube plate of $2\frac{1}{4}$Cr 1Mo steel 400mm thick. Each leg is 4920mm long with the bend radius ranging from 68mm to 650mm. The 'U' tube assembly rests upon the upper flange of the vertical shell and in turn supports the closure head. Examination during shutdown is performed in situ and is facilitated by the ready access available when the head is removed.

An eddy current system has been developed and Fig 1 shows the equipment during a site inspection of the No 3 evaporator bundle.

The system operates at 400KHz and employs specially designed, flexible rotating probes capable of examining the bore of the straight legs and the 'U' bends as far as the bend centre line. The rotating probe contains two search coils, differentially wound, in the plane of the tube wall and in close proximity to the bore surface. The probe head can be seen in Fig 2 and in Fig 3 the flexible drive assemblies and motor housing. This housing, whose diameter is 19.7mm, also contains the rotary transformer necessary to connect the rotating heads to the rigid cable system. The method is capable of detecting surface defects as shallow as 0.1mm and will accurately quantify within the range 0.1–0.5mm deep. At the operating frequency the "skin effect" prevents accurate sizing of defects greater than 0.5mm deep and precludes the inspection of OD defects. The extra coverage required will be achieved by the use of an ultrasonic system. This arrangement comprises a multiplexed array of transducers mounted in a spiral about the tube axis, each probe scanning a sector of the probe periphery as the assembly is withdrawn through the tube. Preliminary trials have suggested an accuracy of better than 0.0125mm for wall thickness measurements down to 1mm. The system is nearing completion.

SUPERHEATER AND REHEATER TUBING

In contrast to the ferritic evaporator both these units are made in Type 316 stainless steel and a different closure head design is used. The tube plate is itself the vessel closure plate with two concentric hemi-toroidal manifolds.

These are permanently welded to the antler pipes which lead up to the main headers. Access to the tube plate face is therefore restricted to a series of hand holes. These are shown in Figs 4 and 5. The limited headroom which in places reduces to some 60mm aggravates the manipulation problems. Despite these restrictions equipment has been developed to provide intrascopic and eddy current inspection of the 'U' tubes.

Each superheater has 520 tubes of 15.9mm OD x 2mm wall thickness with straight legs approximately 8.2m long and 'U' bends varying from 105–215mm mean radius.

Special test coil probes were developed for each unit. These contain an exciting coil and two search coils, differentially wound, lying normal to the tube axis. This can be seen in Fig 6 which also shows the articulation necessary to achieve entry to tubes not directly below a hand hole. 90KHz has been found to be the optimum frequency for testing the reheater tubing and 30KHz for the thicker section superheater tubes. The sensitivity depends upon the type and position of the defect. Cracklike defects in the bore are detectable at approximately 10% wall thickness and at the OD at approximately 20%. As the technique integrates over a complete tube section it is not very sensitive to fine pitting but wall thinning on the OD can readily be detected.

TUBE PLATE EXAMINATIONS

All units are amenable to examination from the tube holes using suitable diameter eddy current probes. However, as this can only identify defects either breaking the surface or very close to it ultrasonic techniques have also been applied.

Two basic approaches have been made, both being applied from the tube hole. One is a simple 2MHz twin crystal compression probe assembly which projects the ultrasound radially to examine the ligaments between adjacent holes. The beam, as applied, is essentially horizontal and is therefore optimised for vertical curtain cracks between tube holes. With the high attenuation material considerable fall off in sensitivity occurs with distance but adequate remains for ligaments at 50mm range. The effectiveness of the technique has been satisfactorily demonstrated on a series of test blocks.

Site examinations using this technique have confirmed and defined defective areas within superheater tube plates. Fingerprint information will be compared with subsequent examinations to monitor any crack growth and thereby the efficacy of modified operation procedures.

The second probe assembly contains transmitter and receiver crystals for surface shear waves which travel around the wall of the hole into which the probe is placed. The information is thus similar to an eddy current inspection in that little penetration occurs and the search is restricted to the surface layer.

FIG 1 EXAMINATION OF NO 3 EVAPORATOR TUBE BUNDLE

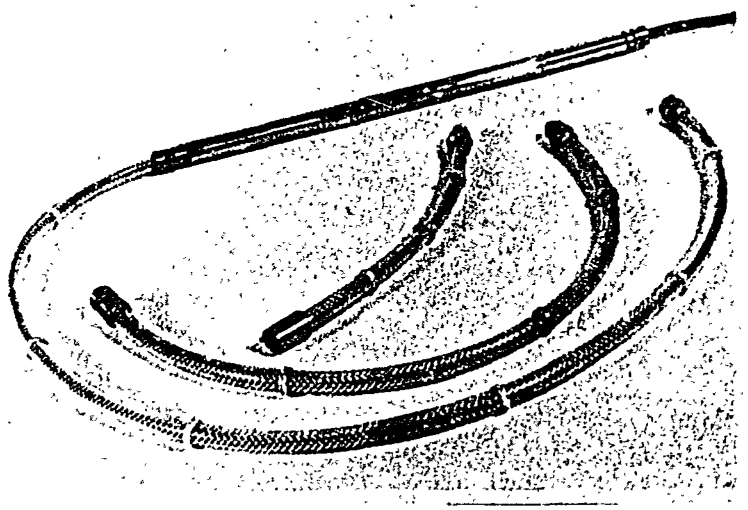


FIG 3 FLEXIBLE DRIVE AND MOTOR HOUSING ASSEMBLY

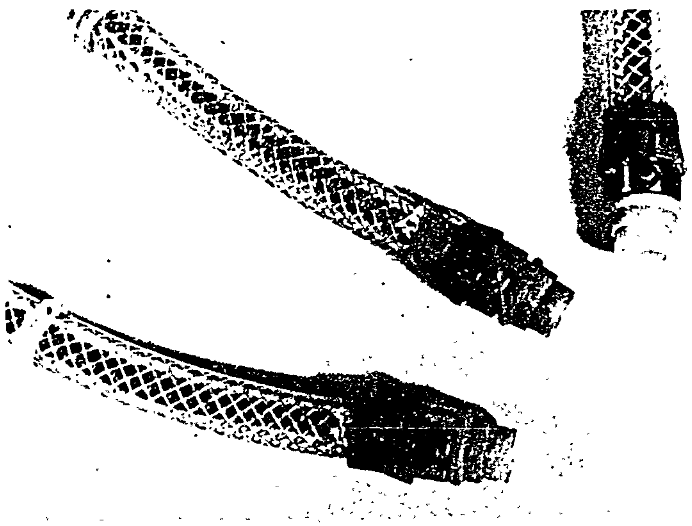


FIG 2 EDDY CURRENT PROBE HEADS FOR EXAMINATION OF EVAPORATOR TUBES

FIG 4 ACCESS TO REHEATER OUTER TOROID

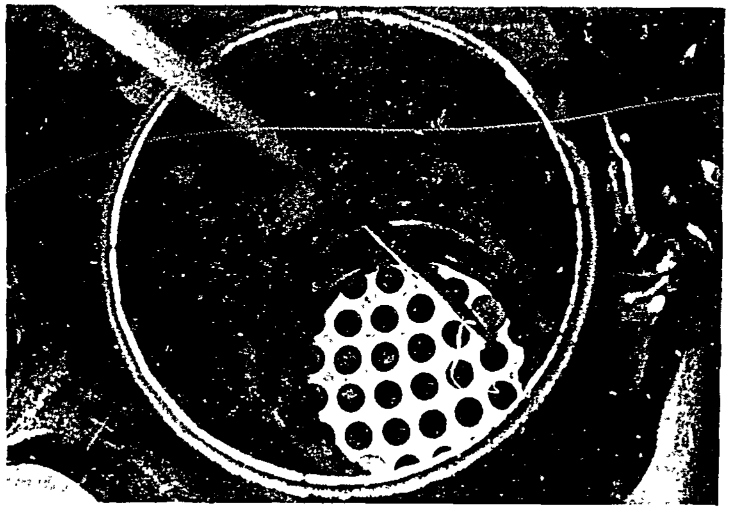


FIG 5 EXAMINATION VIA INNER TOROID HANDHOLE

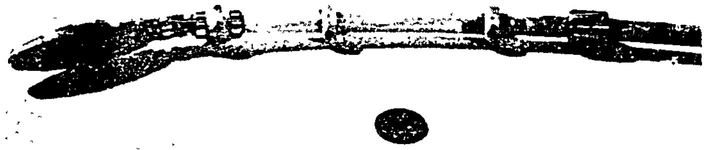


FIG 6 PROBE ASSEMBLY

A. Bret, B. Gallet, E. Tomachevsky, "In-Service Inspection and Monitoring of LMFBR in France". (France)

1 - INTRODUCTION

Le titre de la réunion "In-Service-Inspection and Monitoring of LMFBR'S" résume bien les deux grandes familles de moyens qui sont utilisées pour connaître l'état des structures des principaux composants d'une centrale nucléaire : Réacteur, générateurs de vapeur ...

L'Inspection en Service est réalisée périodiquement lors des arrêts du réacteur, généralement en temps masqué par rapport à la manutention des assemblages. Les méthodes sont souvent identiques à celles utilisées pour le contrôle de la fabrication des composants : courants de Foucault (eddy current), ultra-sons (ultra sonic), méthode visuelle quand cela est possible. Cependant le milieu ambiant est hostile : rayonnement, température ; il nécessite des aménagements et la mise en oeuvre à distance des matériels de contrôle.

La surveillance continue des structures et des paramètres de fonctionnement du réacteur, indique à tout moment la qualité du fonctionnement de l'ensemble du système. Cette surveillance est réalisée principalement par :

- des mesures physiques : températures, débits, réactivité, activité, contraintes ...

- des mesures de déplacements ...

- la détection de fuite de sodium ...

- une méthode assez récente : l'écoute acoustique.

Dans la suite de cette communication, nous allons essayer de faire le tour des méthodes utilisées en France pour réaliser l'inspection en service et la surveillance des centrales nucléaires à sodium.

2 - METHODES D'INSPECTION PERIODIQUE

2.1. - Méthodes locales - Inspection de surface

2.1.1. - Méthodes visuelles

Trois méthodes ont été développées au CEA pour l'Inspection en milieu actif ou en gaz chaud. Il s'agit :

- du périscope,
- de l'endoscope,
- de la caméra de télévision.

2.1.1.1. - Périscope (figure 1)

Le périscope a été utilisé avec succès sur le réacteur PHENIX pour inspecter les structures du bloc réacteur

situées au dessus du niveau libre du sodium : dessous du toit, du bouchon tournant; la partie haute de la traversée de la rampe dans la cuve interne ..
(figure 2) Passage de la rampe dans la cuve interne.
(figure 3) Vue de dessous du bouchon tournant et du positionneur.

Le matériel utilisé est constitué par :

- un périscope d'environ 4800 mm de long et de 100 mm de diamètre équipé d'un objectif qui pivote dans le plan vertical d'un angle de 125°, l'ensemble du périscope tourne autour de son axe sur 360°.

  Le périscope est implanté dans une traversée standard du bouchon tournant par l'intermédiaire d'un sas chauffant qui assure le préchauffage de l'objectif.

  La température maximale d'utilisation est 180° C.

  Le périscope peut être équipé d'un appareil photographique.

- un projecteur de dimensions identiques à celles du périscope, dont la lampe (puissance 650 W) est refroidie par un débit d'argon.

Les photographies réalisées à l'aide de ce matériel sont de bonne qualité.

2.I.I.2 - Endoscope

L'endoscope a été utilisé avec succès sur le réacteur PHENIX pour examiner les dépôts d'aérosols dans l'espace annulaire entre la dalle et le bouchon tournant. Il est introduit dans des trous, équipés de vannes, prévus à l'aplomb de l'espace annulaire

(figure 4) Vue de l'espace annulaire entre le bouchon tournant et la dalle partie haute.

(figure 5) Vue du même espace annulaire partie médiane

Il est à remarquer qu'il n'y a pratiquement pas de dépôts.

2.I.I.3. - Caméra de télévision. (figure 6)

La caméra de télévision est utilisée couramment sur le réacteur RAPSODIE.

L'ensemble est constitué par une perche rigide terminée en partie basse par une caméra de télévision conçue pour travailler sous rayonnement, refroidie par une circulation d'azote.

L'ensemble permet la visée axiale et la visée radiale, dans ce dernier cas l'extrémité de la caméra est équipée d'un miroir fixe à 45°. L'ensemble de la perche et de la caméra tourne autour de leur axe vertical.

L'éclairage (2 ou 3 lampes à iode) est situé à l'extrémité de la caméra autour de l'objectif. Ces mêmes lampes assurent le préchauffage et le chauffage de l'objectif et du miroir.

La température maximale d'utilisation est 150° C.

L'exploitant du réacteur RAPSODIE est satisfait de son matériel.
(figure 7) Sodium à 150° vue de dessous des têtes d'assemblages.

2.I.I.4. - Réacteur SUPER PHENIX.

Sur le réacteur SUPER PHENIX il est prévu d'utiliser :

a) 2 périscopes :

- un périscope court (longueur 5 mètres) pour inspecter au dessus du sodium au niveau nominal lors des manutention d'assemblages.

- un périscope long (longueur 15 mètres) pour inspecter lors de la baisse du niveau sodium au dessous des têtes d'assemblages.

Les projecteurs associés seront équipés de lampe de 1000 W.

Le périscope long pourra être implanté soit sur le Bouchon Couvercle Coeur, soit sur le Grand Bouchon Tournant; le petit périscope pourra être implanté sur le Grand Bouchon Tournant

b) L'endoscope :

Des trous sont prévus au droit des espaces annulaires pour implanter un endoscope.

c) L'inspection visuelle de l'extérieur de la cuve principale de SUPER PHENIX est également envisagée. Le dispositif, composé d'un chariot (figure 8) équipé d'une caméra de télévision se déplace entre la cuve principale et la cuve de sécurité. Ce dispositif en cours d'étude est décrit dans le rapport joint en annexe I : "IN SERVICE INSPECTION OF THE MAIN VESSEL OF SUPER PHENIX"

2.I.2. - Les méthodes utilisant les particules magnétiques, les liquides pénétrants, le potentiel électrique et l'holographie acoustique n'ont pas été développées en FRANCE pour l'inspection des réacteurs rapides à sodium.

2.1.3. Contrôle par courants de Foucault

Cette méthode est en cours de mise au point et d'essais pour le contrôle des générateurs de vapeur du réacteur SUPER PHENIX. (Fig. 9)

Le but de cette inspection est le contrôle périodique de la santé des tubes des générateurs de vapeur et la recherche des tubes détériorés par l'effet de chalumeau lors d'une petite réaction sodium eau.

La longueur des tubes à contrôler peut atteindre 80 mètres. Suivant le type de générateur de vapeur :

- les matériaux à contrôler sont : l'Incoloy 800, l'acier austénitique ou l'acier ferritique.
- les diamètres extérieurs des tubes varient de 18 à 25 mm, l'épaisseur de 2,3 à 3 mm.

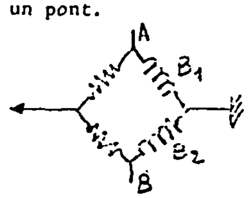
L'appareillage utilisé comprend :

- une partie détection, transmission et traitement du signal
- une partie mécanique constituant le support.

a) La partie détection, transmission et traitement du signal comprend :

- deux bobines de détection B1 et B2 implantées dans la sonde et reliées à un pont.

Amplificateurs traitement du signal



tension alternative entre A et B

- deux conducteurs coaxaux
- un ou plusieurs générateurs de fréquences alternatives
- un ensemble de traitement du signal, de visualisation et d'enregistrement.

L'interprétation des signaux reçus est très délicate : la différence entre les signaux dus à des défauts dans le tube (fissure, corps de chalumeau...) et les signaux dus aux variations géométriques du tube (variations locales d'épaisseur) ou à l'environnement du tube (grille support du faisceau tubulaire, gouttes de sodium) est difficile à réaliser.
Pour résoudre partiellement ce problème, les deux bobines de la sonde sont alimentées simultanément par 2 fréquences sinusoïdales très différentes. La combinaison des signaux de sortie permet d'éliminer un paramètre à la fois : soit les entretoises, soit les gouttes de sodium ...

Des essais satisfaisants ont été réalisés.

Le CEA pense réaliser au cours de cette année des essais avec trois fréquences sinusoïdales superposées ce qui permettrait d'éliminer 2 paramètres à la fois.

b) La partie mécanique comprend :

- la sonde comportant les deux bobines de détection et deux centrages à griffes assurant le positionnement des bobines dans le tube.

- le câble à deux conducteurs coaxiaux (diamètre extérieur 8 mm) guidé par des olives fixées tous les 15 cm sur le câble.

- un réservoir sous pression contenant le tambour de stockage du câble et son système de déroulement. L'enceinte est reliée au tube du générateur de vapeur à examiner par l'intermédiaire d'un tube souple.

La sonde, la gaine du câble et les olives sont réalisées avec une résine à faible coefficient de frottement. L'avance de la sonde dans le tube est assurée par la pression contenue dans le réservoir.

Lors de l'inspection, le générateur de vapeur est vidangé côté eau et côté sodium.

Les résultats obtenus actuellement sont les suivants :

- Une sonde à été enfilée dans un tube en hélice sur une longueur de 80 mètres de longueur, puis extraite. Le dépouillement des mesures effectuées est en cours.
- La sensibilité de la méthode sur des tubes neufs est la suivante :
  . sur les tubes en incoloy ou en acier austénitique, sensibilité de 10 % de l'épaisseur pour des fissures longitudinales ou des amincissements.
  . sur les tubes en acier ferritique cette sensibilité n'est que de 30 %.

En exploitation industrielle, le CEA pense aboutir à des sensibilités respectivement de 15 % et 35 % à l'aide du système utilisant les 3 fréquences.

A noter que cette méthode a été aussi développée pour l'inspection des Générateurs de vapeur des réacteurs à eau pressurisée. L'inspection avant divergence des réacteurs de FESSENHEIM est en cours.

2.1.4. Mesure des déplacements en Réacteur des têtes d'assemblages combustibles par ultrasonographie (Fig. 10, 11, 12 et 12 bis)

- Déplacement latéral des têtes d'assemblages

La mesure du déplacement s'effectue à partie d'un dispositif spécial introduit dans un canal expérimental. La méthode consiste à visualiser, par ultrasonographie, une configuration de 7 assemblages et à mesurer, sur le relevé cartographique, leur positionnement relatif et leur positionnement par rapport à l'axe du canal expérimental.

Dans PHENIX cette méthode doit permettre de visualiser 21 assemblages répartis en 3 groupes.

- Déplacement vertical des assemblages

Le répérage de l'allongement des assemblages par rapport à un niveau défini sur le dispositif peut être fait en même temps que l'ultrasonographie. La méthode interferomètrique ultrasonore en impulsions se prête bien à cette mesure.

- Dispositif mécanique immergé

Le dispositif mécanique permet le déplacement d'un transducteur piezoélectrique haute température et d'un miroir localisant associé. Le principe de déplacement du transducteur repose sur les propriétés du parallélogramme déformable articulé à un guidage rectiligne et à un centre d'oscillation. (fig. 10)

- Essais effectués

Le relevé ultrasonique a été effectué en eau, les essais en sodium n'ont porté jusqu'à présent que sur la mécanique proprement dite. (fig. 11, 12 et 12 bis)

2.1.5. Ultrasonographie d'une plaque tubulaire d'échangeur SUPER-PHENIX. (figure 13)

On a procédé à plusieurs relevés ultrasonographiques en eau, d'un élément de plaque tubulaire SUPER PHENIX comportant 15 tubes soudés suivant un pas rectangulaire.

Ces relevés ont été effectués en utilisant conjointement la méthode impulsion écho, le technique du balayage mécanique en immersion, des transducteurs haute température (4 MHz), un dispositif à miroir focalisant.

2.2. - Méthodes locales - Inspection de volume

2.2.1 - Contrôles radiographiques

A notre connaissance le seul exemple d'utilisation de la radiographie sur du matériel radioactif est le dispositif de radiographie du canal d'irradiation des dispositifs d'essais du réacteur expérimental PEGASE. Ce matériel était équipé d'un système de grille tournante en plomb pour éviter que le film sensible soit voilé par les rayons gama émis par le canal d'irradiation.

Par contre, la radiographie (ou la gamagraphie) est utilisée pour le contrôle des structures et des circuits non actifs. Cette méthode permet de comparer facilement les clichés réalisés lors de la fabrication et du montage et ceux réalisés lors de l'inspection en service.

Au mois d'Août 1975 certaines parties des générateurs de vapeur ont été contrôlées par gamagraphie (figure 14) en particulier la position des grilles support des tubes d'eau ainsi que la position de ces tubes d'eau par rapport au tube de sodium, ceci dans les coudes.

L'examen avait été satisfaisant.

2.2.2. Contrôle par ultra-sons

Cette méthode de contrôle est envisagée pour l'inspection en service de la cuve principale de Super Phénix :
Un capteur à ultra-sons focalisé est aussi implanté sur le chariot se déplaçant entre la cuve principale et la cuve de sécurité, le couplage est obtenu par un liquide (Fig 8).

Ce dispositif est décrit dans le rapport joint en annexe 1 : "In Service Inspection of the main vessel of Super Phénix."

2.2.3. Neutronographie, gama scanning

Nous pensons qu'il ne faut pas oublier de signaler ces deux méthodes qui permettent d'obtenir de précieux renseignements sur l'état du combustible. Malheureusement l'assemblage combustible doit être extrait du réacteur pour être examiné.

La neutronographie est utilisée pour l'examen des assemblages du réacteur PHENIX.

2.2.4. Contrôle des sous-collecteurs des générateurs de vapeur de PHENIX, suite à la fuite d'eau intervenue le 24 novembre 1975

(fig. 14 et 15)

Après avoir détecté la fuite d'eau sur le générateur de vapeur n° 1 au niveau de l'alimentation de l'évaporateur, il fut procédé à l'examen par gamagraphie et par ultra-sons de tous les sous collecteurs d'alimentation des 3 générateurs et des tubes partant vers les générateurs en 4 niveaux : repères 1,2,3 et 4 de la figure 16. Cet examen a permis de déterminer que :

- les manchons B en A 48 situés entre le sous-collecteur A et le tube C pénétrant dans le générateur de vapeur (partie évaporateur) sont plus ou moins érodés (épaisseur initiale 7 mm).

- les tubes C sont en bon état

- aucune loi de répartition des manchons usés ne peut être dégagée.

- les manchons les plus usés sont tous situés sur le même sous-collecteur.

Après examen, il résulte qu'une érosion -corrosion est provoquée par le jet d'eau instable sortant à grande vitesse du diaphragme D .

Il fut donc décidé à court terme :

- sur les générateurs de vapeur 2 et 3, de protéger les manchons dont l'épaisseur était inférieure à 5 mm par des manchettes intérieures en acier inoxydables, l'épaisseur relevée la plus faible étant de 4,3 mm (l'épaisseur de rupture donnée par le calcul est de 2,9 mm).

- après autorisation des services compétants, le réacteur est redémarré le 11 décembre 1975 avec 2 boucles sur 3.

- par la suite, le sous-collecteur défectueux du générateur de vapeur n° 1 a été changé.

A long terme :

- un nouveau modèle de diaphragme est étudié
- tous les sous-collecteurs seront changés.

Pendant l'arrêt de janvier 76, un nouveau contrôle par gamagraphie et ultra-sons a été réalisé, contrôle qui a permis de :

- voir l'évolution de l'usure par rapport au contrôle de décembre
- de déterminer une loi d'usure des manchons non protégés et des manchons protégés et d'évoluer ainsi leur "temps de vie".

2.3. Expérience d'une inspection improvisée de surface et de volume de la cuve de sécurité du Réacteur RAPSODIE (Fig. 16 et 17)

Cette inspection réalisée à l'aide d'un périscope et d'un capteur à ultra-sons avait pour but de contrôler l'état de la cuve de sécurité : corrosion éventuelle de la face extérieure et mesure de l'épaisseur.

Cette inspection fut décidée peu de temps avant sa réalisation; elle fit donc appel à du matériel assez rudimantaire mais efficace.

Cette inspection est décrite dans le rapport joint en annexe II.

2.4. Méthodes globales

2.4.1. Test de pression

Cette méthode n'est pas développée en France pour les réacteurs rapides étant donné que les cuves et les composants contenant le sodium ne sont pas sous pression.

2.4.2. Test d'étanchéité

2.4.2.1. Détection et localisation de fuite de gaz radioactif sur le réacteur RAPSODIE.

La détection d'une fuite de gaz actif est réalisée à l'aide du système DPGR (Détection de particules de gaz radioactifs) qui prélève dans chaque local du bâtiment réacteur une petite partie du gaz ambiant Lorsqu'une contamination de gaz radioactif est détectée, le local est isolé et, à l'aide d'un tuyau souple branché sur le DPGR, les parties délicates des circuits (raccords...) situés dans le local sont contrôlés.

2.4.2.2. Détection de fuite de sodium entre la cuve principale et la double enveloppe de PHENIX. (Fig. 18)

Le fond de la cuve double enveloppe est cloisonné en 6 secteurs qui comportent chacun une bougie de détection de sodium.

Cette bougie est introduite et positionnée grâce à un tube qui remonte jusqu'au niveau de la dalle.

La bougie est constituée par l'extrémité d'un câble pyroténax à 2 fils nikel, dénudés sur 30 mm, protégés par un capotage.

Chaque bougie est reliée à un système qui compare sa résistance à une valeur déterminée. Lorsqu'il y a fuite, le signal délivré actionne une alarme.

3. METHODES DE SURVEILLANCE EN CONTINU

3.0. Mesures effectuées sur les structures

Parmi les mesures effectuées sur les structures du réacteur nous prendrons comme exemple les mesures de déplacement.

En effet sur PHENIX puis sur SUPER PHENIX, la position du sommier peut être contrôlée en fonctionnement par des moyens optiques.

Dans tous les cas, il s'agit de mesures relatives par rapport à des états de référence.

3.0.1. Réacteur PHENIX

Le dispositif de mesure de la position du sommier comprend :

- 2 perches étanches, remplies d'hélium, liées à la dalle et appuyées sur le sommier. Une mire est positionnée en partie basse de chaque perche au niveau de l'appui sur le sommier ; la fermeture en partie haute est réalisée par un verre au plomb surmontée d'un prisme.
- un théodolite à interférences mesure les variations de la position de la mire, donc du sommier, dans les trois directions X, Y et Z. La précision sur la mesure est $\pm$ 10 mm.

3.0.2. Réacteur SUPER PHENIX

Ce système PHENIX n'a pas pu être reconduit sur SUPER PHENIX car le sommier est entièrement couvert par les bouchons tournants. Il est remplacé par deux mesures indépendantes :

a) Mesure du déplacement des pompes primaires. (Fig. 19)

Les pompes primaires sont liées aux sphères d'alimentation du sommier par un centrage pratiquement sans jeu, et sont supportées au niveau de la dalle par un système assimilable à une rotule. Un miroir fixé sur la pompe reçoit et réfléchit un rayon lumineux.

La déviation du rayon lumineux est donc proportionnelle au déplacement de la pompe, donc au déplacement du sommier dans le plan horizontal.

La précision obtenue sera de l'ordre de 2 à 3 mm.

b) Mesure du déplacement du cercle d'appui du platelage sur la cuve principale. (Fig. 20)

Cette mesure s'effectue entre la cuve principale et la cuve de sécurité. Un rayon lumineux traverse la dalle au travers d'un bouchon équipé d'un verre au plomb, se réfléchit sur un miroir A situé sur la cuve de sécurité, puis sur un miroir B situé sur la cuve principale au niveau de l'appui du platelage, puis à nouveau sur le miroir A.

La déviation du faisceau réfléchi est mesurée à l'aide d'une lunette.

Une première visée permet de contrôler le déplacement du miroir situé sur la cuve de sécurité, une deuxième visée mesure le déplacement de la cuve principale dans le plan horizontal X et Y. L'altitude du cercle d'appui est obtenue par une mesure de distance.

Dans le plan XY, la précision sera de l'ordre de 2 à 3 mm.
Dans le sens vertical, la précision sera de l'ordre de 5 à 7 mm.

3.1. Méthodes acoustiques

3.1.1. Bruits d'origine hydraulique

3.1.1.1. Détection acoustique d'un entrainement d'argon dans le coeur de RAPSODIE.

Au cours d'un démarrage du réacteur Rapsodie ou a constaté une absence quasi totale du bruit de fond acoustique : une vanne d'argon incomplètement fermée permettait un entrainement d'argon dans le sodium du coeur. Après blocage de la vanne le bruit de fond s'est accru progressivement pour se stabiliser neuf heures après à la valeur nominale. L'enregistrement de la puissance moyenne du bruit permet de visualiser ce phénomène. On a là des résultats intéressants sur le temps minimum de dégazage. (Fig.21 et 22).

Un essai d'entrainement d'argon a permis de constater que le seuil de sensibilité est de l'ordre de $5,5.10^{-4}$ en volume (chute de 5 dB de la puissance moyenne du bruit).

3.1.1.2 Ebullition dans RAPSODIE - EXPERIENCE NABO.

BUT DU DISPOSITIF.

Le dispositif NABO a été conçu en vue de provoquer dans le coeur de RAPSODIE une ébullition de sodium à 900°C sous une pression absolue de 1,2 bar.

Cet essai a pour but de contrôler l'efficacité d'un dispositif d'écoute pour détecter l'ébullition dans les réacteurs rapides.

LE DISPOSITIF.

Il est semblable extérieurement à un assemblage RAPSODIE. Il renferme une capsule à double paroi qui contient sept aiguilles en tantale gainées en Inconel. Le dispositif est refroidi par un double circuit de sodium, l'un intérieur, l'autre extérieur à la capsule.

ESSAIS EFFECTUES.

Deux essais d'ébullition ont été effectués.

L'ébullition franche a été nettement détectée et caractérisée par l'analyse par autocorrélation du signal acoustique demodulé.

3.1.2. Bruits d'origine mécanique

3.1.2.1. Détection acoustique sur RAPSODIE.

La détection acoustique permet d'effectuer une surveillance globale d'ensembles mécaniques. Elle peut ne mettre en oeuvre qu'un appareillage peu coûteux composé essentiellement d'un microphone, d'un amplificateur et d'un enregistreur ou alarme. Elle est particulièrement indiquée pour la surveillance d'endroits peu accessibles comme c'est le cas des compartiments des pompes du circuit primaire de Rapsodie.

Mais la méthode ne pourra être utilisable que lorsque les haut-parleurs des compartiments seront débranchés du circuit de transmission d'ordres.

3.1.2.2. Surveillance par détection d'émission d'ondes de contrainte

Quatre voies de détection EOC ont permis d'effectuer la surveillance de la cuve principale à partir de capteurs placés à la tête de quatre suspentes, pendant les diverses étapes de la montée en température de PHENIX. Les éventuelles émissions d'ondes de contrainte n'ont pas pu être détectées en présence du bruit de fond important capté sur les voies.

Un essai de localisation a été tenté et réussi à partir d'une émission effectuée par chacun des quatre capteurs. Il a mis en évidence des trajets de propagation préférentiels.

3.2. Mesures des vibrations

Le suivi vibratoire sur PHENIX revêt les trois aspects suivants :

coeur : à l'aide des fonctions de cohérence appliquées aux mesures de vibration et aux fluctuations neutroniques on peut mettre en évidence des défauts naissants.

machines tournantes : on étudie la signature vibratoire des pompes et des groupes turbo-alternateurs à l'aide de l'analyse spectrale des enregistrements magnétiques effectués sur ces machines au début et à la fin de chaque cycle.

surveillance du mode de refroidissement des structures :

Grâce à l'étude des fluctuations des thermocouples placés sur différents points des structures.

Les développements futurs pour Super Phénix sont essentiellement :

. La construction d'une boucle d'essai de vibration pour essayer des maquettes à l'échelle 1/7 ou 1/8 sous un débit double ou triple.

. La recherche de solutions aux problèmes d'instrumentation et plus particulièrement celui de la durée de vie des capteurs, et celui des parasites industriels.

On dispose à cet effet d'un banc d'essai à l'échelle grandeur 1 : le réacteur PHENIX.

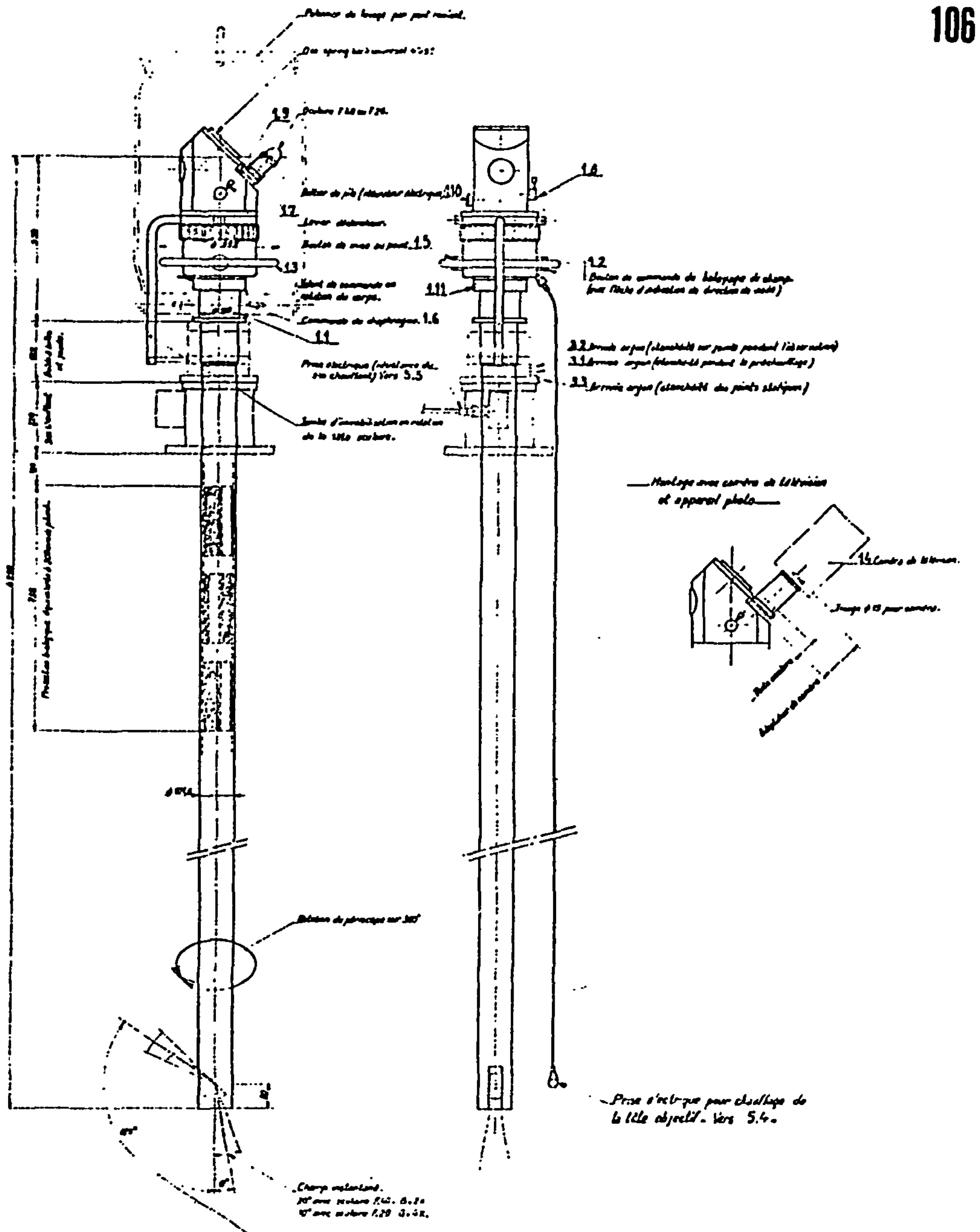


FIG. 1

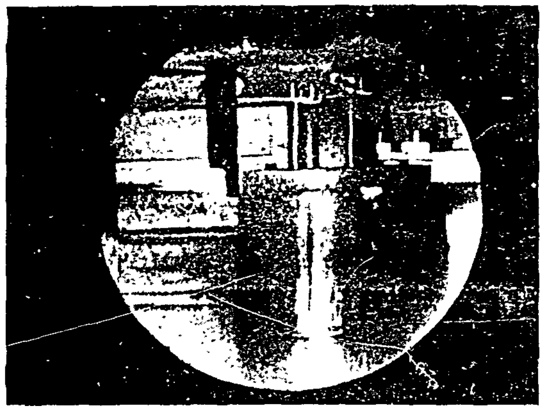


FIGURE 2
PHENIX
Passage de rampe dans la cuve interne

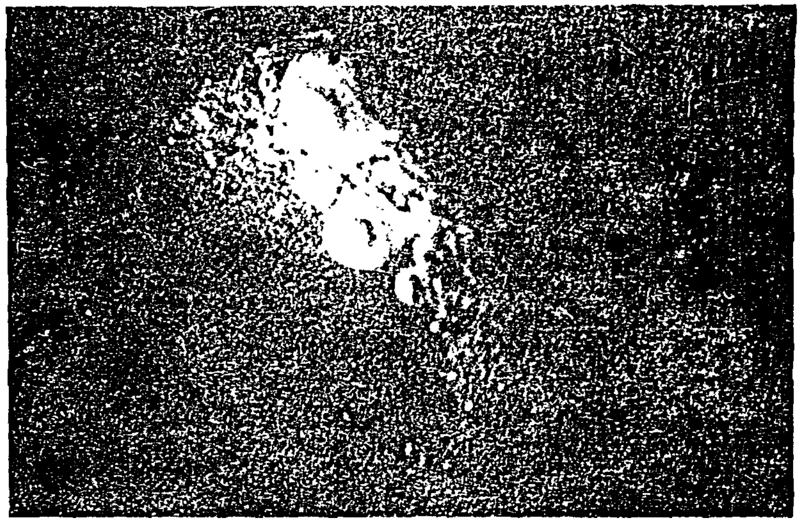


FIGURE 4
PHENIX : Vue de l'espace annulaire entre bouchon tournant et dalle, partie haute.

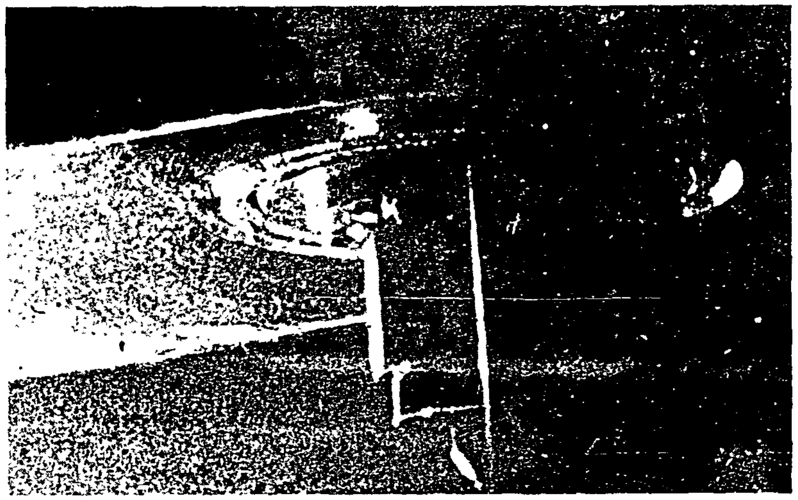


FIGURE 3
PHENIX
Vue du dessous du bouchon de la machine de transfert et de l'orienteur

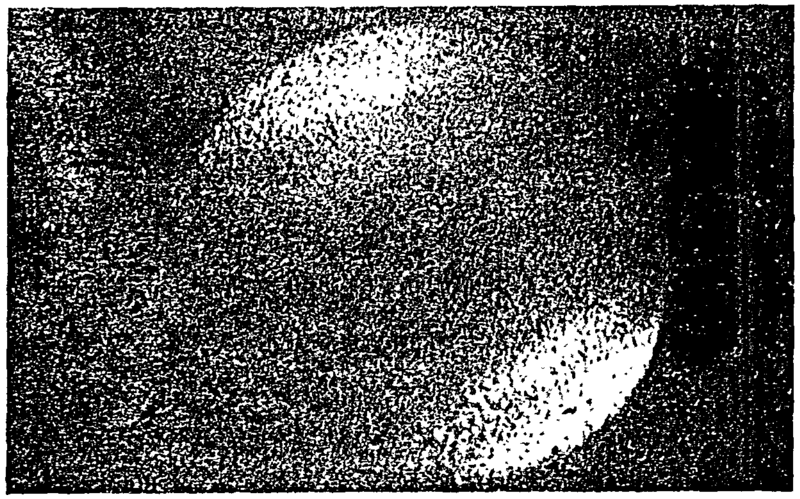


FIGURE 5
PHENIX : Vue de l'espace anuulaire entre bouchon tournant et dalle, partie courante.

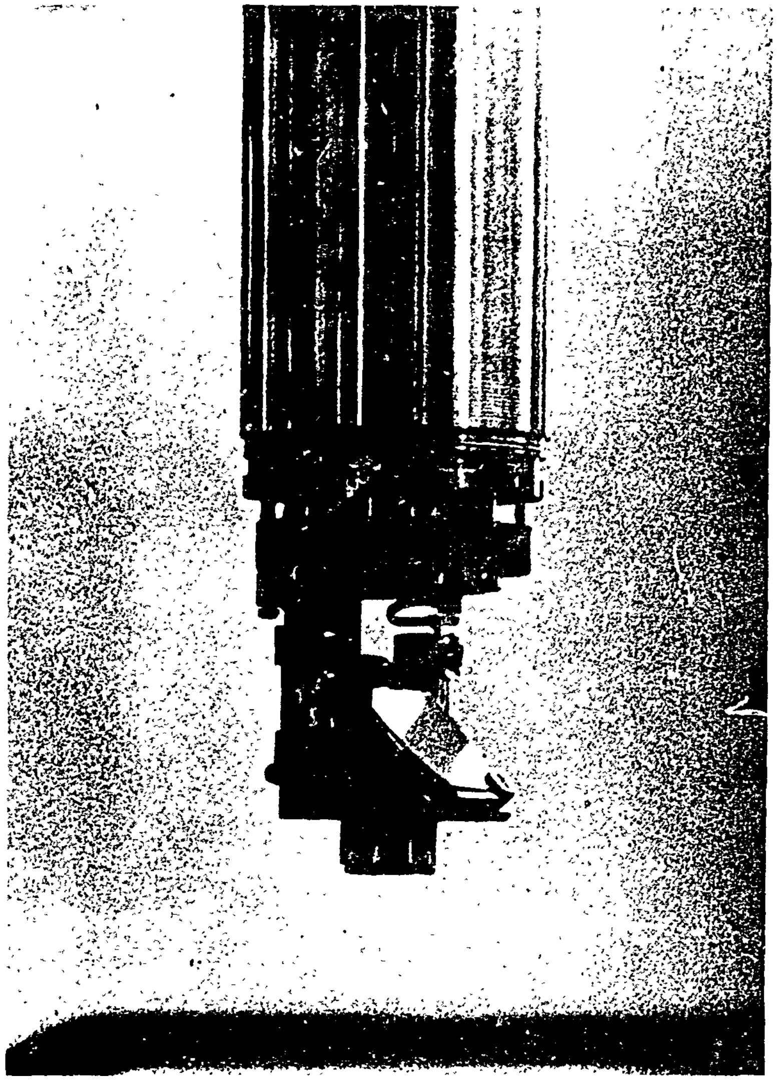


FIG. 6.

Tube T.T.I. partie basse - On distingue les porte-lampes, lampes à diode, miroir et lentille frontale (visée transversale)

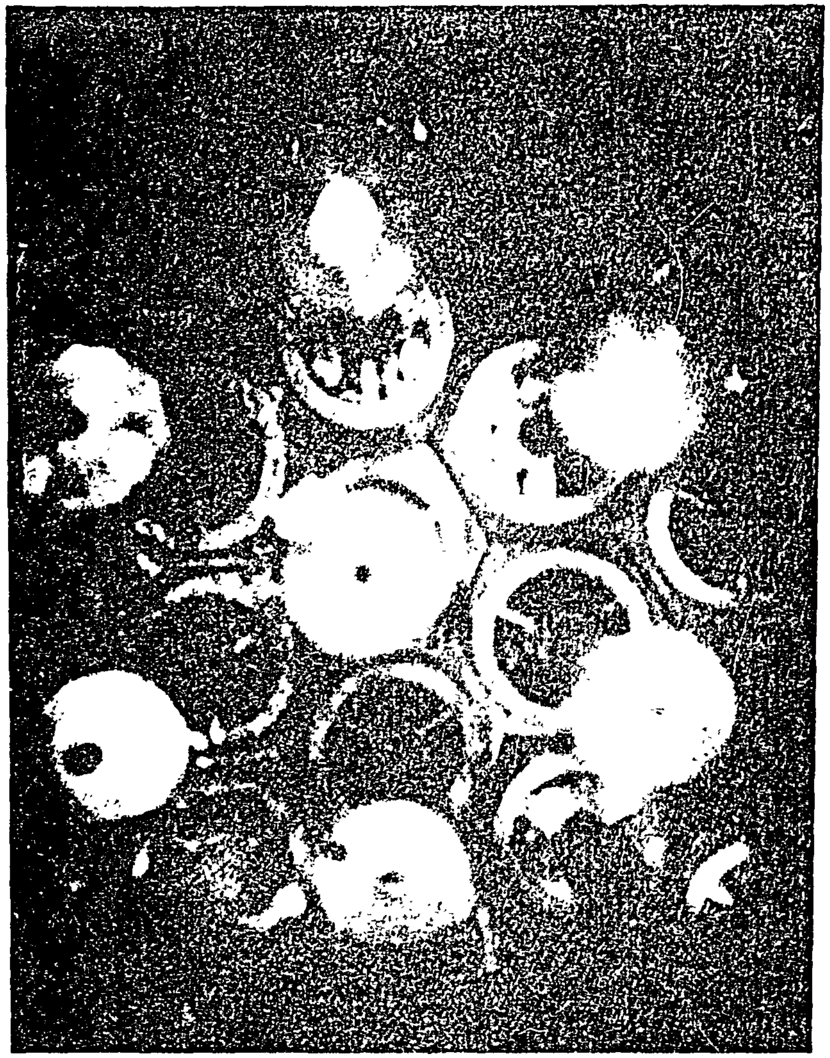


FIG. 7.

Essais en sodium à 150 ° C - Visée axiale, réglage sur sommet d'hexagone D = 114 mm

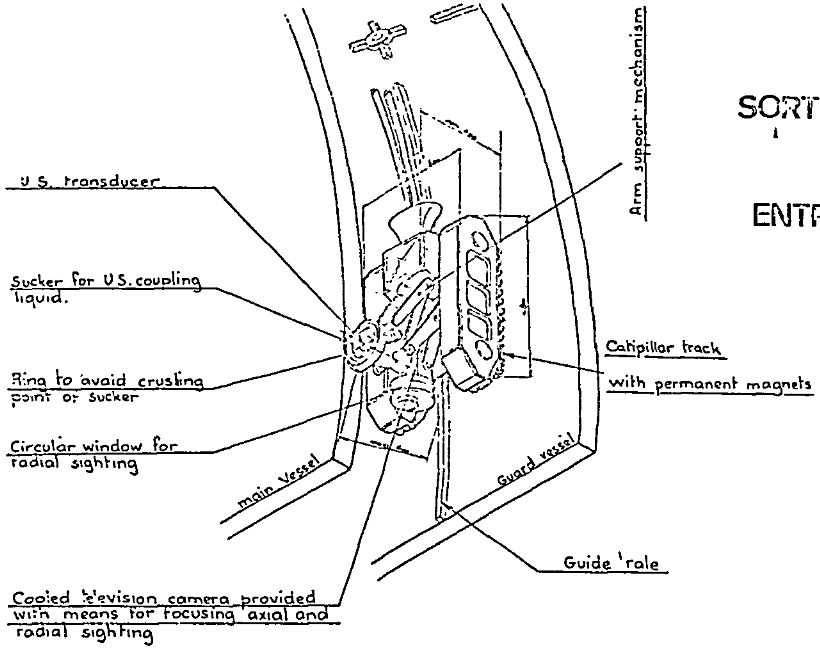


FIG. 8.

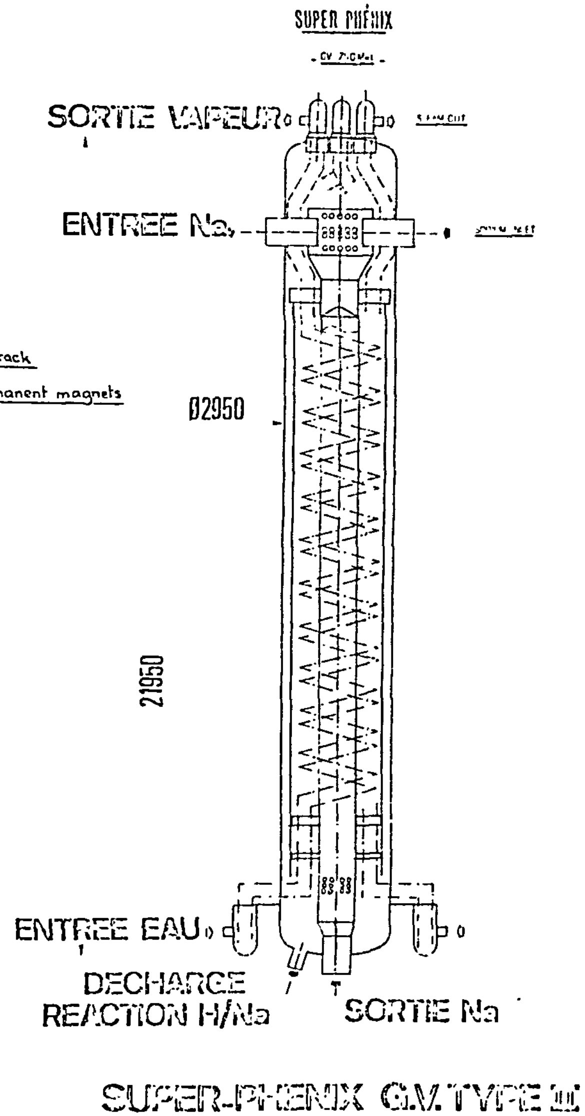
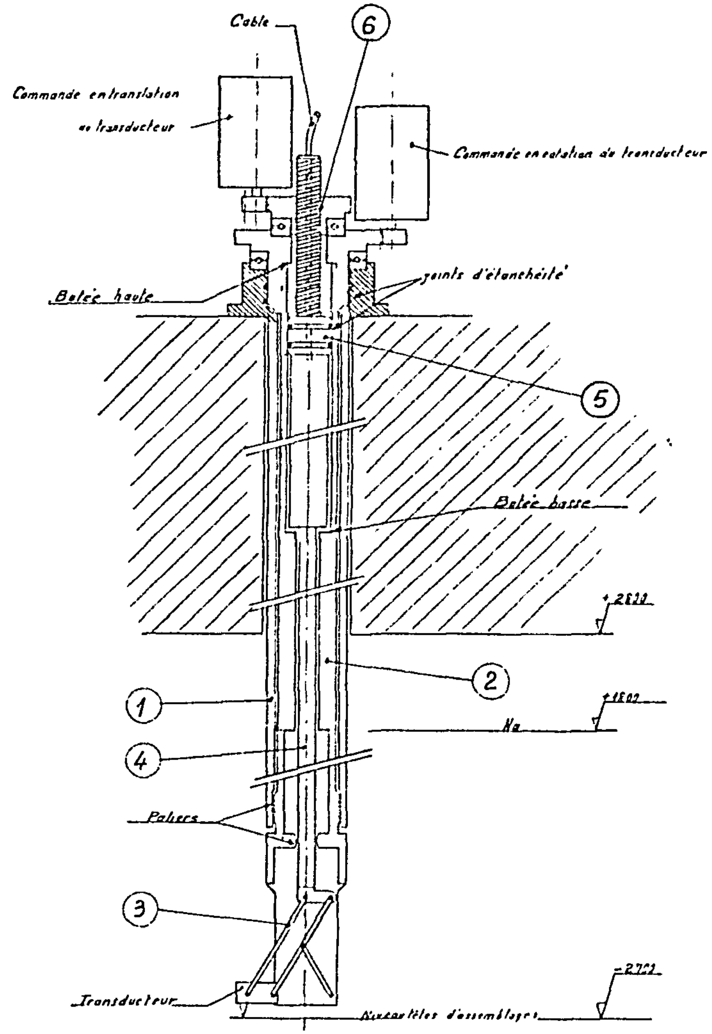
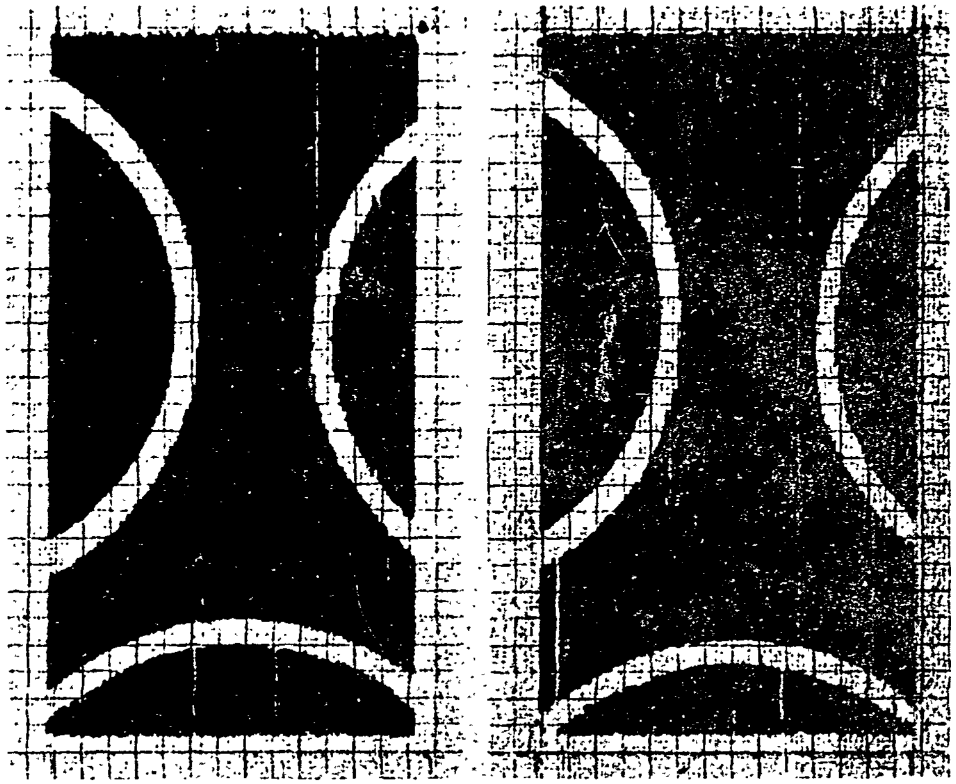


FIG. 9.



CONCEPTION GENERALE DU DISPOSITIF DE MESURE EN REACTEUR

FIG. 10.



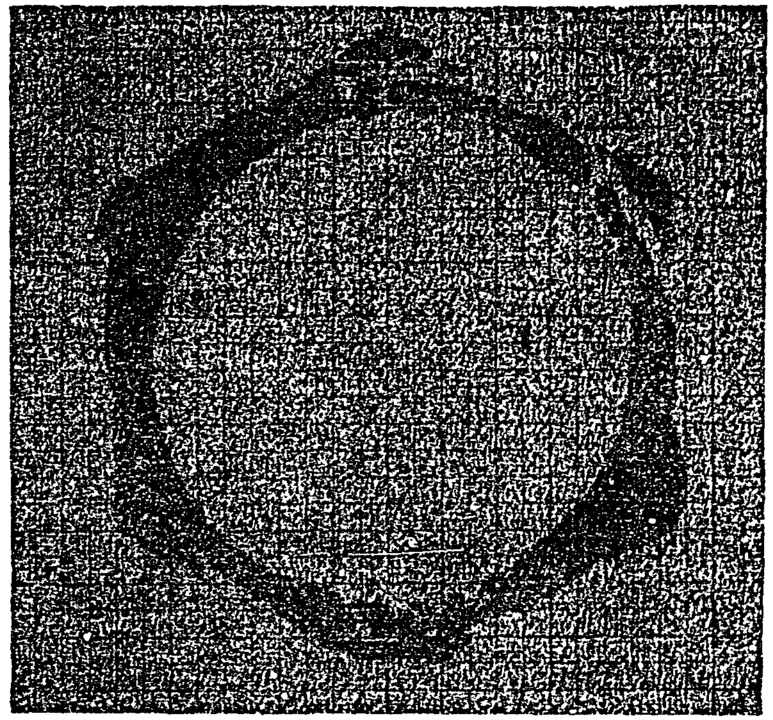
Gaines hexagonales au contact

Gaines hexagonales distantes de 4mm

Ultrasonographie
têtes d'assemblages type Phenix

Visualisation au niveau supérieur avec dispositif de focalisation
Distance entre gaines hexagonales

FIG. 11.



Ultrasonographie en eau
tête d'assemblage type Phenix

Visualisation globale à
partir du niveau superieur de la tête.

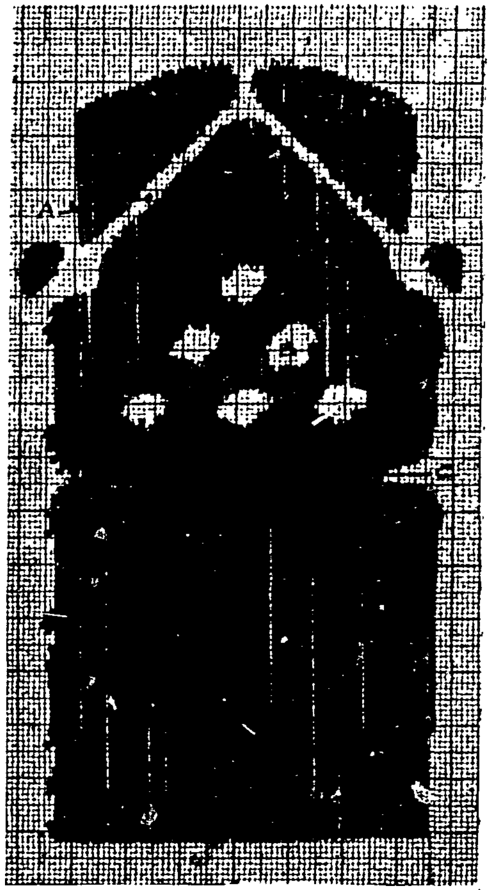
FIG. 12.

FIG. 12.

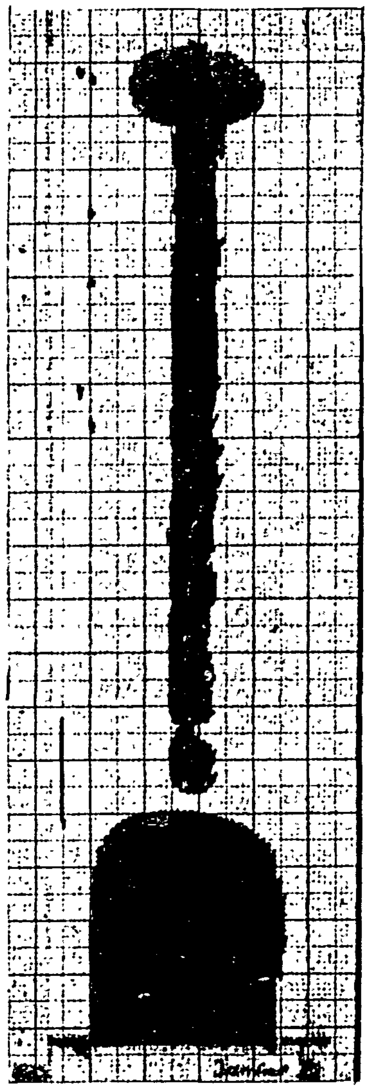
ULTRASONOGRAPHIE

Visualisation en eau

Tête d'assemblage PHENIX
A rampe d'orientation.
B trous de denoyage
C ligne de Soudure (Tête/gaine)

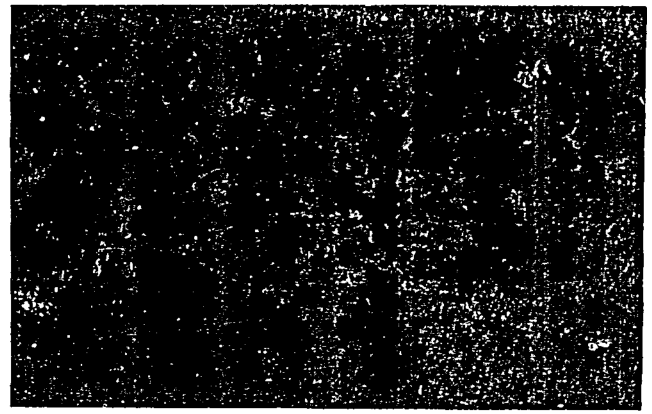


Tête d'assemblage RAPSODIE

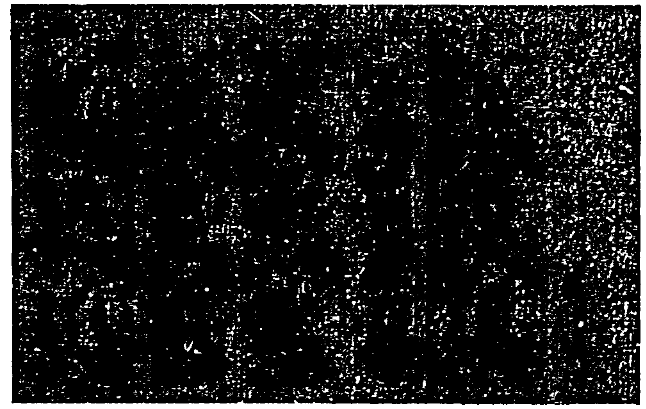


Visualisation sous eau des echos dans le plan du sommet des soudures

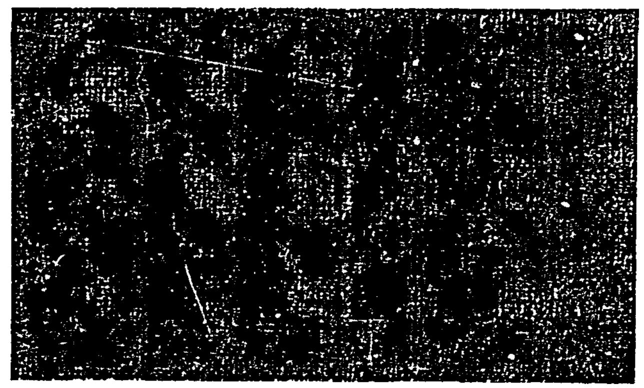
Traducteur avec miroirs quadratiques



Gain de reception : 70 dB



Gain de reception : 64 dB



Gain de reception : 66 dB

FIG. 13.

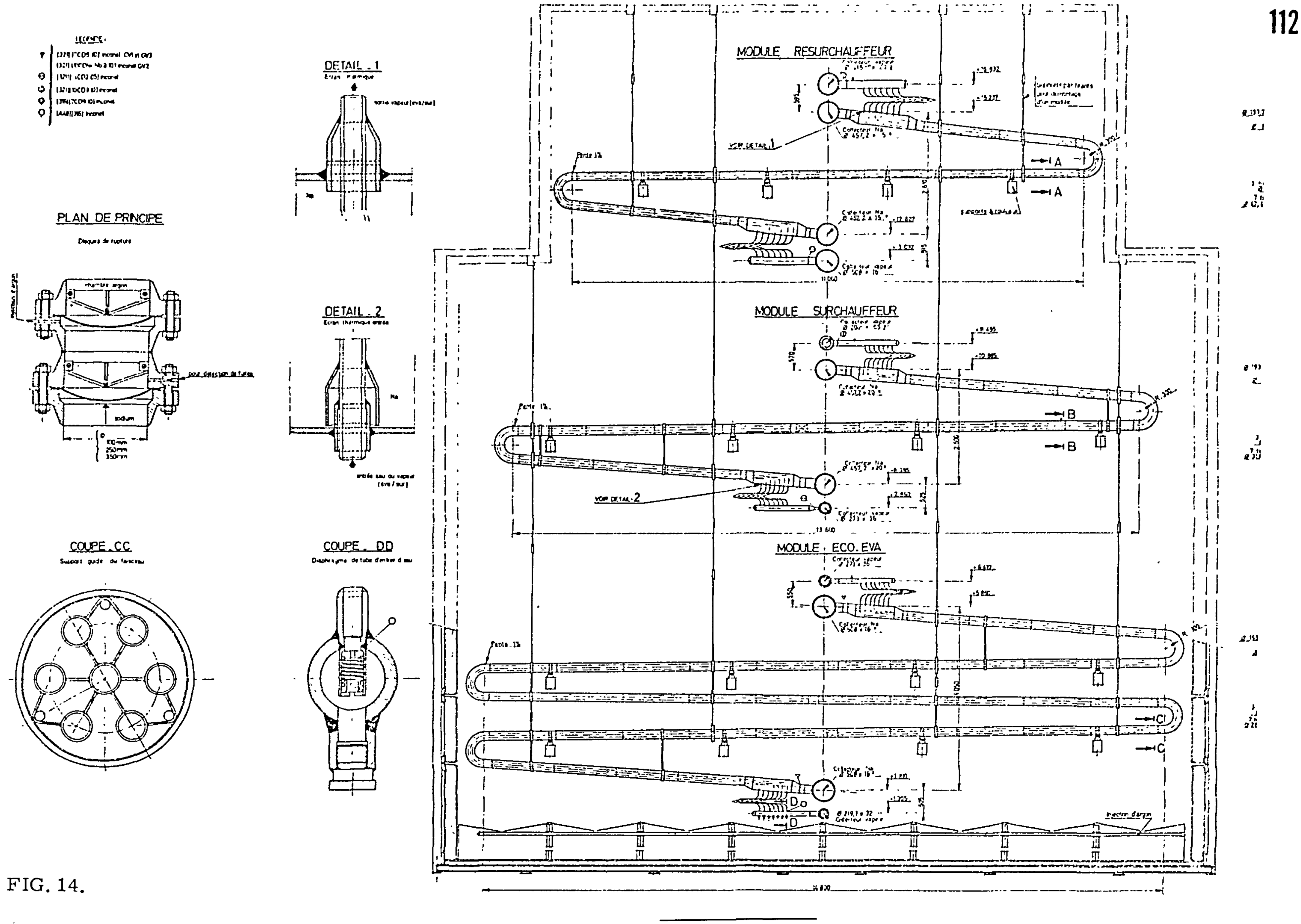
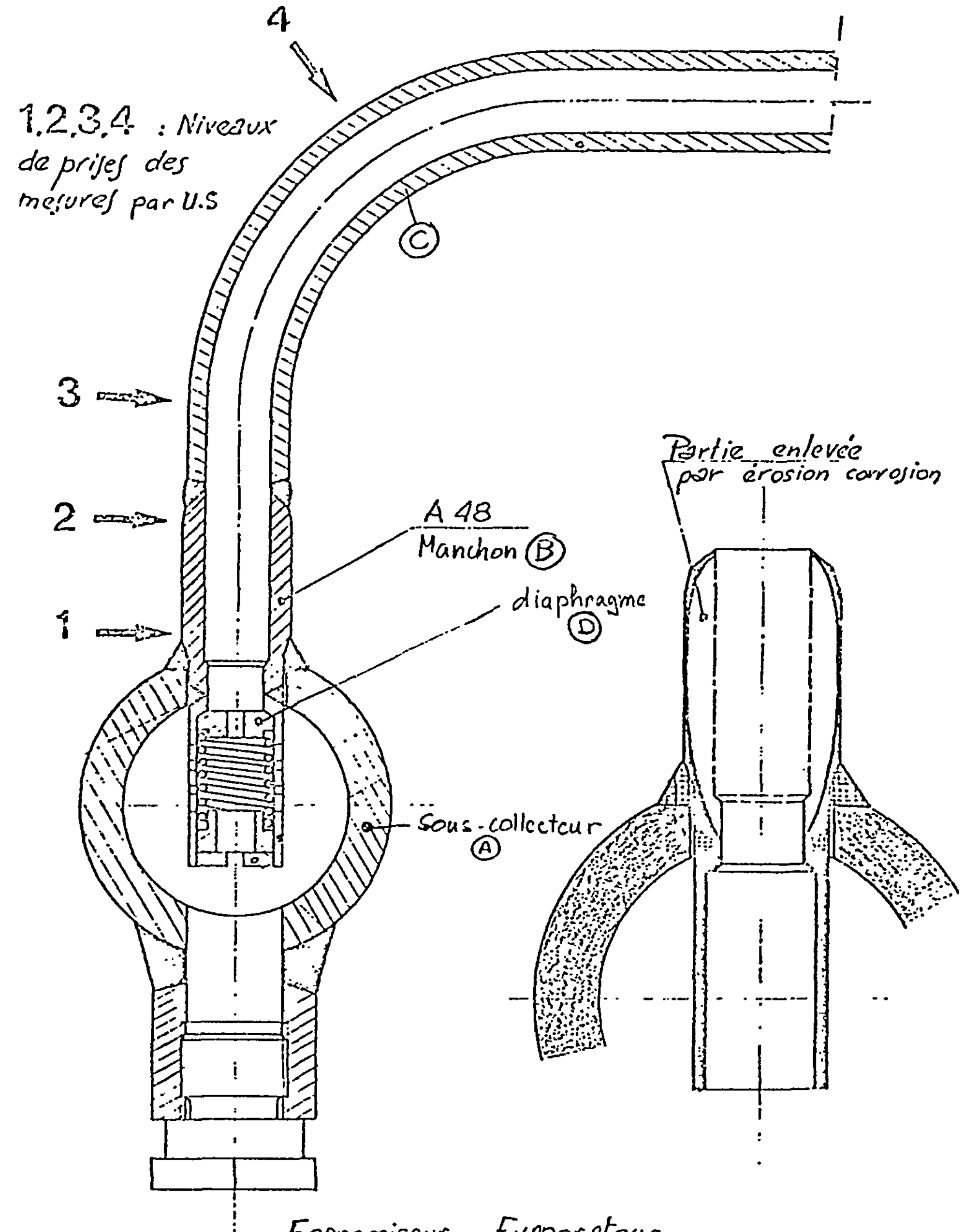
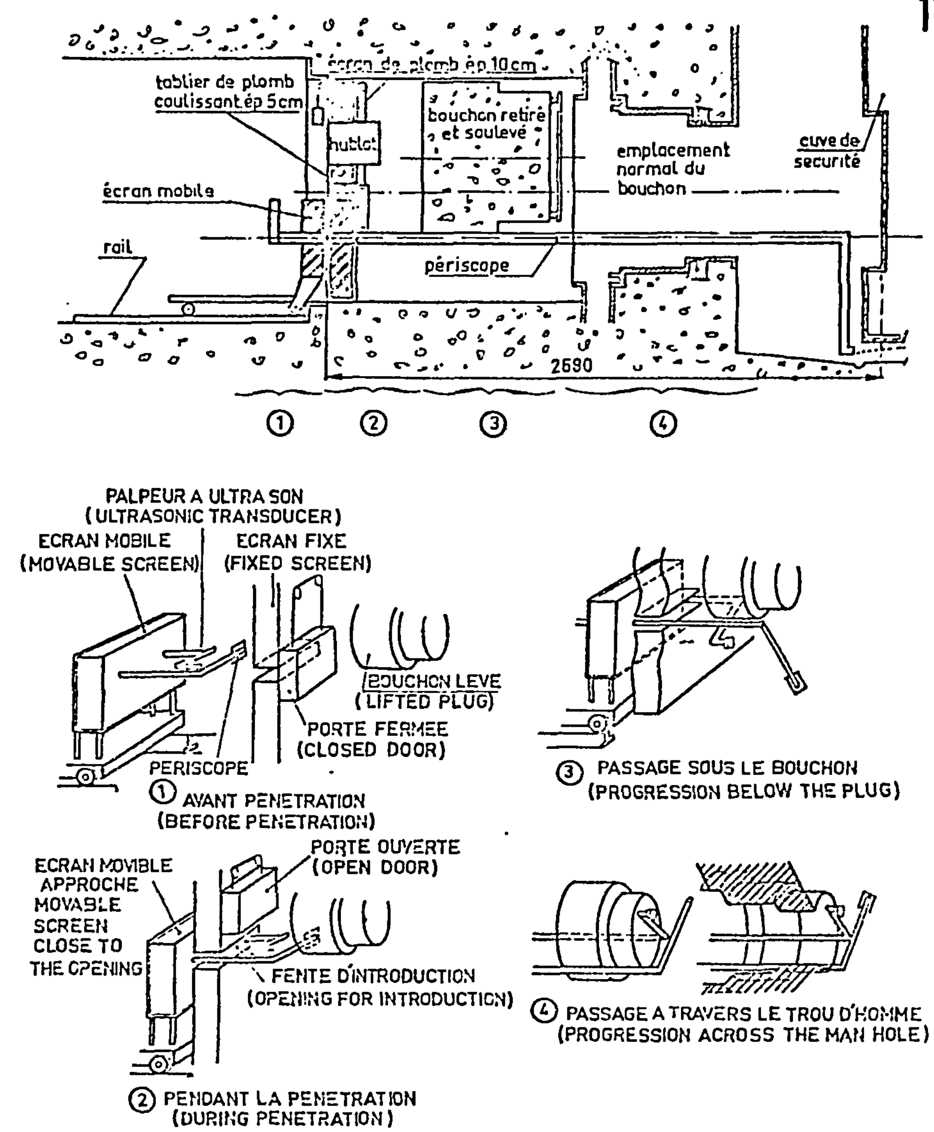

DETAIL . 1
PLAN DE PRINCIPE
DETAIL . 2
COUPE . CC
COUPE . DD
MODULE RESURCHAUFFEUR
MODULE SURCHAUFFEUR
MODULE . ECO. EVA
VOIR DETAIL 1
VOIR DETAIL 2
sodium
Na

FIG. 14.



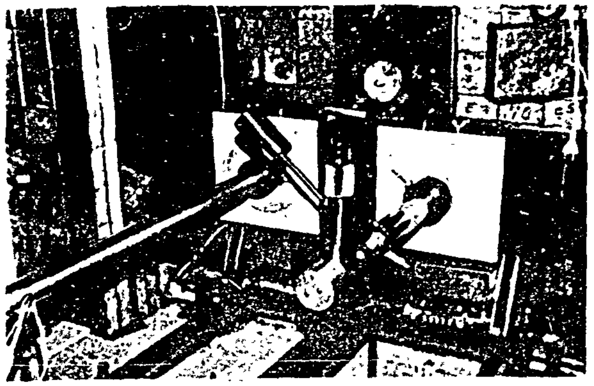
Economiseur - Evaporateur

FIG. 15. Diaphragme de tube d'entrée d'eau



INSPECTION EN SERVICE DE LA CUVE DE SECURITE
DU REACTEUR RAPSODIE

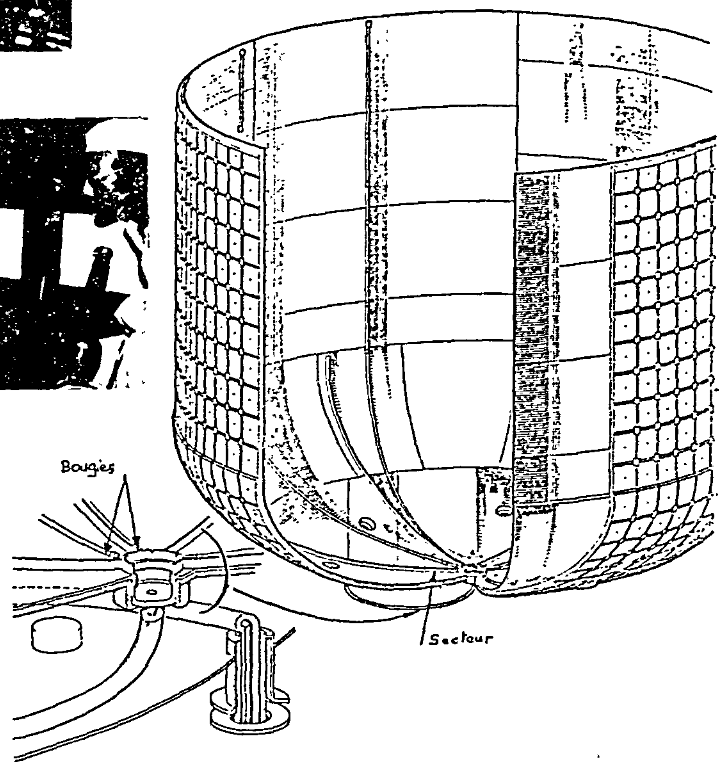
FIG. 16. Phases d'introduction de l'appareillage d'inspection



- CHARIOT MOBILE EQUIPE ET PROTECTION FIXE
- OBSERVATIONS VISUELLE
- PRISE DE PHOTO
- PREPARATION AVANT INTRODUCTION

FIG. 17.

Système de détection de fuite entre la cuve principale et la double enveloppe



DOUBLE ENVELOPPE

FIG. 18.

Mesure de déplacement du Sommier

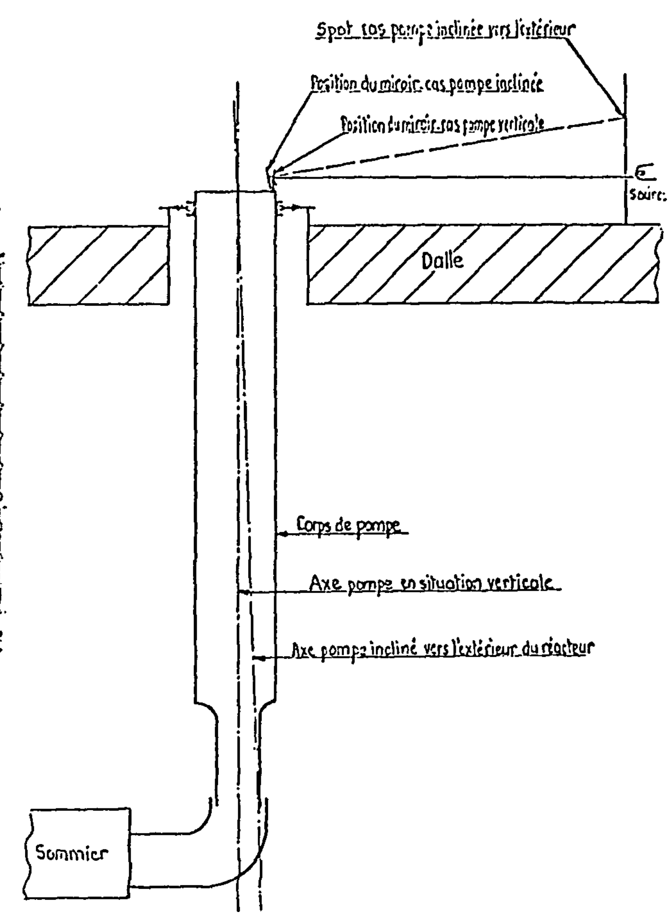


FIG. 19.

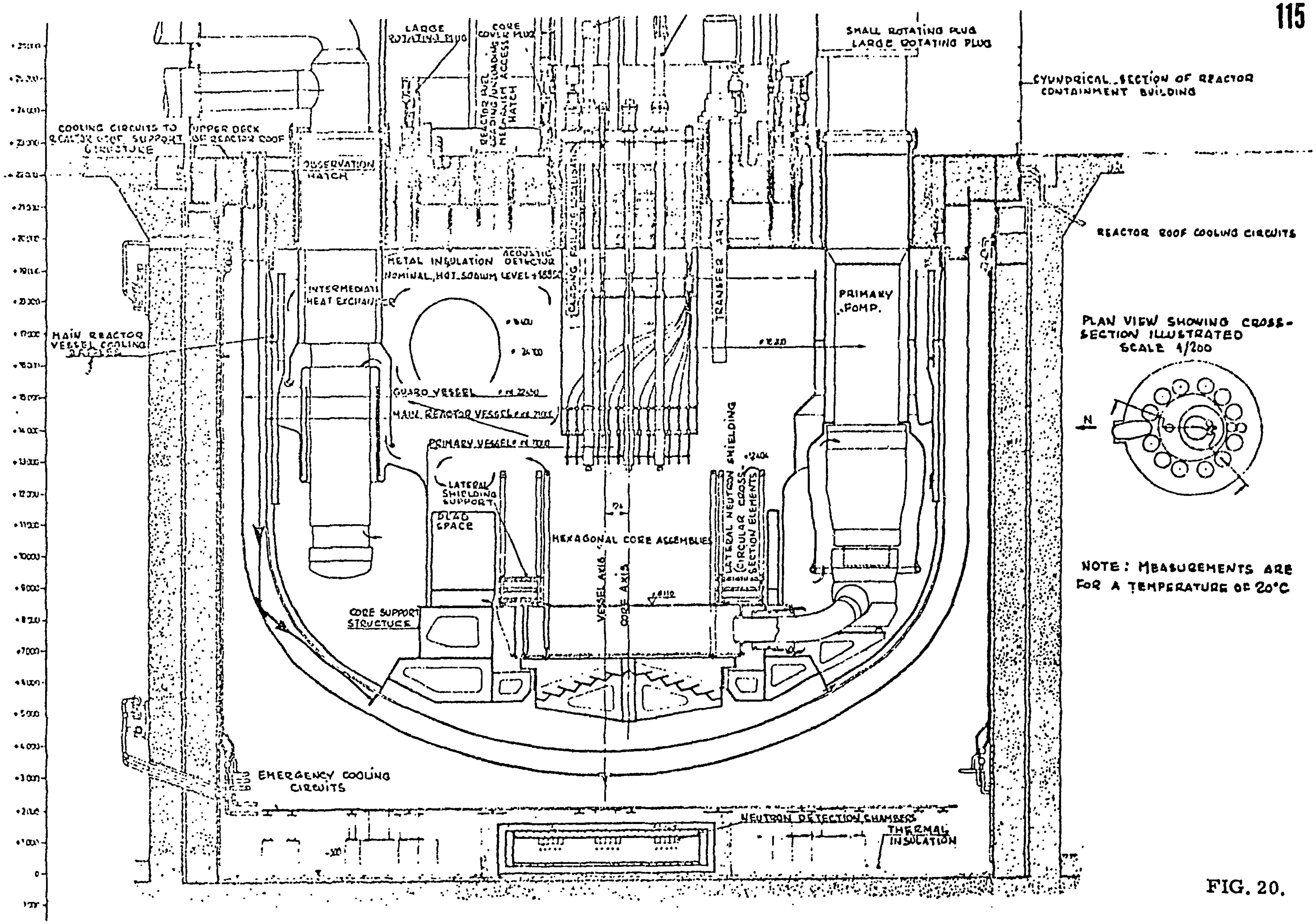
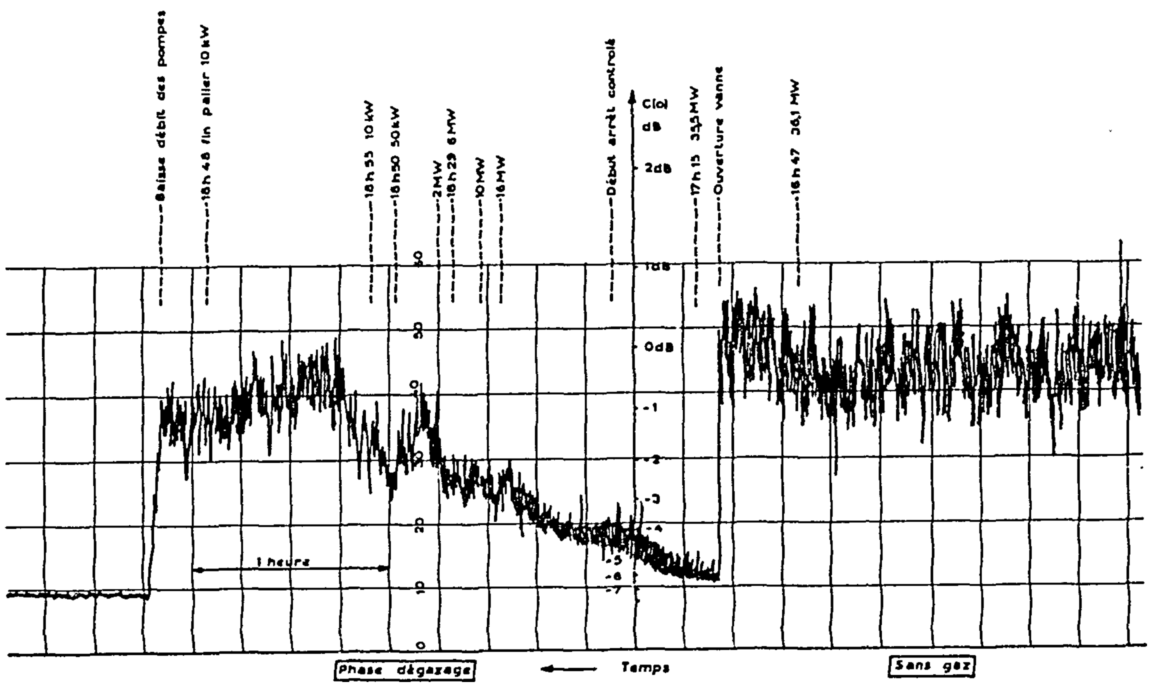
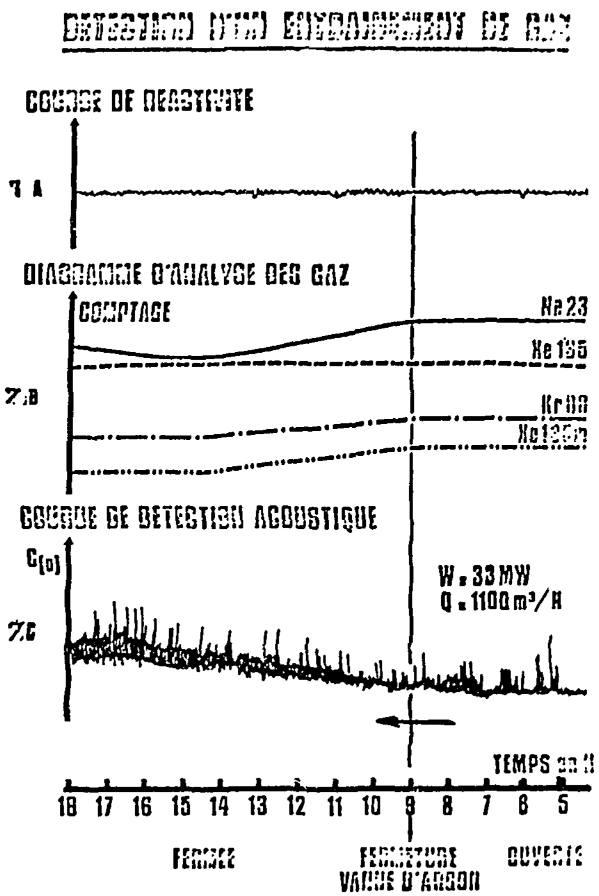

LARGE ROTATING PLUG
CORE COVER PLUG
REACTOR FUEL LOADING/UNLOADING MECHANISM ACCESS HATCH
SMALL ROTATING PLUG
LARGE ROTATING PLUG
CYLINDRICAL SECTION OF REACTOR CONTAINMENT BUILDING
COOLING CIRCUITS TO REACTOR ROOF SUPPORT STRUCTURE
UPPER DECK OF REACTOR ROOF
OBSERVATION HATCH
REACTOR ROOF COOLING CIRCUITS
METAL INSULATION
ACOUSTIC DETECTOR
NOMINAL HOT SODIUM LEVEL
CLADDING FAILURE DETECTION
TRANSFER ARM
INTERMEDIATE HEAT EXCHANGER
PRIMARY PUMP
MAIN REACTOR VESSEL COOLING
GUARD VESSEL
MAIN REACTOR VESSEL
PRIMARY VESSEL
LATERAL SHIELDING SUPPORT
DEAD SPACE
HEXAGONAL CORE ASSEMBLIES
LATERAL NEUTRON SHIELDING
CIRCULAR CROSS-SECTION ELEMENTS
VESSEL AXIS
CORE AXIS
CORE SUPPORT STRUCTURE
EMERGENCY COOLING CIRCUITS
NEUTRON DETECTION CHAMBERS
THERMAL INSULATION
PLAN VIEW SHOWING CROSS-SECTION ILLUSTRATED SCALE 1/200
N
NOTE: MEASUREMENTS ARE FOR A TEMPERATURE OF 20°C

FIG. 20.



ENTRAINEMENT D'ARGON EN PUISSANCE P = 36 MW 5 JUIN 1972

FIG. 21.



RAPSODIE

FIG. 22.

E. J. Burtun, "The Development of Acoustic Monitoring Techniques of LMFBRs". (United Kingdom)

1. INTRODUCTION

Acoustic monitoring techniques are being developed for nuclear reactor systems, one specific example of considerable international importance being the use of acoustic emission to prevent pressure vessel failure in PWRs. The techniques have an added interest in sodium cooled reactors because of the need to provide information that might have been obtained by optical methods but for the opacity of sodium. This paper is concerned not to give a comprehensive review of techniques but to give a selected presentation of topics which are either of special importance or ones in which significant advances have been made recently.

The topics are discussed in terms of the instrumentation technique to achieve the anticipation or the monitoring of incipient events of various modes of failure. Manufacturing defects may be identified by ultrasonic inspection or by stress wave emission. Mechanical failures arising from maloperation may be detected by visualisation under sodium using ultrasonics. Mechanical failures arising from material loss by corrosion or erosion may be anticipated by the detection of acoustic events. Overheating leading to core damage may be detected from the noise of sodium boiling. Mechanical failure from fatigue may be anticipated from an understanding of the vibrational modes of the sodium and its coupling with the structure.

2. STRESS WAVE EMISSION

An extensive investigation has been made into the use of acoustic emission as an early warning indicator of structural failure in steels of general engineering practice[1]. This has thrown up two difficulties in the application of the technique to problems in the LMFBR system, the first dependent on the acoustic characteristics of the materials and the second, related to the first, on the signal/noise ratio achievable in large components.

The acoustic properties of materials have been obtained from laboratory measurements on specimens and these are reported fully by Ingham et al[2][3]. These showed that from tensile tests maximum emission was associated with general yielding followed by a decrease in emission rate as gross yielding spread through the ligament area. Acoustic emission generally increased with increasing tensile strength and decreasing elongation although steels which showed well defined discontinuous yielding produced higher acoustic activity than would be inferred from strength and ductility alone. Fracture toughness tests have shown that acoustic emission increases with decreasing toughness and typical relationships are shown in Fig 1. Steels which failed by brittle fracture were characterised by a rising emission rate at failure, whereas steels which failed by ductile fracture showed similar characteristics to the results from the tensile specimens.

The investigations of Dawson and Ingham[4] showed that there was considerable difference in detection sensitivity between laboratory and large scale tests, simulating practical reactor situations. This arose from dispersion of the signal, attenuation along the path of the stress wave and differences in sensor sensitivity. It was concluded that an improvement in detection sensitivity of about x 20 (26 db) would be required to identify defects in ductile steels.

Therefore the assessment of the technique for the stainless steel materials in the LMFBR must take account of these difficulties. The acoustic characteristics of candidate materials needs to be measured and, probably, detection sensitivities improved. Due allowance must be made for the effect of background noise in practical situations and it may well be difficult to achieve a net improvement in the capability for defect detection.

Applications reported in the USA to monitoring during welding using signal enhancement techniques have been encouraging and this looks potentially promising given the necessary development. Application to the integrity of the vessel of the primary tank does not look promising with the relatively low pressurisation involved during proof testing but further assessment is required.

The most interesting application so far has been the use of the technique by Bentley and Cowen[5]. Austenitic specimens, bent into a U shape and restrained by a bolt, were heated in a sealed-capsule containing caustic soda and water. An acoustic waveguide was added to the specimen and extended to a position where the temperature was low enough to attach a standard acoustic emission transducer. The capsule was heated up to 350°C over several hours and then cooled. The chart record from single channel counting equipment is shown in Figure 2. The emission is consistent with stress corrosion at the U-bend. The investigation is continuing to establish by an independent measure of damage the relation between emission and corrosion cracking.

3. ULTRASONICS

Ultrasonics may be used both for volumetric inspection and for visualisation techniques. The application of the NDT methods, developed for use in air or water, are discussed elsewhere but the common factor is the technique used for transmitting and receiving ultrasonics in hot sodium. The main choice lies with piezo-electric transducers suitably adapted for the environment. For use at temperatures up to 300°C Bishop[6] is developing encapsulated lead titanate zirconate soldered to the protective diaphragm. Two problems require further attention, firstly the provision of suitably resistant damping materials and secondly the provision of a diaphragm which is easily wetted by sodium at 300°C. For the second of these, an investigation is being made of the efficacy of a sacrificial gold layer, first suggested by Ord and Smith[7] and of nickel. For use at temperatures up to 650°C Bishop et al[8] are developing lithium niobate transducers. The outstanding problem is to bond the crystal to the protective diaphragm. Pressure bonding has been shown to be inadequate and techniques of brazing which do not give rise to loss of piezo-electric characteristics from the diffusion of impurities from the braze into the crystal are being investigated. The effect of irradiation is equally important and the first investigations[8] have shown that the crystal damage arising from helium and hydrogen accumulated from the Li6 (n, α) reaction is best avoided by using Li7 depleted material although even then the displacement damage may still be significant close to the core centre.

The problems of applying ultrasonic viewing methods with existing technology to fast reactors have been discussed by McKnight et al[9]. Because of inadequate testing and proving of high temperature transducers, waveguides are planned for two applications, the sweep arm and the core component identifier.

The proposed design for the sweep arm is based on an approach to the liquid-filled waveguide concept which is the subject of a patent application by Barnes and Fothergill[10]. The design features are shown in Fig 3. The waveguide comprises a vertical tube open at the lower end and closed at the upper and filled with reactor sodium. The losses associated with the diaphragm coupling waveguide to the reactor, as in the VISUS system of Lions[11], is therefore avoided. The sodium is lifted in stages by evacuating the tube. Cooling of the upper end of the tube is provided so that the lead zirconium titanate transducer is eventually immersed at a temperature well below its curie point.

The waveguide is limited in height with this system, with the result that the waveguide itself does not breach the reactor containment. This has certain safety advantages, but complicates somewhat the procedure for changing the transducer. Other features provided, apart from the basic movement of rotation of the waveguide, allow for vertical movement, and remote adjustement of the directing mirror below the waveguide(12).

The purpose of the core component identifier is to provide a check on the various fuel movements in the reactor. The proposal is to read a code on the surface of the component by reflection of an ultrasonic beam. The reading device is to be mounted on the fuel charging machine itself, scanning of the code by the ultrasonic beam occurs automatically by the fuel handling operations themselves. The liquid filled waveguide system is not compact enough for this application. Instead in the arrangement indicated in Fig 4 a vertical solid steel waveguide and reflector combination is used to inspect the surface of an assembly about 0.5 m away. The surface feature of the assembly is interpreted as a binary code. A favoured scheme is to machine circumferential shallow grooves into a cylindrical section of the assembly. The groove is shaped to deflect the ultrasonic beam. Orientation of the assembly is unimportant with this method, and the structural strength is not significantly altered.

The critical problem at this stage of development is concerned with the waveguide design and the consequences of using solid steel for this. The difficulties of steel waveguides when used for pulse-echo ultrasonics are discussed in reference(13). Each returning echo is accompanied by a long series of trailing pulses which arise through mode conversions in the steel bar. Waveguides of several metres length add the complication that most of the transmitted energy is returned in the trailing pulses rather than the original echo. Application of the solid waveguide to the identifier instrument is simplified however because the position of a likely target (ie the fuel sub-assembly) is known precisely, and because the wanted information is a simple fluctuation of the echo. Electronic systems capable of resolving the information are readily devised.

The development of these relatively simple instruments into a more general viewing capability is being undertaken. An important aspect of this is the study study of the information processing required to present an image easy for the reactor operator to understand. The aerospace, sonar, NDT and medical fields provide many similar problems. Advantage is being taken of the recent advances in image science, for example the use of various transform methods (both Fourier and Walsh) to reinforce image boundaries by modifying the spatial frequencies of a display or record. Digital processing is being used on simulated situations from which the reactor instrument can be specified. Functions which are being considered in these studies include means of recording in detail the actual installation and the relative spatial arrangement of components as distinct from the designed features, and means of recording operational movements of components and, if possible, long term mechanical deformations.

4. CAVITATION

Cavitation is defined here as the process of vapour bubble growth and collapse in the changing pressure field as the fluid passes through the reactor component. It is distinct from the common engineering usage where, for example, in a pump, its onset is recognised by the fall in hydraulic performance. It is important to minimise cavitation for two reasons; firstly to reduce the risk of damage from erosion; secondly to reduce the background noise when using acoustic diagnostic techniques for core protection.

In PFR most attention has been paid to two components, the sub-assembly and the pump. The investigation of cavitation in the sub-assembly has been principally a study of the hydraulics and this is described by Collinson(14). It is worth noting that an acoustic detection, based on the count rate arising from the collapse of individual vapour bubbles, was used as the main criterion of intensity of cavitation.

For the PFR pump, the specification agreed with the manufacturer was that at the design point there should be no visible evidence of bubble formation on the impeller blades. The use of visual techniques is obviously not practicable in sodium and the alternative method of using acoustic listening methods has been investigated. In the earlier experiments, using water, results were confusing but by minimising spurious noise and attenuation effects, and by having a panoramic viewing system, it has been found that similar results could be obtained using acoustic and visual methods. This is illustrated in Figure 5 which shows the relation between noise (at 40 kHz) and inlet pressure for one particular pump. An interesting feature of this curve is the steep rise in noise once cavitation starts. Thus if damage from cavitation erosion is important and if this noise curve is typical there may not be a clear criterion for its avoidance after the inception of cavitation. The degree of cavitation to accept from a sodium coolant pump is presently under review. Additional experiments have been carried out to locate cavitation sources on pumps using the triangulation techniques developed for stress wave emission measurements by Bentley et al(16). The first measurements were made on a stationary centrifugal pump with simulated cavitation sources and showed that despite the complexity of the transmission paths the sources could be uniquely located in the three dimensional structure. Further measurements have been made on an operating pump system. This readily distinguished pump from valve noise. Two sources were identified in the pump casing, one indicating cavitation over the impeller blades and the second stationary, indicating a leak from high to low pressure. The investigation is continuing with the development of specialised equipment for the source location of intense cavitation.

5. ACOUSTIC DIAGNOSTICS

Acoustic diagnostics may be used to monitor the signature of the rotating machinery for significant changes but the dominant interest has been the assessment of acoustic methods to detect sodium boiling in the core. The problem divides into three parts, the characterisation of the signal, the background noise and the reactor detection system.

The modes of boiling in fault situations is a complex study, outside the terms of this paper and aspects may be seen from the papers at the sixth meeting of the Liquid Metal Boiling Working Group (Risley October 1975). Simulated fault studies are defined using either out-of-pile sodium rigs or in-pile experiments. A typical investigation has been carried out on a single pin forced convection sodium boiling experiment with the CEA in which the acoustic measurements were made by Macleod et al(17). With a constant power supplied to the heater pin, the flow was set to a high value and then reduced in steps to the boiling region. The relationship between pressure drop across the test section and the mass flow produces the characteristic S curve and this is shown in Fig 6. At the same time the variation in acoustic signal as a function of flow was also measured and this is also shown in Fig 6. From the measurement it was concluded on this rig that both sub-cooled and bulk boiling produced clearly detectable acoustic signals in the initial stage of each boiling process. Further such experiments are planned, especially to simulate local boiling in a cluster of pins.

The background noise arises mainly from the coolant pump and also from the sub-assemblies. Cavitation is avoided as much as possible as discussed in section 4 above. For PFR, measurements were made at the model stage, during water testing at the manufacturer's works and during sodium commissioning and these are described by Seed et al[18].

The detection of the signals is made through steel waveguides inserted into the primary sodium pool to within 15 cm (6 in) of the sub-assembly exits. Lead zirconate titanate accelerometers are fitted to the top of the waveguide outside the main radiation field and at a relatively low temperature. The coverage of the waveguides was investigated during special commissioning experiments on PFR. At the same time, sodium boiling was induced within a small electric boiler placed inside three rigs inserted into core positions of PFR. This has enabled a rough calibration to be made between the detection sensitivity of the waveguides and the acoustic output estimated to arise from specific faults, based on the simulated out-of-pile experiments. This has led to an improved assessment of the value of acoustic detection of boiling particularly as a useful safeguard against "Spert accidents", ie damage arising from the explosive vaporisation of sodium coming into contact with overheated fuel elements.

For further investigations, acoustic transducers are being developed by Bishop[6] to enable direct measurement of pressures in sodium to be made and a typical design is shown in Fig 7.

6. ACOUSTIC VIBRATION

In a fast reactor, acoustic energy mainly produced locally at the coolant pumps, is transmitted through the fluid to the various structures. In assessing the likelihood of structural damage arising from this acoustic excitation, particular attention has been paid to the vibration of the primary tank and pipework. To obtain a thorough understanding of the processes involved, simple shapes (tanks, strips and tubes), were set up in the laboratory and these were excited by an electromagnetic vibrator in the surrounding or contained liquid. For the cylindrical tank it was found that an axisymmetric sound field in the liquid which on standard elastic theory would give rise to "breathing" mode vibration in the cylindrical wall also set up short wave length flexural waves. These waves gave rise to a higher stress, by a large factor, than the standard estimate. Calculations of the resonant modes of this system have been published by Bentley and Firth[19]. The mechanism of coupling is incompletely understood and work is proceeding. Some results on the vibration of a flat strip in a liquid surface have been published[20].

During commissioning of PFR, measurements were made both of vibration levels in the principal components by Nicklin[21] and of their relationship to pressures measured in the sodium by Bentley, Howard and Rowley[22]. Sodium proof PZT pressure sensors were used for temperatures up to 250°C and these detected pressure pulsations from the pump which were a significant source of structural vibration. Further useful measurements were made with accelerometers which were mounted on the outside of the primary tank and which have continued to operate successfully up to full power reactor temperatures. They show evidence of structural vibrations excited by the pump and therefore allow both structural behaviour and acoustic liquid pressures to be monitored. Direct monitoring of components is also possible before irradiation with encapsulated strain gauges which operate satisfactorily at reactor power temperatures.

Basic studies are continuing in the laboratory to understand the mechanism of coupling between acoustic and structural modes. At present investigations are concentrating on the effect of mechanical imperfections, for example, variations from perfect cylindrical symmetry. At the same time the value of two models are being examined, the first at $\frac{1}{8}$th scale; the second at $\frac{1}{4}$ scale. The first model would determine broadly which components are important, either vibrating strongly, or determining the distribution of energy. It will also give experience in the development of techniques, for example, data handling.

An important long term objective of all these investigations is to develop a sufficient understanding of the vibrational behaviour of the reactor components that simple and robust instrumentation can be specified to monitor vibrational levels during power operation to give assurance of their continued safe operation. Thus it can be foreseen from the above results that monitoring of the vibration of the primary tank using robust accelerometers could give information on the acoustic fields in the primary pool. Similar monitoring of the primary pipework could be achieved if radiation and temperature resistant transducers become available.

7. CONCLUSIONS

The recent developments have shown that acoustic monitoring has a significant role to play in assuring the reliability and safety of LMFBRs. At present several applications are restricted by the lack of adequately reliable high temperature transducers but significant progress is being made. The most fruitful area would seem to be the increasing use of computers to improve signal enhancement techniques, to improve data reduction and archiving, and, particularly in sodium viewing, to improve display presentation. An increasing use of correlation techniques, both to achieve a location capability, as already demonstrated in stress wave emission and cavitation application, and to achieve simultaneous detection on two or more physical variables should enable more sensitive detection of events anticipating structural and other failures.

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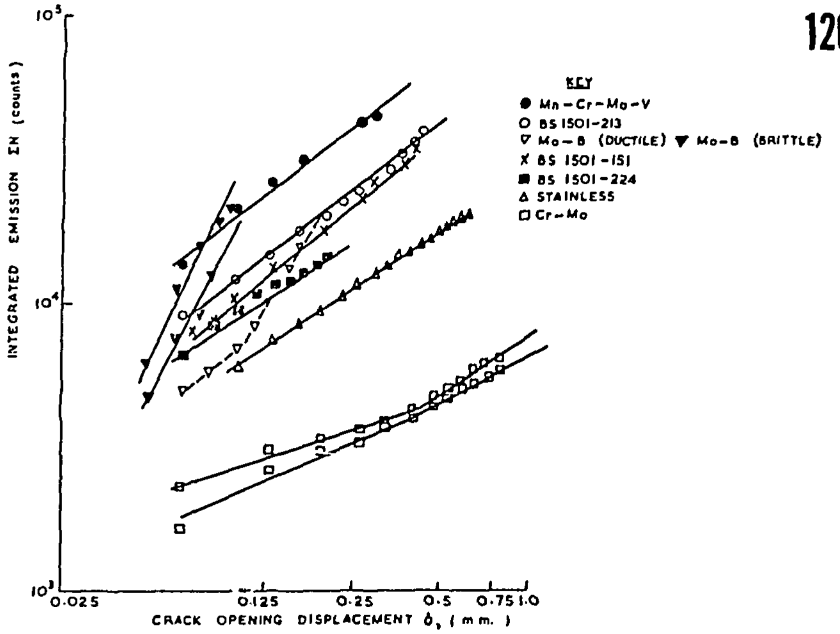

FIG 1 INTEGRATED EMISSION AS A FUNCTION OF FRACTURE TOUGHNESS FOR ROOM TEMPERATURE BEND TESTS

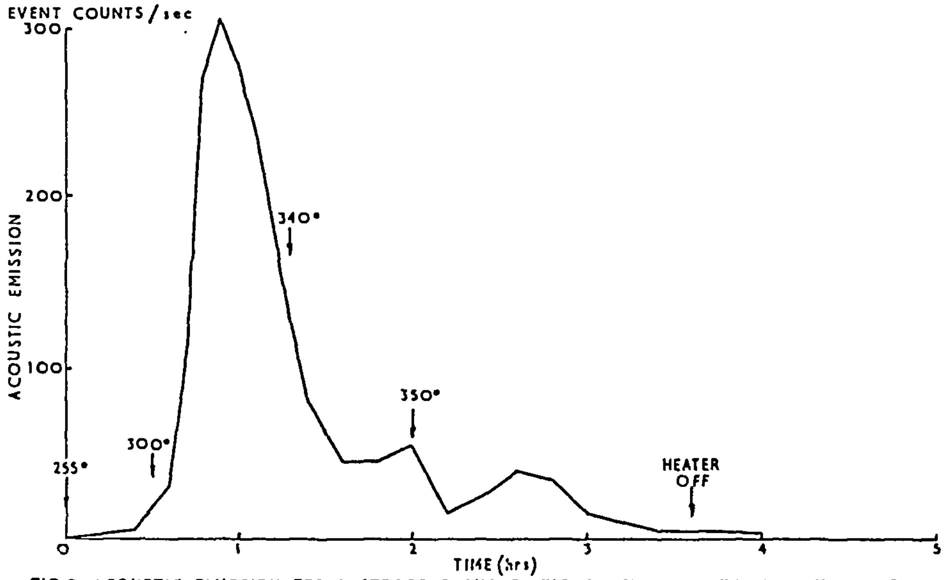

FIG.2 ACOUSTIC EMISSION FOR A STRESSED AUSTENITIC SPECIMEN HEATED IN CAUSTIC SODA

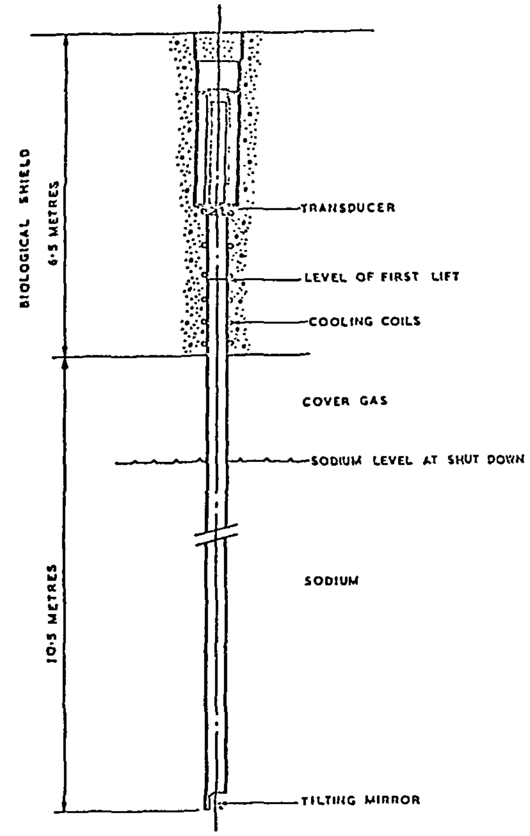

FIG.3 SWEEP ARM WITH VACUUM LIFT WAVEGUIDE

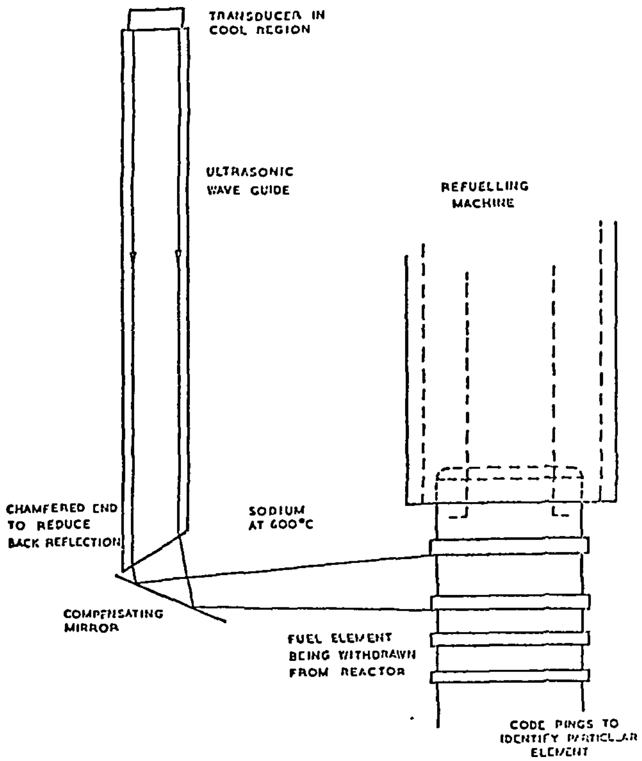

FIG.4 ELEVATION SHOWING IDENTIFIER PRINCIPLE

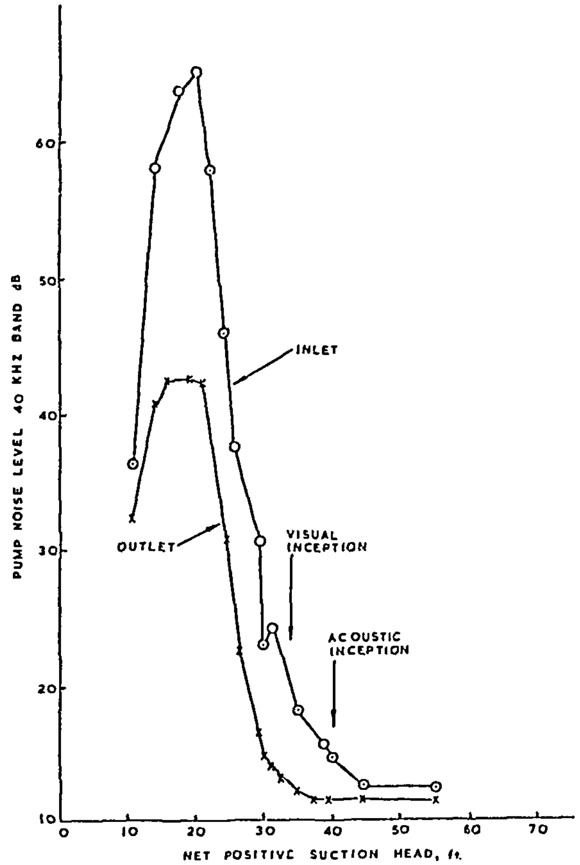

FIG.5 INCEPTION OF CAVITATION IN A PUMP

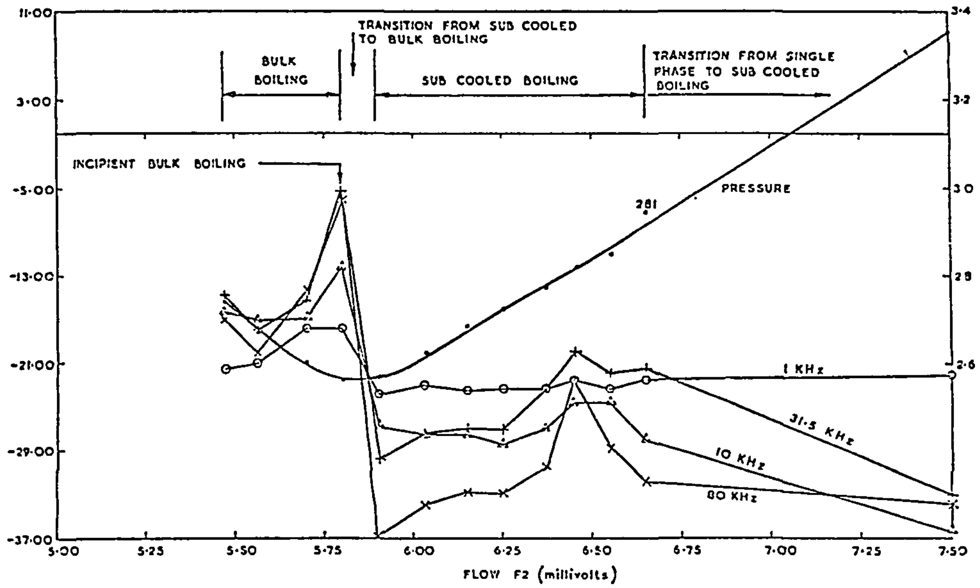

FIG. 6 NOISE V. FLOW 40 KW.

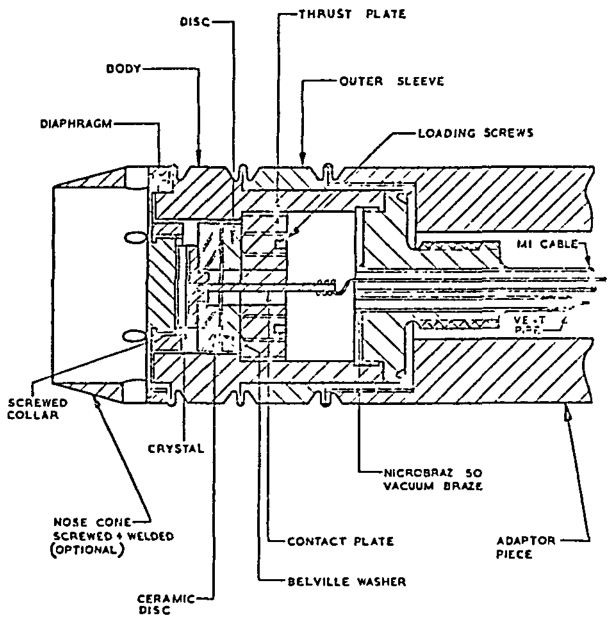

FIG. 7
ACOUSTIC PRESSURE TRANSDUCER MK II

A. C. E. Sinclair, A. Tobias, D. C. Connors, "Multi-Channel Acoustic Emission Surveillance of a Pressure Vessel during Proof Test". (United Kingdom)

SUMMARY

An acoustic emission analysis system (ACEMAN) designed for acoustic source location was used to monitor the proof test of a steam drum for Inverkip Power Station. The extensive surveillance region included a representative sample of welds and nozzle array complexity.

In spite of a large noise background, sophisticated signal discriminators and multi-sensor timing correlation permitted location of several distinct areas of acoustic activity. Differing emission patterns with pressure pointed to a variety of source mechanisms. Factors important to the acoustic emission assessment of structural integrity are discussed.

1. INTRODUCTION

The objective of acoustic emission inspection during the proof test of pressurised components is to provide information on the flaw content of these components (Bentley et al., 1972; Waite and Parry, 1971; Vetrano, Jolly and Hutton, 1972; Birchon, Dukes and Taylor, 1973; Chretien, Bernard and Barrachin, 1973; Gopal, 1974; Eisenblätter et al., 1974; Bell, 1974; Ying, Hamlin and Tanneberger, 1974).

Normal non-destructive testing of pressurised components is intended to ensure that such defects as remain in components, after manufacture and before the proof test, are negligible as far as the integrity of the component is concerned. Nevertheless, as an additional safeguard, hydraulic proof testing of pressurised components prior to service use is mandatory and well accepted by manufacturers and users. In addition, repeat proof tests may be made to demonstrate continuing component quality.

A successful proof test should demonstrate that no flaw exceeds a limiting size, but the presence of smaller defects will not be indicated. It would be desirable if the test could be used both to locate the smaller defects and to assess their size in the manner required, for example, by the 'Rules for inservice inspection of nuclear power plant components' (ASME, 1974). In the case of repeat proof tests any growth of defects between tests would be measured.

The feasibility of acoustic emission inspection has been examined in laboratory studies of stressed specimens. For mild steel a common pattern has been found for the dependence of emissions on deformation. On first loading of a notched specimen, which corresponds to the proof test of a defective plate, emissions occur principally at the boundary between elastic and plastically-deformed regions (Bentley et al., 1972; Palmer, 1973; Picket, Reinhart and Ying, 1971; Ingham, Stott and Cowan, 1974). The emission activity before general yield is correlated with the size of the plastic zone spreading from a crack (Palmer, 1973; Palmer and Heald, 1974), and it appears from the dependence of the emissions on the microstructure of the steel that the emission source for notched specimens is the cracking of pearlite grains (Holt and Palmer, 1974).

A medium size vessel of P.V. steel with a partial penetration slit produced an emission pattern on loading similar to that of the laboratory specimens (Sinclair, Formby and Connors, 1974). Fig. 1 presents the results. Analysis suggested a direct proportionality between plastic volume V_p and emission number N,

$$N = \beta V_p \qquad \ldots(1)$$

With laboratory and medium scale tests showing that plastic yielding associated with significant defects generated acoustic emission, the next stage was to examine a structure in industrial conditions.

For defect detection in industrial conditions several factors need to be considered (Sinclair, Formby and Connors, 1974). The acoustic activity parameter β in expression (1) is a function of the material, of the distance of the acoustic sensors from the source and of the amplitude threshold of the detection equipment. Background noise determines the threshold level, while noise sources other than defects may be within the surveillance area so that emissions from a defect must be distinguished among noise-produced events.

The proof test of a large steam drum manufactured to high standards by Clarke Chapman-John Thompson provided an opportunity for examining results in typical industrial noise conditions, for a vessel with no defects and where the results of conventional NDT were well known. The ACEMAN (acoustic emission analysis) system developed at BNL for source location in extended structures was used. Details of the computer programming associated with the ACEMAN system have been given by Tobias (1974).

2. *EMISSION DETECTION AND LOCATION SYSTEM*

The ACEMAN location system is designed to detect discrete bursts of emissions which accompany the discontinuous deformation of microscopic elements of material in regions containing defects. These bursts propagate from the source to a sensitive sensor, located on the surface of the structure, as Lamb waves (Auld, 1973). A signal resulting from propagation of several plate modes arrives, but the peak energy travels with a well-defined velocity near the shear wave velocity. The separation between sensors of the detection system is normally as large as possible, in order to increase coverage by a given number of sensors, but signal attenuation, wavefront spreading and background noise levels limit the allowed sensor spacing.

Measurement of the sequence of times at which an emission burst wavefront passes successive sensors on a structure permits location of the emission source. The location calculation is particularly direct for sources on rods, plates or cylindrical vessels (Tobias, 1975). An array of at least three sensors is required, while a fourth sensor is desirable in order to resolve potential ambiguities. Any sensor configuration can be used and thus complete flexibility in experimental arrangements is possible.

Figure 2 shows a schematic representation of the ACEMAN location equipment. Signals from piezoelectric sensors, acoustically bonded to the test vessel, pass via narrow-band preamplifiers to range compression amplifiers. Signals up to 50 dB above electronic noise are compressed within a 33 dB range for subsequent tape recording.

Discriminators analyse signals from each channel. These discriminators respond to acoustic signals which exceed defined height and length requirements and which occur following periods of relative quietness during a test. In this way a useful reduction in spurious noise signals is achieved. Following detection of a signal with the required characteristics, a timing pulse corresponding to the leading edge of the emission burst is relayed to a computer. The computer analyses the time intervals in the train of such pulses from the sensor array, recognises valid combinations of intervals, and stores the integrated count of events for each such valid combination. Concurrently, an indication of the emission burst is displayed on a map of the surveyed area.

For source location by a multiple-sensor array, simultaneous detection by each sensor in the array is required within a time window equal to twice the time for sound to propagate from one sensor to another. This requirement for near-coincidence is a powerful technique for noise rejection since noise during pressurisation is often substantially uncorrelated at separate sensors. This can be seen since, with low acoustic attenuation, acoustic waves from noise sources outside the surveillance area propagate to the area. Depending on the structural geometry the propagation may be along several paths. Again, the multiple modes for acoustic propagation along plates produce multiple peaking of the acoustic signals. The combined effect is to fill the test structure with a 'sea' of noise. From time to time constructive interference between the waves would trigger the event recognition discriminator of a given channel but such triggering would be substantially uncorrelated in each channel.

The event rate for near-coincident triggerings at each sensor of an array, for such uncorrelated triggerings on each channel, will be several orders of magnitude down on the single channel triggering rate (Sinclair, Formby and Connors, 1974). Thus, when the time window is τ, the ratio between the coincidence rate r_n for n sensors and the triggering rate for one channel r_1 may be shown to be

$$r_n/r_1 = (r_1\tau)^{n-1}. \qquad \ldots(2)$$

Typically the detection threshold conditions in the ACEMAN system are set to allow 10-20 events per second per channel into the computer. With τ of the order of 2 ms, as in the application described here, the product $r_1\tau$ is about 3×10^{-2}. So even with a requirement for near-coincidence at a sensor triplet (n = 3) the noise background is reduced to about 1.3×10^{-2} events per second and is randomly located in a display.

The noise has a more complicated effect when, in addition to random noise pulses, emission bursts arrive from a source located in the region of interest. It is then possible for signals from this source to trigger only two of the three channels required for location by a given sensor array, while noise triggers the third channel. The result is a spurious location for the source. When this process is repeated, such spurious locations are seen to lie on a hyperbola passing through the source and defined by the time difference between the correctly measured arrivals at two of the sensors.

The ACEMAN system normally operates with four sensors in each locating array. The fourth sensor serves several important purposes. By increasing n in expression (2) from 3 to 4, it reduces the number of apparent locations produced by near-coincidence of randomly arriving signals. And because the time window for the fourth sensor is normally much shorter than that for the other three sensors (Tobias, 1975), the effect is comparably greater (to produce an event rate of only 2×10^{-5} apparent locations per second in the present application). Secondly, it eliminates the spurious hyperbolae noted above. Thirdly, it removes ambiguities in source location associated with dual solutions for the location transformation (Tobias, 1975). Fourthly, it permits larger sensor spacings on closed structures, such as vessels, than are otherwise possible. Sound propagation by multiple paths on a closed structure and the front-back symmetry of certain sensor arrays (such as that employed in the present application) yield potential ambiguities that the fourth sensor eliminates.

3. APPLICATION TO INVERKIP VESSEL

In the present application of the ACEMAN system eight sensors responsive to waves in the 165 kHz region were used. They were mounted on the No. 3 unit manufactured by Clarke Chapman-John Thompson for Inverkip Power Station. The vessel, constructed from steel to BS 1501-271B, was 1.83 m (6 ft) in diameter and had 102 mm (4 in) wall thickness. Table I gives details of the steel.

3.1 Acoustic Propagation

Preliminary measurements were made at 165 kHz frequency to examine the propagation and attenuation of acoustic pulses injected at the surface of the vessel plate. Figure 3 presents the pulse patterns received at varying propagation distances, r, and shows that the peak of the pulse propagated with a clearly defined arrival time, even for distances greater than 10m. The corresponding sound velocity is 3.00×10^3 ms^{-1}. The measurements also showed that acoustic attenuation in the steel of the test vessel was negligible, approximately 0.2 dBm^{-1}, so that simple wavefront expansion produced most of the reduction in signal height with propagation distance. This is shown in Figure 4, where the signal height varies as $r^{-0.57}$. Neither pulse broadening nor signal attenuation thus limited sensor spacing.

A factor which limits the detectability of sources in the neighbourhood of vessel nozzles is the shadowing produced by these nozzles. To investigate this, the injected signal was examined at various points on and behind a nozzle of the Inverkip vessel. Figure 5 summarises the results.

As noted earlier, the signal received by the sensor is very clearly peaked when a line of sight exists to the source (bottom trace in Figure 5). As the sensor is moved so as to have a geometrical discontinuity between itself and the source, however, the arriving signal behaves erratically, is broadened in time and has a less clearly defined peak (upper trace). The arrival time of the peak shows a broad scatter and may be delayed from the calculated time. (Compare the filled circles and crosses in the Figure with the arrival time deduced from the open circles.) Connors, (1973) describes the effects on source location which timing uncertainties generate. Location resolution will be degraded by the scatter in arrival times so that sharp sources will be blurred.

Figure 5 also shows that shadowing reduces the received signal level, presumably as a result of mode conversion and signal loss at the geometrical discontinuities. Thus, source detection in shadowed regions will be biased towards those sources which generate high amplitude emissions.

3.2 Sensor Configuration

With any limited number of sensors on a structure a compromise has to be reached between detailed surveillance of individual features and coverage of an extensive area of the structure. In the present instance no special feature of the vessel was indicated before the test as warranting special attention. Thus, it was determined to maximise the area of vessel covered while ensuring that any detected sources were located unambiguously.

The portion of the vessel selected for inspection was 5 m (17 ft) in length near the centre of the vessel. This region provided a representative coverage of nozzles of differing sizes, contained both circumferential and longitudinal seam welds, and a position where a wooden chock bore part of the weight of the water-filled vessel. These features are shown on a developed diagram of the relevant part of the vessel (Figure 6). The presence in the surveillance region of small lugs welded to the exterior of the vessel should be noted. Ultrasonic examination results, supplied by Clarke Chapman-John Thompson, showed the presence of usual small scattered slag inclusions at welds (Figure 6).

Within the surveillance area the eight sensors were arranged at four circumferential positions, with two sensors diametrically opposite each other on a circumference and thus separated by 2.87 m. The circumferential positions were spaced at half this distance, the sensors being stepped round 90° on neighbouring positions so that an array of centred squares was produced. This is shown schematically in Figure 2 and explicitly in Figure 6.

Such an arrangement allowed the surveillance area to be divided into smaller areas, each covered by four sensors. These four-sensor arrays had identical patterns so that a standard transformation between the data (time intervals) and the location (vessel coordinates) could be employed. While not a need of the ACEMAN system, use of such a standard transformation simplifies analysis.

3.3 Test Procedure

As one objective of the monitoring was to examine the application of the acoustic emission technique during normal industrial conditions, no attempt was made to modify the arrangements used to seal nozzles in the vessel for the hydraulic test. Similarly the test was conducted according to the manufacturer's standard procedures.

4. RESULTS AND DISCUSSION

Figure 7 gives the pressurisation record for the hydraulic test, and indicates the pressure intervals during which data from the eight sensors were recorded on magnetic tape. Up to 9.0 MNm^{-2} (1300 psi) both the rms level of noise and the acoustic activity count rate at each sensor exhibited large fluctuations. The noise level than stabilised and during the remainder of the test considerably exceeded the electronic noise level so that the sensitivity of the detection system was limited by the level of noise generated during the test.

During the pressurisation the computer facility analysed data from only one sensor configuration in real time. This real-time analysis, with location results displayed on a screen, nevertheless gave assurance that no unexpected conditions existed and verified that a simulated emission source, operated intermittently during the test, was always correctly located.

Full location analysis was performed subsequently using the tape recordings which sampled 26% of the pressurisation at intervals in the test (Figure 7). In order to capture as many emissions as possible, signal discriminators were set to allow an average of about 15 noise events per second from each channel. The corresponding output amplitude required from the sensors was then about 20 μV. As noted earlier, the computer rejected the large majority of such noise triggerings. Figure 8 displays the pattern of located acoustic activity on the vessel. The pattern is complex, spots represent each emission event and a number of active areas, ringed in the Figure, emerge from the background.

Figure 9 is a magnification of the display obtained for one of the active nozzles, C5, during the pressure interval 5.52 to 6.89 MNm^{-2} (800 - 1000 psi). Attention is drawn to the noise figures at the right of the Figure, which are described fully by Tobias (1974). Comparing C, the noise count for one channel, with TVALID, the number of events satisfying the coincidence requirements, it is seen that noise events exceed located emissions nearly twohundredfold. Nevertheless, the nozzle activity was clearly evident.

The emission sources identified in Figures 8 and 9 are diffuse, confirming the prediction of Section 3.1 that nozzle shadowing would cause scatter in location. Optimum location requires a line of sight between a source and each of four sensors in a locating array. However, the Figures demonstrate that source detection remains possible for a structure whose geometry, with multiple nozzles, is complex.

It is probable that several emission mechanisms contributed to the emission source pattern presented by Figure 8. From previous experience, water leaks, perhaps only of small magnitude, would contribute to nozzle activity. One nozzle in the surveillance area, D21, was seen to be leaking steadily and this nozzle was acoustically active. Additionally, the bedding down of nozzle closures may have produced emissions. Emissions from welds, clearly shown for the external lugs, must have had a different origin. The probability of diverse emission mechanisms is also demonstrated by the several patterns of acoustic activity with increasing pressure (Figure 10). From laboratory and medium-scale tests, emission activity arising from plasticity at a defect would increase progressively with pressure until material ahead of the defect had yielded.

5. ASSESSMENT OF THE ACOUSTIC EMISSION TECHNIQUE

In considering any new non-destructive testing method it is important that it is not oversold and both drawbacks and advantages should be pointed out. A number of advantages can be clearly perceived for defect monitoring by an acoustic emission system such as ACEMAN.

(a) The technique is flexible in application - any sensor configuration can be used, substantial background noise is tolerable and the operating frequency can be chosen in the reasonably broad range from 100 kHz to 1 MHz.

(b) The equipment on the structure under test is simple, robust and easily positioned.

(c) The technique is long range with sources detectable several metres away from sensors. Thus large-area surveillance is possible in a single operation if required and remote monitoring is possible for inaccessible sites.

(d) Access need be available only to a relatively small number of locations for sensor placement, with advantages in regions of hostile environment.

(e) The technique slots into recognised procedures, and applications can be envisaged during welding, in stress relief and during proof test. During service operation, cracks may be detectable in repeat proof tests and during crack advance by fatigue growth.

(f) Established fracture mechanics calculations aid in defect assessment, since emissions from a defect are produced by changes in the defect parameters, e.g. length and plastic zone size, and these reflect the stress intensity level at the defect. The detectability of the same size defect in various orientations will be greatest precisely where needed, namely when the defect is oriented so as to be significant to structural integrity.

(g) The monitoring is readily made automatic. Subjective judgements and attendant human errors are minimised. Long-lived sensors and remote electronics permit data acquisition over the long term if necessary. Point by point evaluation, required by ultrasonic NDT for example, is avoided, and data treatment by the computer integral to the technique is readily possible.

(h) Permanent data recording for auditing purposes and comparison can readily be made.

Offsetting these advantages, a number of drawbacks must be recognised.

(a) The monitoring requires a loading stress appropriate to the situation - this may be difficult or inconvenient to produce.

(b) System sensitivity depends on noise. When the noise is unpredictable, then so is the sensitivity.

(c) As shown in Figure 8, an emission detection system can be sufficiently sensitive to locate signals from perturbing sources. These must be distinguished from genuine defects detected as in Figure 1, so that operators may employ a system confidently. Clearly more than event counting is required. While analysis by pressure, as in Figure 10, may provide the extra information required, such analysis is facilitated by large numbers of events at a given location, and only the larger defects may be treated in this way. More sophisticated techniques which use the information content of individual events are required.

(d) Multiple emission mechanisms may be associated with defects, including corrosion scaling, plastic yielding and brittle fracture of inclusions.

(e) Even for a well-defined process such as plastic yielding, the emission activity parameter β (equation 1) depends on the material.

(f) Nozzle shadowing results indicate that for source location in a complicated structure the number of sensors needed will increase with increasing structural complexity.

The future direction of acoustic emission development must lead to an ability for distinguishing the signals generated from genuine defects from those arising from the noise background. There are a number of possibly fruitful lines of approach - signal frequency content, analysis of signal amplitude, length and risetime, and analysis of the pressure or stress dependence of the emission activity. Future development must increase confidence in the technique so that the emission activity parameter β, for example, is predictable for different steels. The source mechanisms and principles governing emission generation require elucidation. Finally, a move to defect assessment, drawing from the fields of fracture mechanics and stress analysis, must be accepted before the technique can be applied with assurance.

6. CONCLUSIONS

It is known that defects can be detected by acoustic emission in controlled laboratory and medium-scale tests. The ACEMAN system has now been shown to locate discrete emission sources on a large vessel in industrial conditions. The system, using signal-recognition discrimination and computer timing analysis developed at BNL, was able to operate in the high noise background characteristic of standard manufacturing procedures during proof test.

It is likely that several emission mechanisms were present, and these were reflected in the various patterns of emission from the detected sources as a function of pressure. Several of the sources were associated with vessel weld regions, including nozzles, and externally welded lugs in particular were clearly identified. The high standards of manufacture and inspection associated with this vessel were such that the emission sources had no significance to vessel integrity.

Potential advantages and drawbacks of acoustic emission inspection have been identified. It is necessary that real defects are distinguished from sources which, while insignificant to structural integrity, nevertheless produce acoustic emission. The present programme at BNL is directed towards this end and, concomitantly, towards methods for source assessment.

7. ACKNOWLEDGEMENTS

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TABLE 1

Properties and Heat Treatment of the Steel

	Shell (BS1501-271B)	Nozzle (BS1503-271B)
σ_y	422 - 482 MNm^{-2}	448 - 608 MNm^{-2}
UTS	562 - 621 MNm^{-2}	593 - 710 MNm^{-2}
Composition (typical):	%	%
C	0.145	0.15
Si	0.285	0.23
Mn	1.415	1.26
Ni	0.520	0.35
Cr	0.590	0.87
Mo	0.235	0.27
Va	0.070	0.08
S	0.008	0.017
P	0.012	0.022
Cu	0.140	0.13

Heat treatment:

Hot formed 900-950°C

Normalised 900-950°C

Stress relief 4 h at 630-670°C

Furnace cool to 300°C

Still air cool to ambient

For similar material: K_{Ic} of welds and HAZ > 65.1 $MNm^{-3/2}$

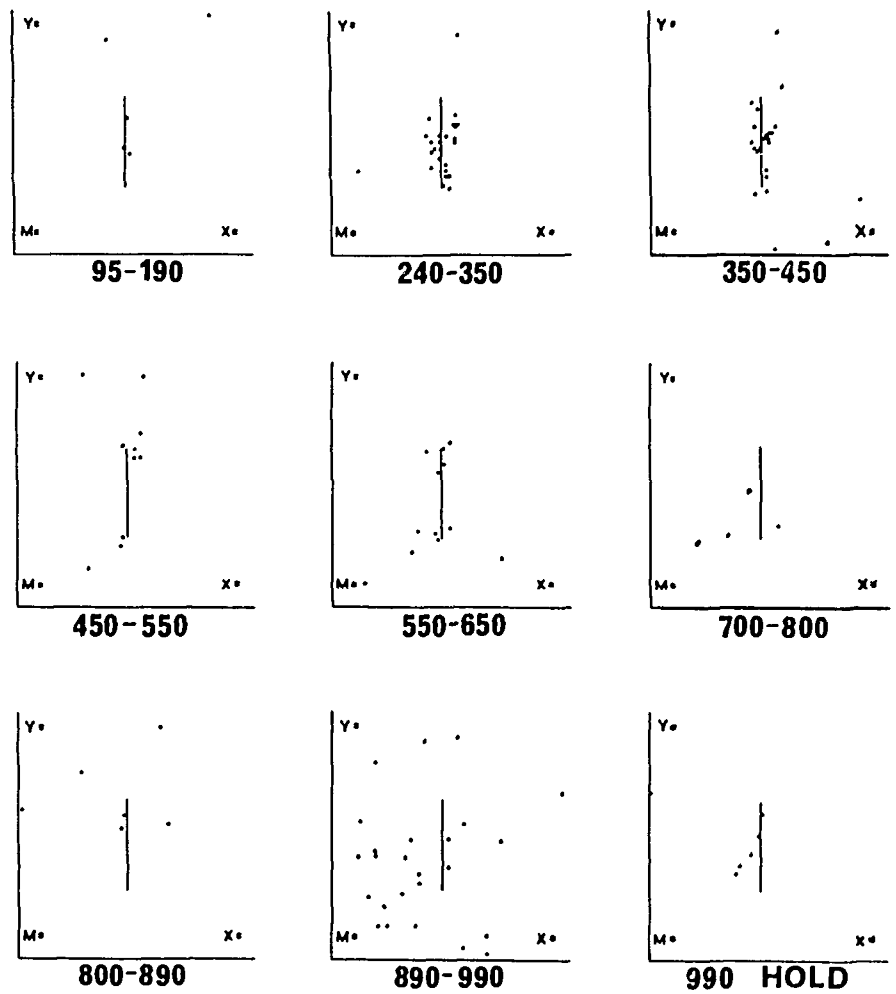


FIG. 1. Emission maps for partial penetration slit in mild steel plate under load. Pressure intervals are shown in psi.

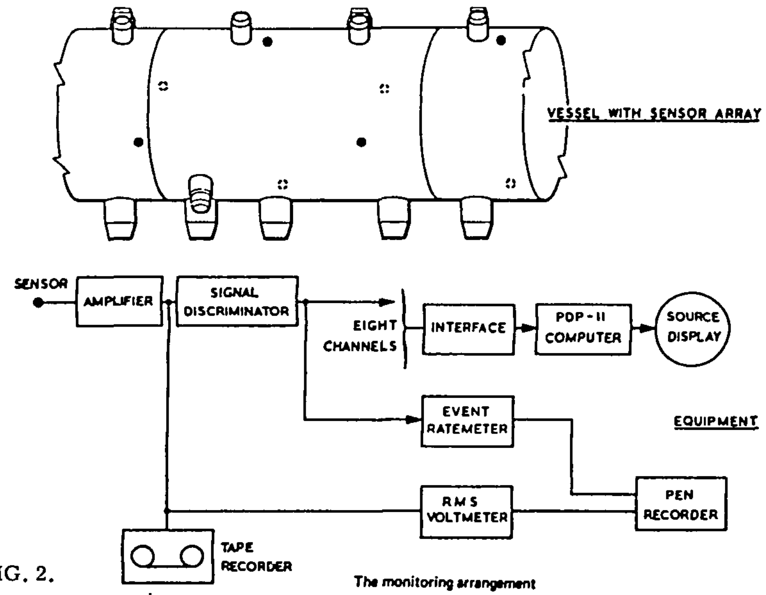


FIG. 2. The monitoring arrangement

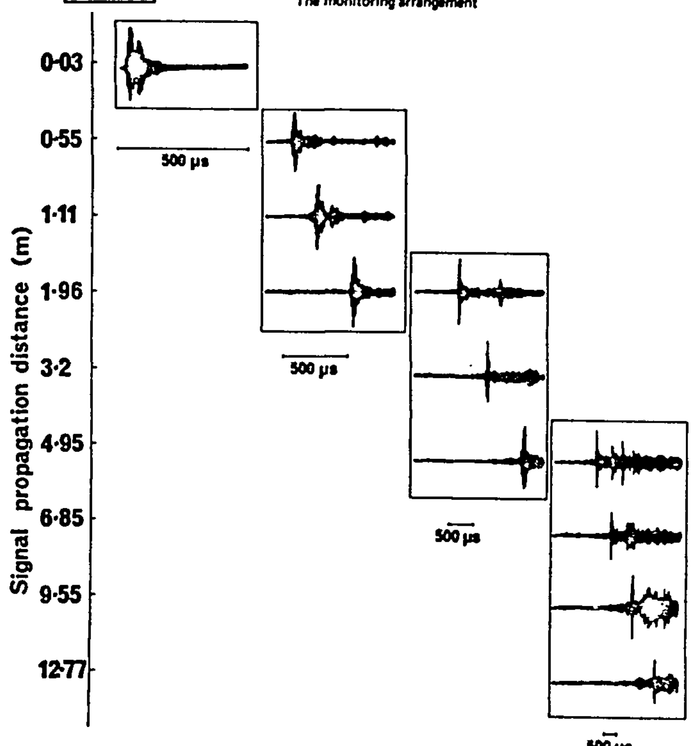


FIG. 3. Reception of acoustic waves near 165 kHz from a simulated emission source on 102mm plate. Peak signal heights vary with distance according to Figure 4.

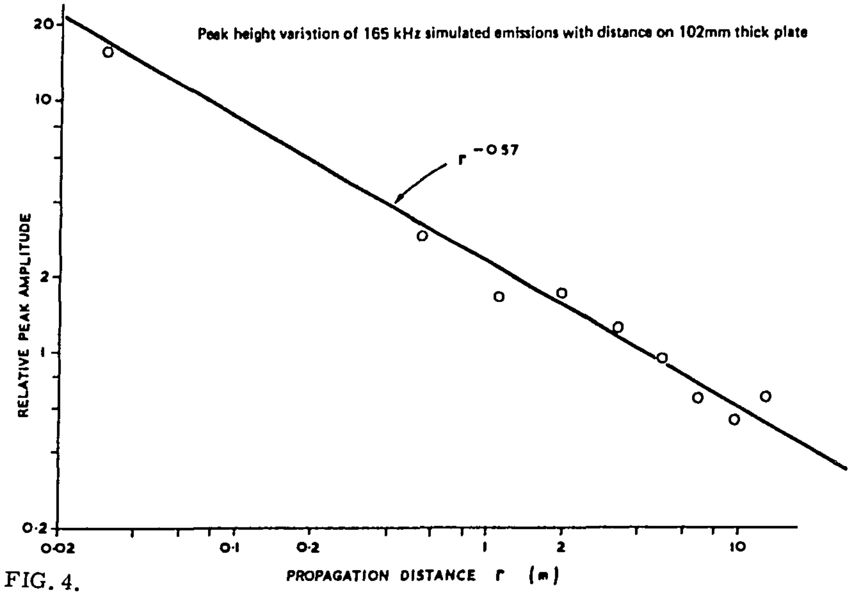


FIG. 4.

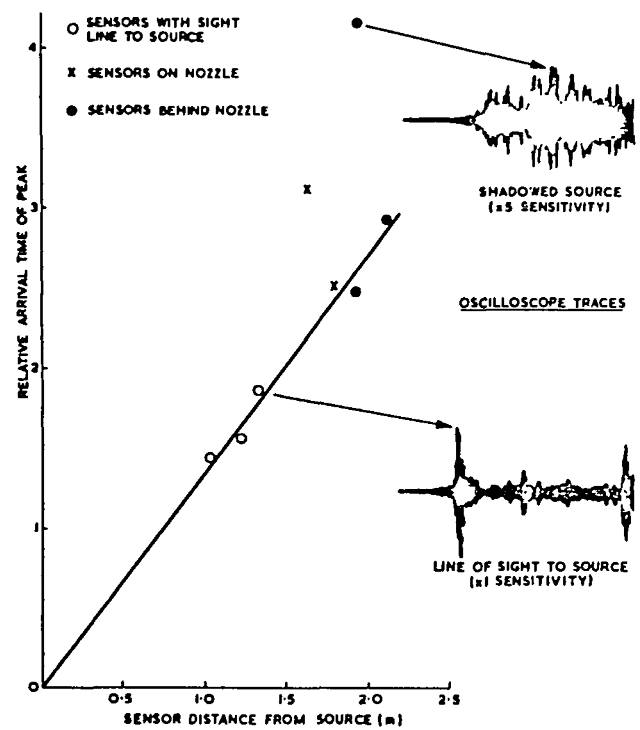
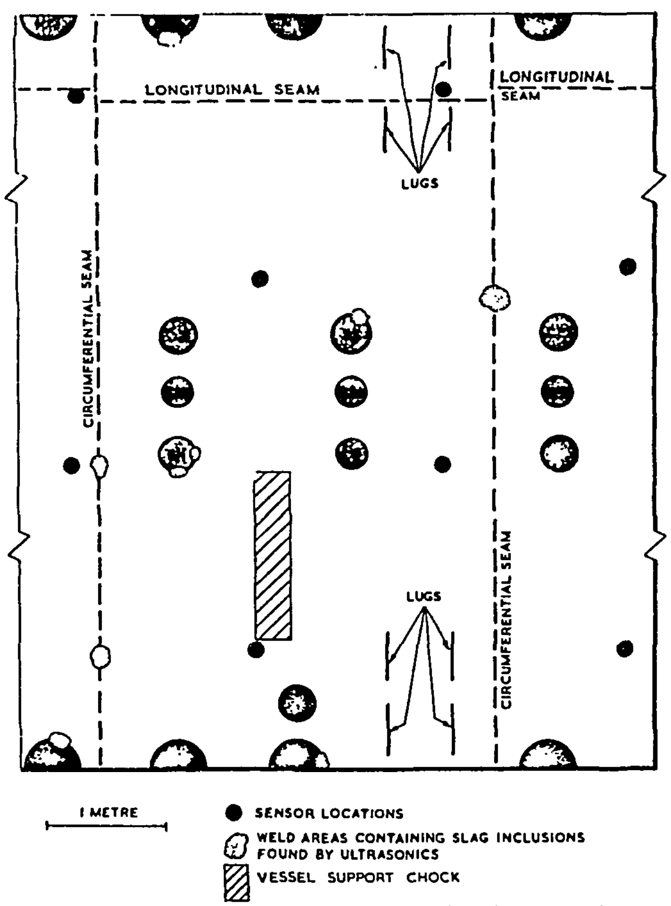
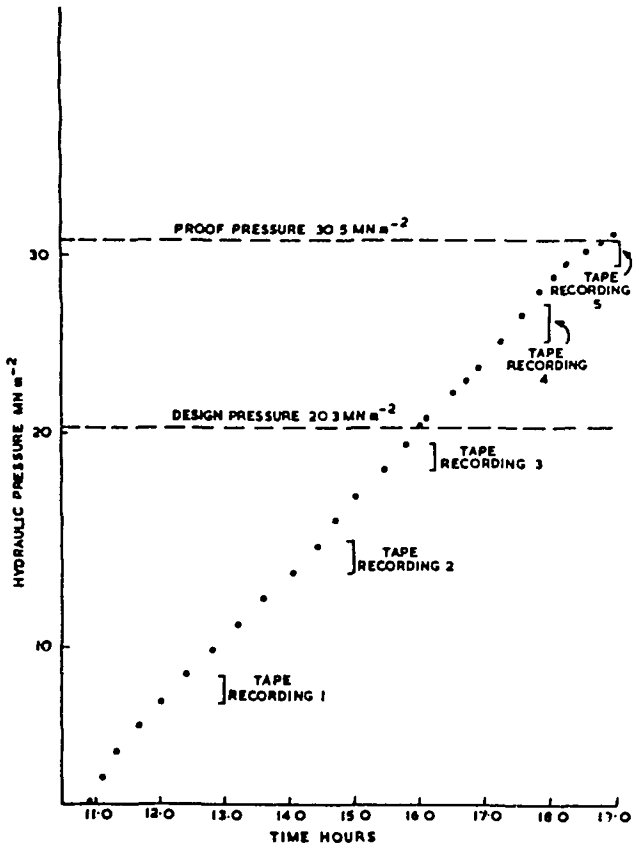


FIG. 5. Effect of shadowing by a nozzle, showing increased risetime and delay of signal peak.



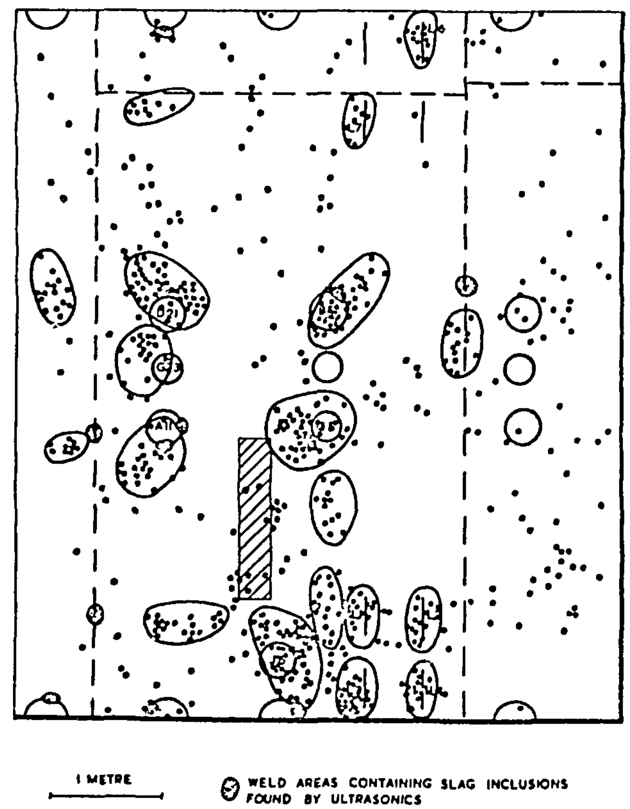
Developed diagram of vessel showing sensor locations with respect to features including welds and nozzles.

FIG. 6.



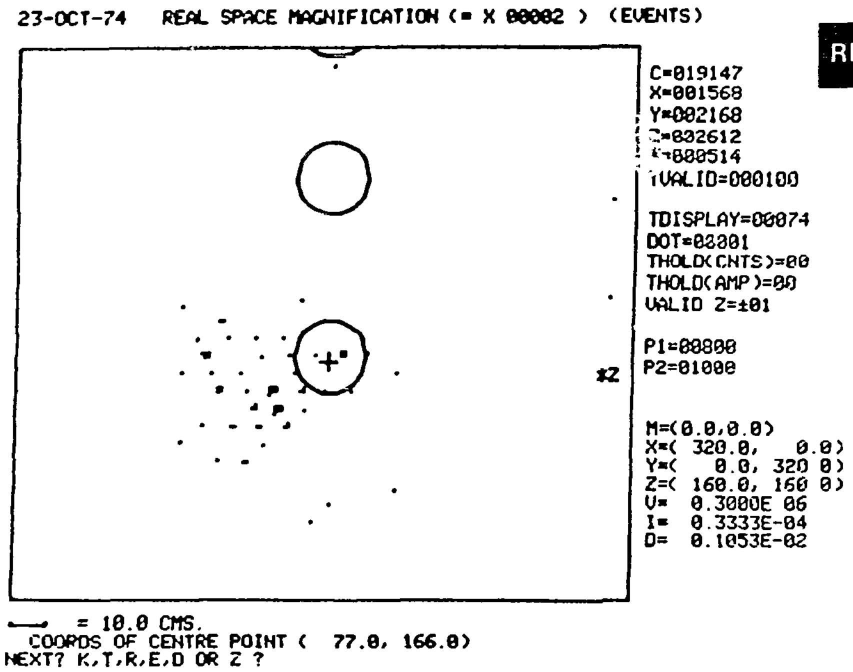
Pressurization record.

FIG. 7.



Acoustic activity sampled during pressurization, on a developed diagram of the surveillance area (Figure 5).

FIG. 8.



Magnified view of activity at nozzle C5 over the pressure intervals 5.5 – 6.9 MNm^{-2} (800 – 1000 p.s.i.).

FIG. 9.

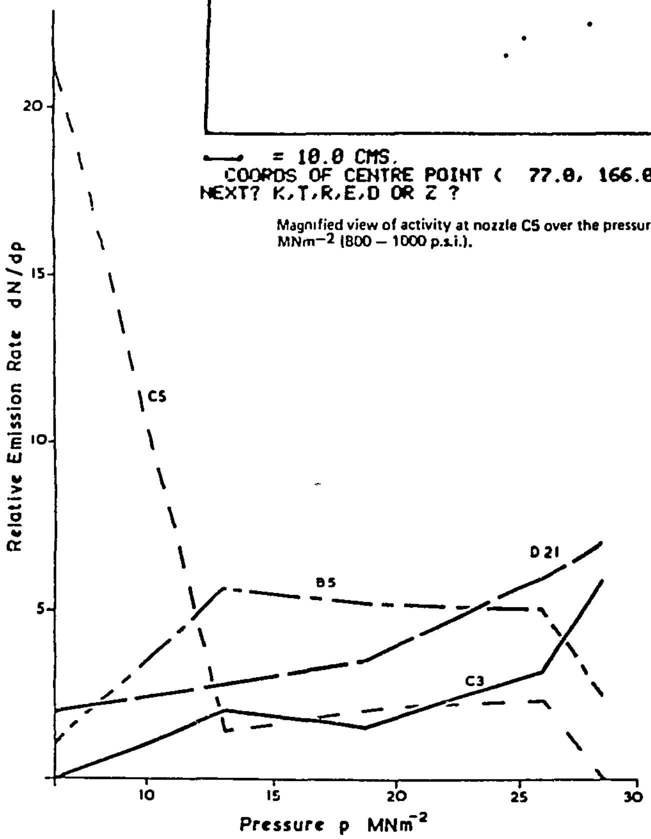


FIG. 10. Dependence of emission rate on pressure for differe .t sources.

REPORT SUMMARY SHEET

Central Electricity Generating Board
Berkeley Nuclear Laboratories

RD/B/N3471
Job No. XE128

C.E.G.B. UNCLASSIFIED

Multi-Channel Acoustic Emission Surveillance of a Pressure Vessel During Proof Test

- by -

A.C.E. Sinclair, A. Tobias and D.C. Connors

SEPTEMBER 1975

SUMMARY

The ACEMAN acoustic emission analysis system developed at BNL was used to detect discrete emission sources during the hydraulic proof test of a steam drum for Inverkip Power Station. The extensive surveillance region covered by the multi-channel system included a representative sample of welds and nozzle array complexity.

In spite of a large noise background, typical of industrial structures and conditions, special signal-recognition discrimination and computer timing analysis permitted clear and unambiguous location of acoustic sources. Differing emission patterns with pressure indicated that a variety of source mechanisms were operating, with active sites being associated with weld regions, particularly nozzles and welded lugs.

Advantages and drawbacks of the acoustic emission technique are identified from the point of view of its use as a method of non-destructive assessment.

K. Förster, "An approach to the On-Load Surveillance of Sodium Cooled Reactors by Acoustic Methods". (Federal Republic of Germany)

1. Introduction

The intensive discussion of the problems associated with the establishment of nuclear energy has led to an increase of safety demands for the design and construction and the operation of nuclear installations. In order to decrease the probability of severe accidents which may endanger the population in the vicinity of a nuclear plant, scientists and engineers are looking for new methods of detecting incipient malfunctions. Control systems are to be developed which are based on physical principles different from those normally used in nuclear plants. The research work in many laboratories indicates that acoustic methods have a high capability of development. In the future they may substantially contribute to the reliable and safe operation of nuclear power plants.

Acoustic measurements are based on the fact that certain processes produce sound waves. The term "sound wave" is standing for all periodical or stochastic phenomena, which appear as pressure variations in fluids or as noise in solid structures. Such sound waves cover a wide frequency range from about a few Hz up to several hundred KHz. According to the operating conditions of a plant or a component under examination the sound waves which are emitted show a characteristic behaviour. If a malfunction occurs it results in a change of the characteristics of the emitted sound. By means of suitable detectors and proper processing methods (signal level control, frequency analysis, etc.) this change can be detected and adequate safety actions can be started.

By means of acoustic methods one can establish continously working control and monitoring systems. The sound waves travel with fairly high velocities at moderate attenuation (at least in the case of noise passing through metallic structures), so the sound can be picked up in some distance from the noise source. This is important, if the sound producing part or area is not accessible. However, the greatest advantage is the possibility to provide an integral control of a large area or a complete system by means of only a few detectors.

That results in a favourable cost-to-efficiency ratio. But this advantage is directly connected with the disadvantages that acoustic systems are susceptible to disturbing background noise, and that the localization of a noise source is difficult. To solve these problems efforts are to be made in the processing of the measured signals. This should not be too difficult since the development in the field of data handling has reached a high level.

2. Specific conditions and requirements of LMFBR's

The problems which must be solved during the development of acoustic control systems for sodium cooled reactors are partially equal or similar to those one can find at other types of reactors (e.g. the cavitation control of pumps). Other tasks are quite specific for a sodium cooled reactor (e.g. the detection of sodium boiling). But for a certain type of plant its specific conditions and requirements have to be taken into account. In the case of a LMFBR the properties of the liquid sodium as coolant, the high temperatures and the materials used are the most restraining facts. Therefore one cannot simply transfer the results from acoustic measurements at e.g. water cooled reactors to sodium cooled ones. At least the hardware of the measuring systems, i.e. the transducers and the cabling in the hot sodium, may substantially differ from that used in the cooler water.

However, one problem is common to all types of nuclear and non-nuclear installations: It is the background noise that is present in any plant where parts are moving or fluids are flowing. The separation of the signals carrying the desired information from the background noise signals can be very difficult, and under unfavorable conditions even impossible. Therefore it is important to get comprehensive and precise knowledge of the background noise behaviour of nuclear systems.

This can be achieved by extensive measurements at single components and complete systems over the frequency ranges of interest. These measurements are on one hand the basis for an optimum design of the acoustic systems (frequency ranges, sensitivities, signal processing techniques), on the other hand they are the starting point for the designer to avoid noise producing constructions, in order to exclude damages by noise generating processes (e.g. cavitation) and to facilitate the acoustic control.

The development work has to be concentrated on two main tasks:

1) Transducers are to be developed which meet the requirements of LMFBR's, i.e. they will have to withstand the aggressive sodium, the high temperature, the high radiation and of course the acoustic loads without any failure over a long period of time (some years or even the lifetime of the plant).

2) Signal processing methods are to be worked out, in order to get high signal-to-noise ratios and to attain a reliable detection of the useful signals out of the mixture of many kinds of disturbing background noises.

3. Research and development work

During the course of the R + D-work for the SNR (Schneller Natriumgekühlter Reaktor, i.e. Fast Sodium-Cooled Reactor) several acoustic experiments have been started or will commence in the near future. The selection of individual tasks was governed by safety considerations. Among a number of various tasks which are partially more conventional or in a similar way valid for other types of reactors, three topics were thought worth while to be considered for the development of acoustic control systems for fast reactors:

1) sodium boiling detection in the reactor core,

2) detection of sodium-water reactions in steam generators and

3) crack detection by stress wave emission analysis.

As one can see from Fig. 1 the first two tasks are concerning certain points of the plant, the third one is related to all parts which are stressed by mechanical or temperature loads. According to the statements of the previous chapter a fourth task can be established:

4) Measurement and analysis of the background noise behaviour of nuclear plants.

3.1 Sodium boiling detection

Flow disturbances in the reactor core, caused by pump failures or fuel element blockages may lead to an overheating in the affected area and if the normal safety systems do not work, may result in a fuel meltdown with all its consequences. The last opportunity to prevent the propagation and to avoid severe damadge is given at the instant when boiling of the coolant occurs. According to its thermodynamic properties sodium forms large bubbles when it boils. These bubbles cause a fairly high noise level when they collapse in the cooler sodium around the affected area. Many experimenters have shown that this noise is measurable. So it should be possible to derive a trip signal for the shut down system from such a measurement.

The acoustic detection of sodium boiling is the topic that brought forth most of the experience available at INTERATOM on the acoustic field. Since some years sodium boiling experiments with a three-pin bundle were performed in a special test section that simulates the conditions of the SNR 300 as far as possible (Fig. 2). Various types of transducers-pressure sensitive as well as acceleration sensitive ones - were used as sound detectors. Besides the boiling noise we measured the background noise behaviour of the test loop. The results are encouraging.

Fig. 3 shows the results of a frequency analysis from the signals of a piezoelectric type transducer developed at INTERATOM. The upper part indicates that the normal background level over a wide frequency range is much lower than the boiling noise. In the middle one can see that mechanically produced noise (knocking or impacting of parts, moving of pneumatically actuated valves, etc.) reaches levels similar to those of the boiling noise in the frequency range up to 40 KHz. Beyond this threshold no significant reduction in the signal-to-noise ratio is found. A much more unfavorable behaviour is shown in the lower part where the boiling noise is compared with cavitation noise that was caused by throttling a valve in the test loop. Cavitation yields a sound spectrum that is quite similar to the boiling spectrum. These results lead to the following conclusions:

1) A boiling detection system should work at high frequencies, i.e. beyond 20 - 40 KHz.

2) LMFBR-plants will have to be designed for extremely low cavitation levels if acoustic boiling detection devices shall be used.

However, a lot of questions are still unanswered. Further work is necessary in order to get a reliable and practicable control system. It is planned :

1) to optimize the sound detectors,

2) to investigate the sound transmission within a fuel element from any axial position to the top,

3) to measure the background noise of nuclear plants (KNK and SNR 300)

4) to develope a signal processing system that is able to detect the boiling start up in time and to localize the affected fuel element.

3.2 Steam generator leak detection

Small leaks in sodium-heated steam generators result in a sodium-water reaction. The stationary reaction zone causes severe wastage of neighbouring tubes in rather short time. In order to prevent propagation to a complete rupture of a damaged tube small leaks must be detected as early as possible. At present the hydrogen content in the sodium resulting from the reaction is used as leak indicator. This control method has some disadvantages: The response time depends on the transport time of the sodium from the leak to the control unit. The signal level is influenced by both the leak size and the sodium mass flow rate in the system. That means that this method is the more ineffective the larger steam generator units are. Therefore it is important for the safe operation of large power plants to look for leak detection methods without a size or design dependent time delay. The measurement of the acoustic noise coming from the sodium-water reaction or from the flow turbulances of the outstreaming water may solve the problem. It is expected that the sound of the boiling water will strongly disturb the measurement. However, there are symptoms which indicate that at rather high frequencies (i.e. beyond 100 KHz) a sufficient signal-to-noise ratio should be attainable. So, e.g. acoustic emission measurements performed during the pressure tests of vessels or primary systems of reactors gave a clear indication of water leaks.

A fundamental investigation is planned in order to clarify the questions under consideration and to back the idea of an acoustic leak detection system by experimental data. Acoustic measurements will be performed in course of a test program on the behaviour of small water leakages into sodium. The main intention of those experiments is to get a better knowledge about the growth of very small leaks.

Fig. 4 shows a schematic view of the test set up. The test vessel is a steam generator model that has been used for large leakage tests. Four test plugs equipped with leaks of different sizes can be installed simultaneously. They will successively be put into operation by filling them with pressurized water. The noise will be measured at various positions of the vessel by accelerometers and pressure transducers. By comparing the acoustic results with the leak rates during the tests we hope to get information about the dependence of the sound generation on the leak size. Tube bundles of different size and geometry can be installed in the test vessel in order to study their influence on the noise transmission from the leak to the pick ups.

Provided that these tests will demonstrate the acoustic method as a suitable control technique, further investigations in more detail will be planned then, including background measurements at steam generators in service.

3.3 Crack detection by acoustic emission analysis

Acoustic emission has become a popular slogan during the last few years. The measurement and the analysis of noise produced by growing cracks or other material defects has come into use for different purposes such as failure detection, materials testing or leak detection. Fairly goot results were achieved when using this method in pressure tests of vessels and primary systems of nuclear plants in order to demonstrate the integrity of the systems. In those tests the acoustic emission measurement has proved as an outstanding supplement of the normally used examination methods. It is nondestructive, has an excellent sensitivity, and needs only an extremely short time to give information about the integrity of the object under examination. Although at the time it is still difficult to classify the emitted noise in order to conclude the type and the importance of a material failure, nobody will query the usefulness of such measurements.

Considering these facts one comes to the conclusion that it is worth while to think over the use of this method as a continuous monitoring system for nuclear plants or components of them. Cracks can be detected when they develop or grow so that complete ruptures of parts of the system can be prevented. Further it is imaginable that periodic inspections will be reduced or even will be completely omitted, or at least that inspection intervalls will be prolonged. Since the danger of severe ruptures within the system is considerably reduced the designer is more independent of safety aspects and has more freedom in planning a reactor system.

However, the use of continuously working control systems at reactor plants is strongly impaired by the operating conditions of those installations, e.g. high temperature, radiation, background noise. Although transducers are being developed for extreme operating conditions, at the time no pick ups are available which permit long operating times without any failure. In this situation, wave guide systems may be an alternative. They are fixed at the interesting points of the plant structure and transmit the sound waves to areas with normal conditions where the pick ups are coupled to them.

Other questions arise from the fact that the acoustic emission behaviour of austenitic steel which is normally used as structural material for sodium-cooled reactors is not yet well known. Because of the rather high toughness the emission rate and the total number of emission events is lower for austenitic than for ferritic materials. But this does not necessarily mean a worse crack detection, too. Cracks should preferably start and grow at points where the material is embrittled by manufacturing procedures or even more by operational loads. This results in a more ferrite like behaviour.

A more basic problem that is common to all types of reactors is the signal-to-noise ratio that is achievable in large plants. The background noise which is caused by fluid flow, friction, vibration or similar phenomena, is a limiting factor for the reliable detection of stress waves coming from cracks. Further, the kind and the qualification of the signal evaluation systems depend on the signal-to-noise ratio. It may be that at high background noise levels complete systems or components are not likely to be controlled by acoustic emission measurements but perhaps only individual limited areas. Signal processing methods may help to eliminate disturbing noise pulses.

In order to answer all these open questions a research program is planned that is to be performed in two phases. In the first stage acoustic emission measurements are foreseen during an extended program of crack growth experiments on components of a large sodium pipe system, such as ellbows, tees, bellows, etc. These tests are to be performed under realistic conditions, i.e. original material, true dimensions, sodium environment, and high temperature. The results are expected to give information about the acoustic behaviour of cracks under fast breeder conditions. A scheme of the test setup is shown in Fig. 5. The test models are mounted in a protective vessel. They will be filled with sodium, heated up, pressurized and then loaded by different kinds of cyclic loads. The noise coming from the growing cracks which are artificially initiated will be measured by sound detectors which are directly attached to the structure or are positioned at the outside of the test vessel and coupled to the noise emitting structure by wave guides.

The second stage of experiments will be performed with the aim to evaluate reliable data of the background noise behaviour of a large nuclear plant. The construction of the SNR 300 offers a unique chance to install an acoustic emission measuring system in a breeder reactor. That is being realized just now at the primary system of the SNR 300 plant. The primary system was chosen for different reasons:

In the primary part the acoustic measurement should be most useful, since that area is no more accessible once it has been in operation unless a high wastage of time and money. Thus normal periodic inspections are not applicable. That area further provides for the extremest testing conditions we can find in the whole plant.

One primary loop will be equipped with a total number of 12 transducers distributed into four control points (Fig. 6). Three transducers at a time are peripherically fixed at the main pipe system close to the inlet and outlet nozzles of the reactor tank. In order to decide which direction the measured noise is coming from - from the reactor internals or along the piping - a fourth pick up is mounted in a certain distance from the first measuring plane. The other two positions are located on the suction side of the pump and at the exit of the intermediate heat exchangers. They allow for the control of sound waves produced by the pump or transmitted from the secondary system. The electrical signals will be conducted from the transducers to a separate control room in the air-filled region of the plant.

The first measurements are planned to commence during the commissioning of the plant. Information about the function of the measuring channels and a general view of the background noise behaviour is expected. Subsequent measurements during the operation of the plant at full power will have to yield detailled knowledge about the longtime behaviour and potential changes both of the measuring system and the background noise. The results of these experiments will be compared with the acoustic emission signals from the crack growth tests. This comparison should make it possible to decide whether a crack or leak detection system on an acoustic basis is practicable.

In this connection the development of localization methods is of great importance. The detection of growing cracks in a pipe, of small leaks in a steam generator or of blocked fuel elements in the reactor core by acoustic methods would obviously be a considerable progress in the safety technology, but it would be still more advantageous if one in addition to the detection of a malfunction could simultaneously localize its position.

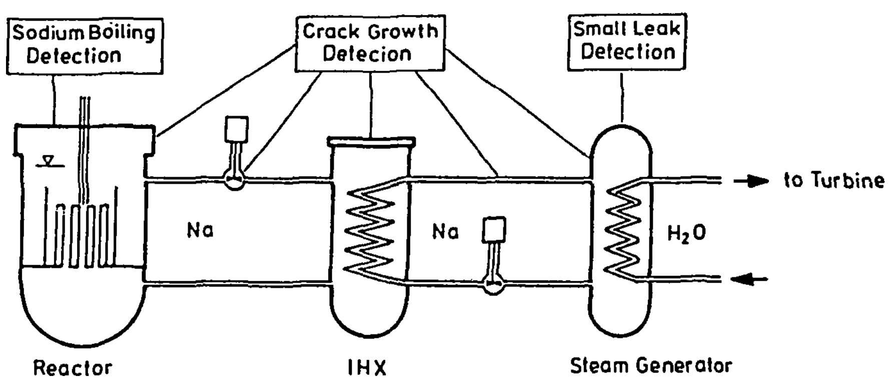
To give a summary of the problems which will have to be solved, all aspects of the research work as it is planned for the development of the SNR 2 are put together in Fig. 7.

4. Outlook

From the research work described above we expect a lot of information about the usefulness and applicability of acoustic control methods at sodium-cooled nuclear plants. The three tasks which were reported about must not be regarded isolated. They are some of the most interesting examples of a palette of measurements which seem to be promising for the acoustic surveillance. Further vibration measurements are under discussion. So, e.g. a vibration control of the reactor internals and the primary system is provided for the commissioning phase of the SNR 300 plant. From these measurements experience is expected concerning the continuious vibration monitoring of critical components during reactor operation.

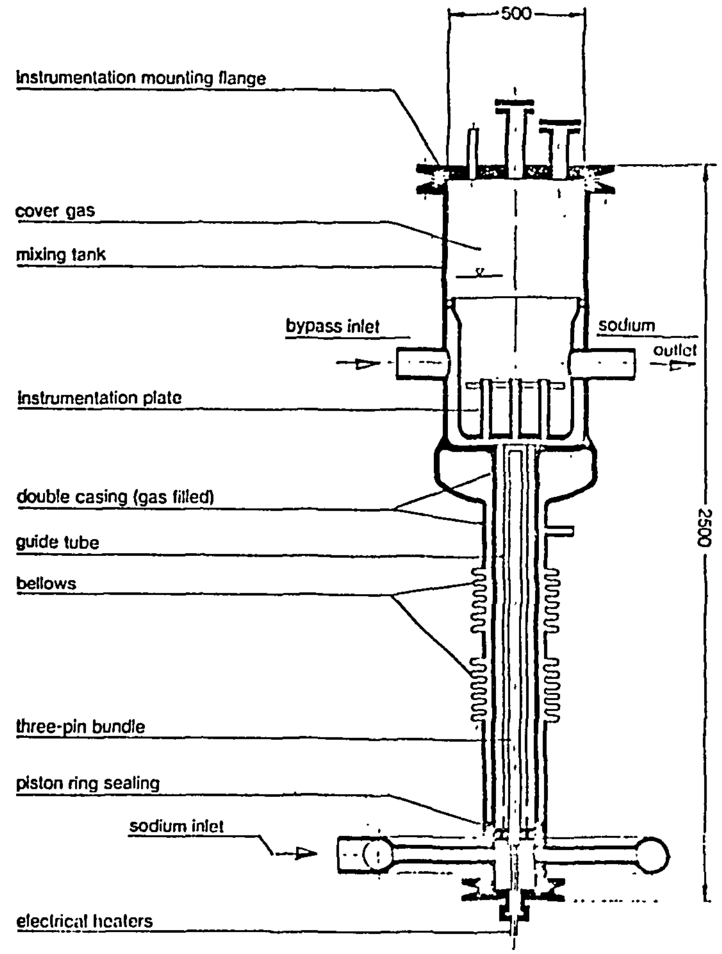
Also the combination of different methods must not be overlooked, so e.g. vibrational or acoustical measurements may be combined with neutron noise measurements.

As a summarizing conclusion one can make the following statement: Although a lot of questions and problems are still open, new control methods come into use. They are based on principles which are not yet common to nuclear plants. But one can be optimistic that the development work will be successful. In the future acoustic and other unusual methods will prove as a reliable part of control systems for nuclear installations.



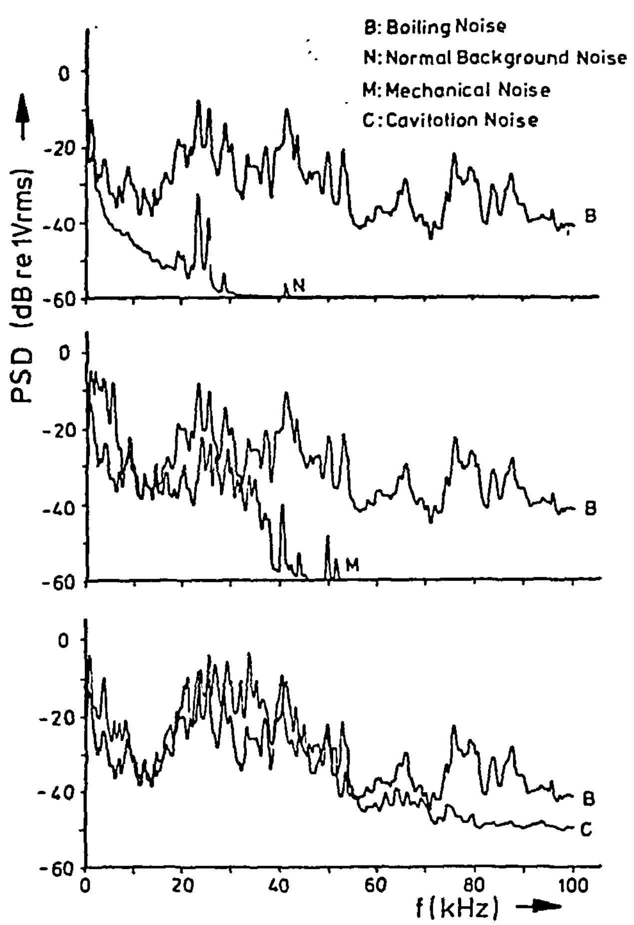
Acoustic Surveillance of LMFBR's

Fig. 1



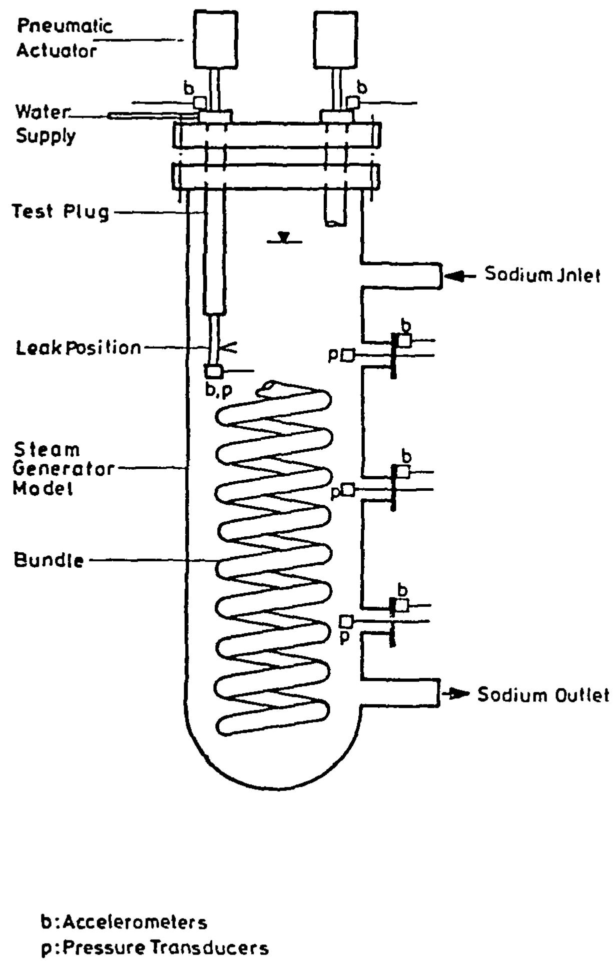
Test section for sodium boiling detection tests

Fig. 2



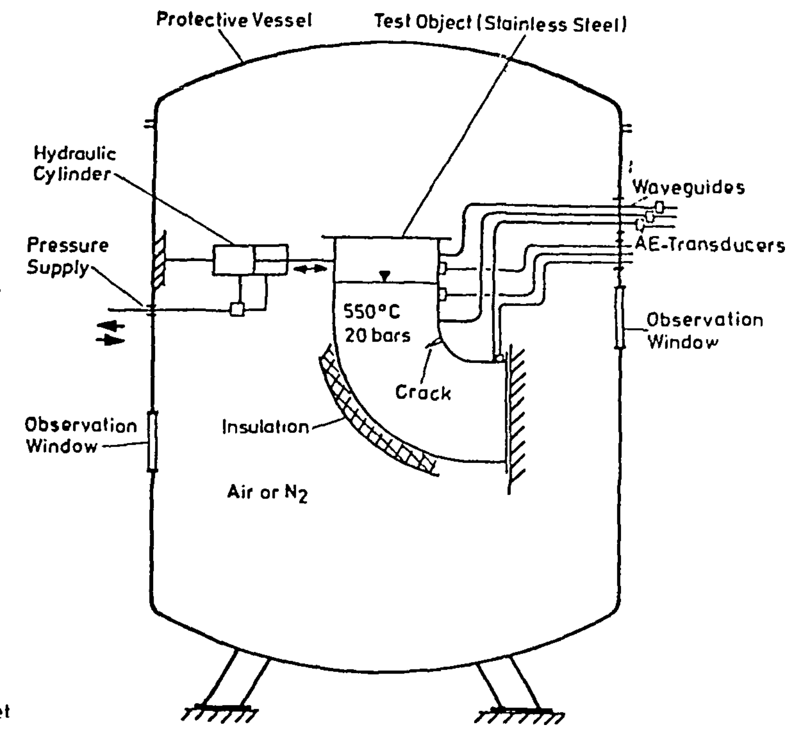
Acoustic Detection of Sodium Boiling
Power Spectra of Li NbO$_3$-Detector (INTERATOM)

Fig. 3



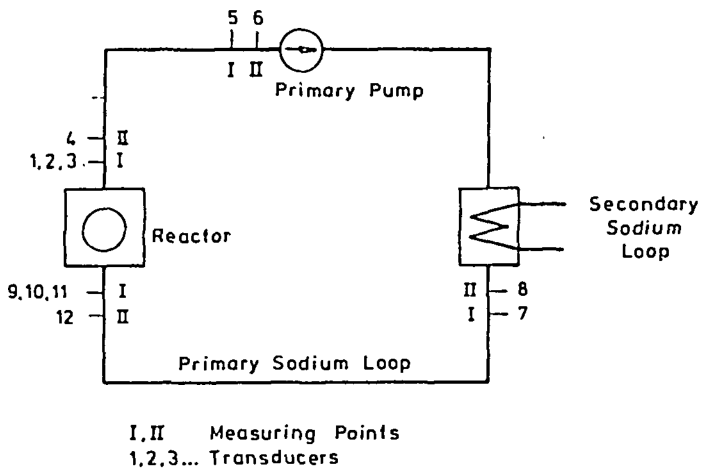
Test Setup for Small Water Leak Detection

Fig. 4



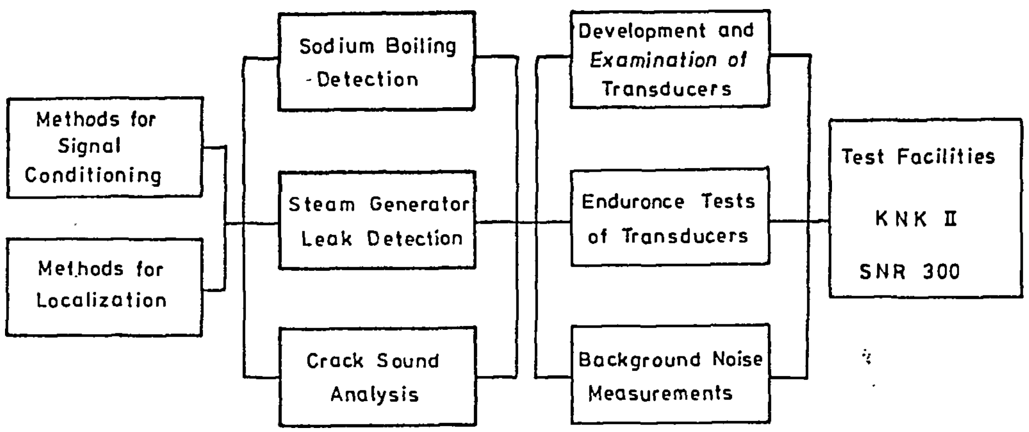
Test Setup for Crack Growth and Acoustic Emission Measurements

Fig. 5



Acoustic Emission Measurements at the SNR 300
Arrangement of Measuring Points in the Primary System

Fig. 6



Acoustic Surveillance

Fig. 7

E. G. Tomachevsky, "Appliance of Stress Wave Emission in Phenix Reactor". (France)

Les essais de surveillance par détection d'Emission d'Ondes de Contrainte ont été faits en 1973 et en 1974 sur la cuve principale du réacteur PHENIX pendant les principales phases des essais de contrôle, notamment lors des premiers chargements de la cuve. C'est ainsi, que l'on a pu enregistrer les émissions lors des premières montées en température à 450° et à 520°C et lors du premier arrêt d'urgence par chute de barre, le réacteur se trouvant en palier aux conditions nominales de fonctionnement.

La cuve est suspendue à la dalle au moyen de 21 suspentes. Les capteurs de détection EOC ont pu être couplés sur 4 d'entre elles situées sensiblement sur les axes principaux de façon à couvrir toute la cuve (voir planches 1 et 2). Les avantages de cette disposition sont :

- fonctionnement des capteurs à la température ambiante et non à la température de la cuve,
- accès relativement facile aux capteurs par trous de poing pratiqués sur les couvercles des logements de tête de suspente,
- préamplificateurs situés à proximité des capteurs d'où courte longueur des câbles de liaison et fonctionnement à la température ambiante.

Mais ces avantages ont pour contrepartie les inconvénients suivants :

- grandes distances entre capteurs (au moins 15 m),
- faible nombre de capteurs de surveillance : 4 seulement à cause de l'encombrement des autres trappes.

La cuve se trouvant normalement à la température de 520°C et les têtes de suspente à la température ambiante, la liaison cuve-suspente est soumise à d'importantes contraintes d'origine thermique à chaque variation brutale de la température de la cuve, risquant d'entrainer des plastifications successives (effet de rochet). La détection d'émissions engendrées par ces plastifications est donc d'un grand intérêt.

Du fait de la disponibilité que de 4 trappes, 4 liaisons cuve-suspente seulement sont situées à proximité d'un capteur. Cette proximité permet aux capteurs de recueillir les signaux même faibles provenant de ces liaisons privilégiées. L'amortissement dû à la distance ne permet à ces capteurs de ne recevoir des autres liaisons que des signaux puissants forcément moins nombreux.

Une telle disposition permet tout de même une surveillance efficace à l'aide d'un équipement de comptage travaillant d'une manière indépendante sur chaque voie. En revanche, elle est moins favorable à l'emploi d'un équipement de localisation qui ne peut prendre en compte que des signaux arrivant au moins sur deux voies.

On sait que l'équipement de comptage n'effectue aucune discrimination entre les signaux d'amplitude supérieure au seuil. Il reçoit donc non seulement les signaux originaires de la liaison mais aussi tous les autres. La somme de ces signaux constitue une sorte de bruit de fond dont l'évolution est caractéristique. On a pu identifier ainsi des changements de régime des pompes principales au seul examen des enregistrements EOC dont un exemple figure sur la planche 3.

La surveillance ni pendant les premières montées en température à 450°C et à 520°C, ni pendant un essai d'arrêt d'urgence par chute de barres faisant descendre brutalement la température de 520° à 250°C n'a révélé aucune augmentation alarmante d'émission.

On peut en déduire qu'aucun défaut ne s'est développé pendant ces surveillances ce qui n'est pas tellement surprenant par suite du faible nombre d'heures de fonctionnement et de la sévérité du contrôle tant pendant la fabrication que pendant le montage.

Des essais de localisation ont été effectués sur la cuve principale de Phénix. Les émissions engendrées par un simulateur ont été parfaitement localisées ainsi qu'on peut le voir sur la planche 4.

L'étude du rapport signal/bruit des émissions simulées à partir de chacun des capteurs donne une idée des directions de propagation préférentielle des signaux, les transmissions latérales étant meilleures que les transmissions diamétrales. Voir planche 5.

L'équipement de détection est visible sur la planche 6.

CONCLUSION

La campagne d'essais de détection d'émission d'ondes de contrainte (EOC) a prouvé que l'on pouvait, en prenant des précautions, principalement contre les parasites électriques, détecter des signaux dans un environnement de réacteur.

Le bruit de fond du sodium n'est donc pas un obstacle insurmontable. Les bruits de manoeuvres de chargement n'ont même pas été visibles sur les enregistrements.

On estime que pour obtenir une détection efficace il faut disposer les capteurs suivant un maillage de 2 à 3 m. On est loin du compte dans le cas présent avec des distances théoriques de parcours de l'ordre de 12 m qui peuvent être comptées d'au moins 15 m à cause des cheminements tourmentés autour des obstacles. Dans ces conditions l'amortissement dû à la distance élimine tous les signaux dont la puissance à l'émission est insuffisante pour les faire émerger du bruit de fond à l'arrivée. Le maillage disponible ne permet donc que la prise en compte des signaux puissants, en nombre limité.

La disposition d'un capteur par suspente aurait évidemment permis une surveillance beaucoup plus fine.

La méthode de comptage utilisée au début ne considère que les signaux d'amplitude supérieure à un seuil donné sans considération de forme, de coïncidence, ni d'origine. Des signaux discrets sont comptés de la même manière que des pics du bruit de fond général. Cette méthode ne peut donc que donner une allure du régime de fonctionnement. Les paramètres de réglage (seuil, gain et filtrage) ont une grande influence sur l'allure des enregistrements.

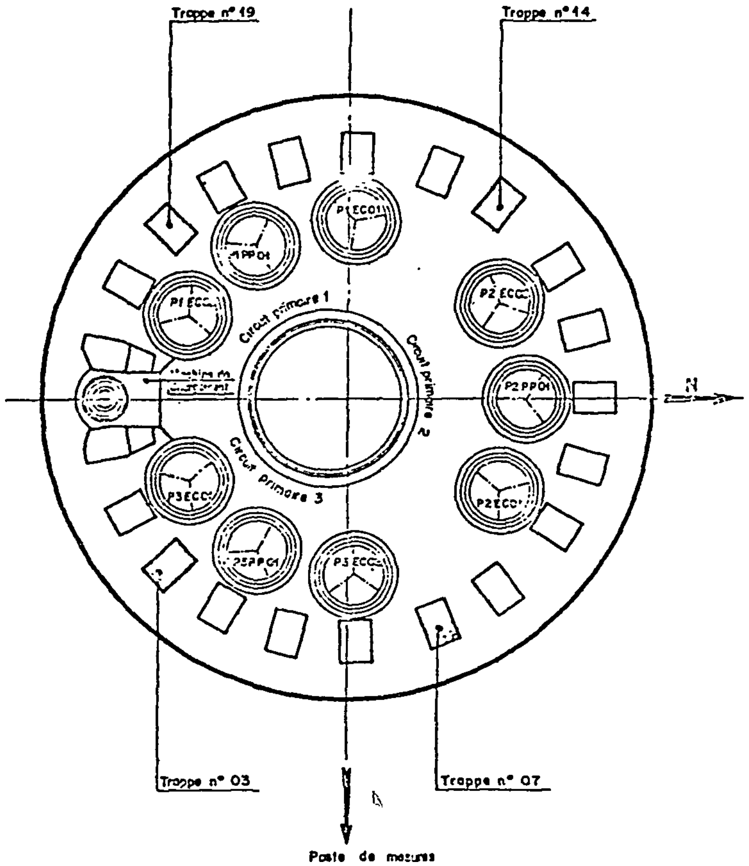
L'emploi d'un localisateur grâce à la comparaison des temps d'arrivée des signaux sur les différentes voies, permet de différencier les signaux entre eux et d'éliminer ainsi les pics parasites émergeant du bruit de fond général du réacteur. La localisation des lieux d'émissions - toujours pour des raisons d'amortissement - ne peut être effectuée que pour des émissions puissantes, donc rares dans le cas présent.

Si on avait pu disposer d'un capteur sur chacune des 21 suspentes on aurait pu surveiller individuellement chacune des liaisons cuve-suspente et préciser les sources d'émission de signaux de puissance relativement modeste.

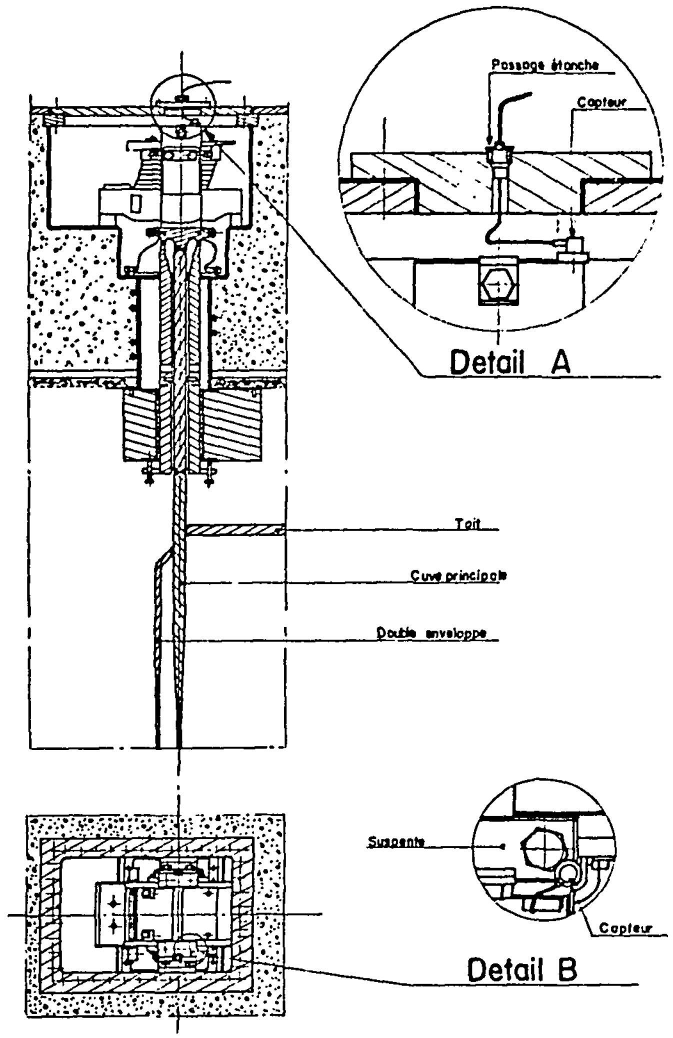
La comparaison avec les autres systèmes de surveillance n'a rien donné, les phénomènes surveillés, très différents, n'ayant pas obligatoirement la même origine dans le temps. (Sauf bien entendu des manoeuvres ayant des répercussions immédiates et générales telles qu'arrêt d'urgence, démarrage, etc...).

L'absence de signaux puissants montre tout de même qu'il ne s'est rien passé d'anormal pendant les périodes de surveillance. La comparaison d'enregistrements futurs avec les enregistrements déjà effectués permettra de discerner d'éventuelles modifications d'allure qui pourraient se révéler utiles tant au Constructeur qu'à l'Exploitant.

Enfin, grâce à la possibilité d'installer rapidement dans la salle d'essai (puisque les lignes sont tirées et les capteurs couplés) on a la chance de pouvoir effectuer toute détection EOC, pratiquement au moment voulu si le besoin s'en faisait sentir. On dispose également là d'un excellent banc d'essai pour le matériel de détection EOC proprement dit, notamment pour l'étude de la durée de vie des constituants les plus exposés.



Répartition des points de surveillance EOC
Planche 1



Disposition du capteur sur sa suspente
Planche 2

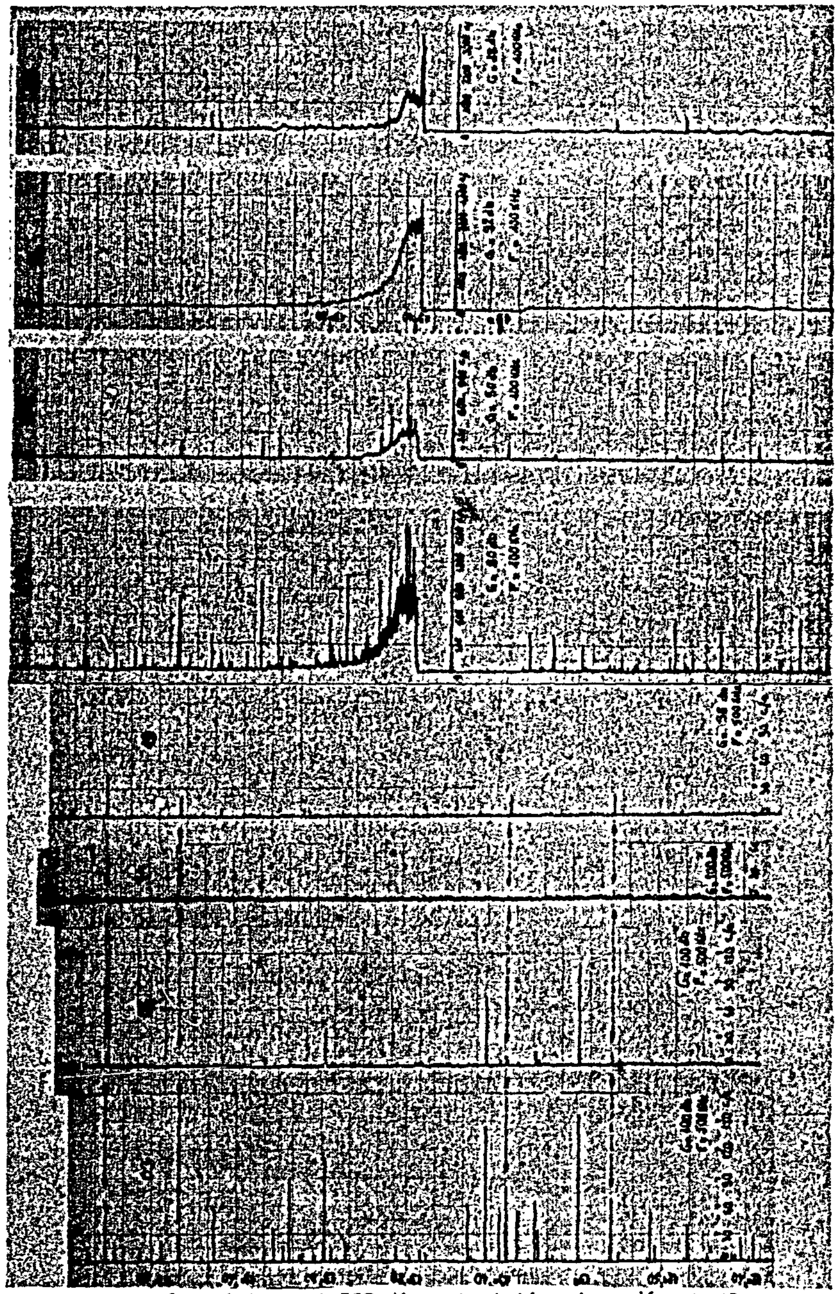


Planche 3 Enregistrement EOC d'une tentative de redémarrage de la pompe 2 (en haut) et d'un fonctionnement en palier (en bas)

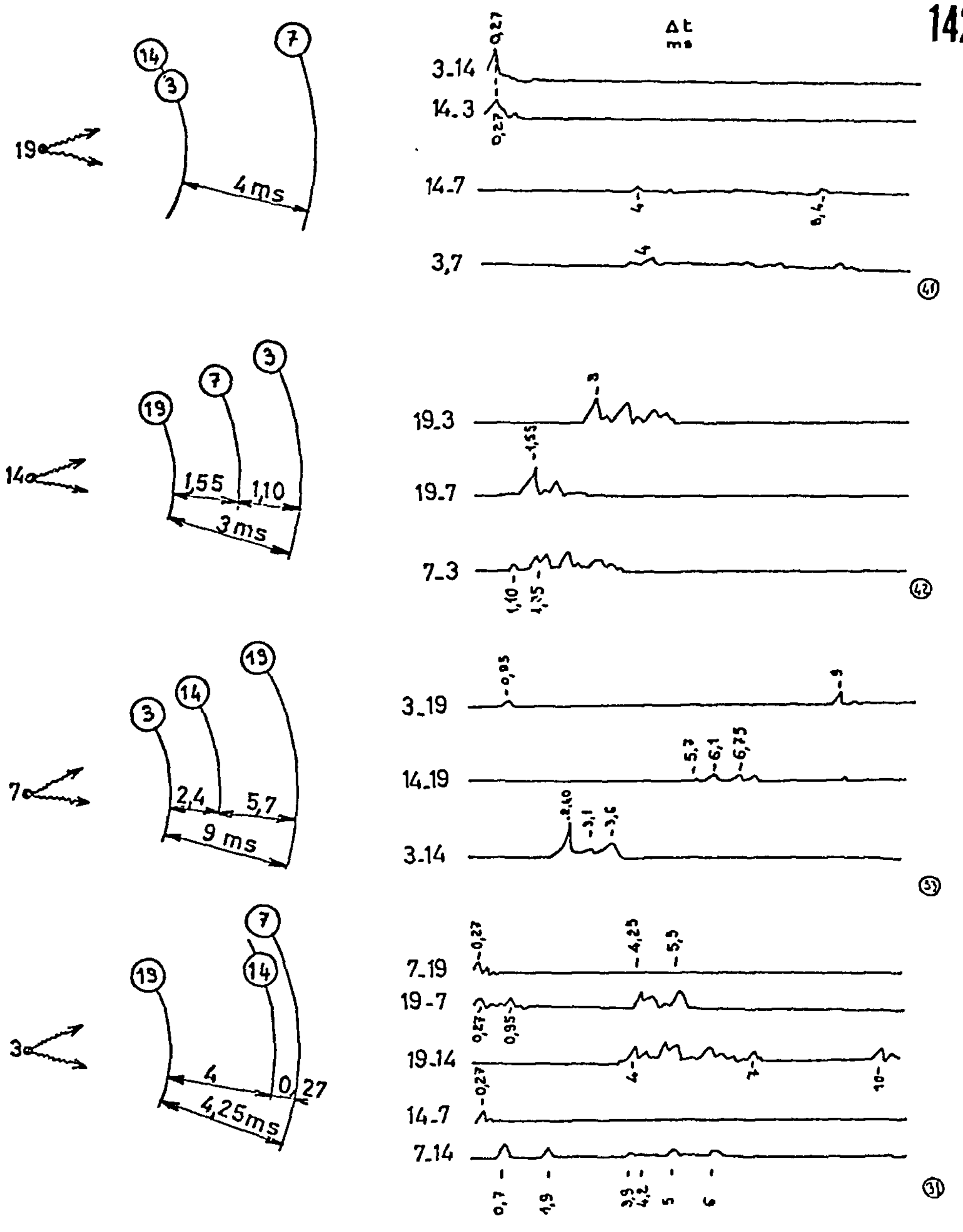
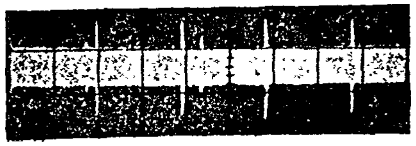


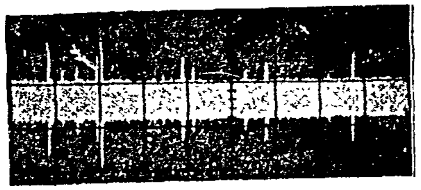
PLANCHE 4 Localisation d'émissions simulées (dépouillement)

Exemples de réception d'émission simulée

Emission en 7 le 9.1.74 à 17h35
Réception en 3
amplitude 500 mv/carreau
temps 500 ms/carreau
gain 100 db



Emission en 7 le 9.1.74 à 17h36
Réception en 14
amplitude 500 mv/carreau
temps 500 ms/carreau
gain 100 db



Emission en 3 le 9.1.74 à 18h20
Réception en 7
amplitude 500 mv/carreau
temps 500 ms/carreau
gain 110 db

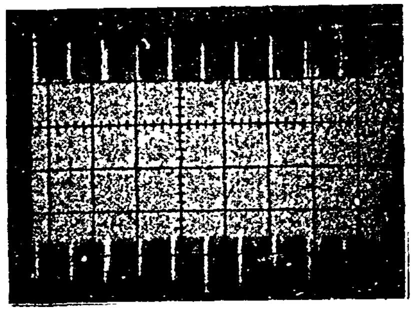


Tableau des rapports signal/bruit

Réception / Emission	3	7	14	19
3		3	1,82	2,74
7	3,6		3,2	2,4
14	2,27	4,27		4,10
19	3,37	2,42	3,84	

Planche 5

Propagation des signaux
Etude du rapport signal /bruit

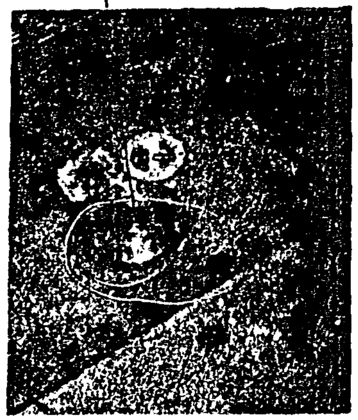


Planche 6

Vues de l'équipement de détection EOC sur le réacteur
Phénix

Th. J. Tromp,*) "Vibration-Acceleration Measurements on Prototype Steam Generators". (The Netherlands)

1. INTRODUCTION

As part of the design and test program for SNR-300 steam generators a program was carried out to ascertain that no vibration difficulties will arise in the steam generators. Within the frame work of this program the following tests were carried out:

1.1. Straight tube steam generator 85 MW

Model tests on mock up twice the size of the sodium entry section of the 85 MW straight tube steam generator. In this test hot water was used. The purpose of the model test was to establish the excitation forces and frequencies of the tubes.
In conjunction with these tests "finite element" calculations were carried out.

1.2. Helicoil steam generator 85 MW

Model tests on the tube bundle were carried out in order to find flow induced fluctuating forces on the tubes. Again this in conjunction with calculations which were carried out for both the evaporator and superheater.

1.3. Straight tube prototype superheater

Vibration measurements were carried out in the 50 MW sodium component test facility**).

1.4. Helicoil evaporator

See point 1.3.

The points 1.3. and 1.4. are within the scope of this meeting. Therefore the measurements on the prototypes will be discussed in the following.

*) NERATOOM, the Hague/Holland
**) of TNO-Hengelo

2. STRAIGHT TUBE SUPERHEATER

2.1. Equipment and set up

The superheater is part of the 50 MW prototype steam generator tested in Hengelo.
On this component measurements were carried out by means of pick-ups that were lowered in the steam tubes.
The pick-ups comprised two accelerometers with their measuring axis perpendicular to each other.
The measuring range of the accelerometers was up to 2000 C/s.
The accelerometers were fitted in a cartridge which could be positioned and clamped*) anywhere in the tubes.

The tests were done at full sodium flow; sodium velocity: 3.5-4 m/s; temperature 200°C. Since the pick-ups were lowered from the steam side the tube could not be pressurised. This means that the tubes were not stressed. Three tubes at the circumferences of the bundle and one in the centre were monitored in this manner. One reference pick-up was used. The signals obtained were recorded on magnetic tape; frequency range: up to 5000 C/s. Amplitudes were obtained via double integration.

2.2. Results

Recorded were frequencies of:
75, 135 and 365 C/s. Some signals at 50 C/s were observed. The amplitudes that resulted from these measurements were extremely low and were in the range of: 2 . 10^{-9} m.
During the various tests no signals in the axial direction of any importance were obtained. Not even in the entry/mixing area of the steam generator.

3. HELICOIL EVAPORATOR

3.1. Tests on outer shell

3.1.1. Equipment and set up.

The evaporator is shown in figure I. This unit has basicaly the same tube bundle as the SNR units.

*) by means of pressurised air.

However the shell, sodium nozzles and water/steam in- and outlet differ. The sodium velocities are in the range of 1.5-2 m/s.

As shown in fig.I on three spots accelerometers were attached to the shell. The transducers were mounted on steel rods, of 0.2 m length and 0.015 m diameter, perpendicular to the shell.
The measuring range of the transducers was up to 40-50 kC/s. The signals were recorded.
The lower frequencies were recorded with FM; up to 1000 C/s. Direct magnetic tape recordings were made for the range of 200 C/s - 25 kC/s.

The tests were done at load conditions (flow) variing from 15% - 100%, during a operating time of approx. 3000 hrs. After roughly every 600 hrs a measurement run was made.

3.1.2. Results

The spectra recorded remained stable over the 3000 hr period. In the low frequency range 3.15 - 400 C/s, the vibration levels were very low and had nearly the same magnitude as the background noise levels. This holds true for all load conditions.

In the higher frequency range two peaks of 3150 C/s and 10.000 C/s were found. In some cases an additional peak of 16.000 C/s was observed. The displacements that were obtained from these measurements were very low. They were in the range of : 10^{-8} m, although locally larger values are possible.

In order to find out where these signals originated, the pump was checked by means of two accelerometers. The result was that the pump did not generate the 3150 and 10.000 C/s signals. Furthermore the signals were there with only sodium flowing. After careful analysis we have to say that we do not know where the 10.000 C/s signals comes from.

There is an impression that it might have been caused by turbulence in the sodium. However we are sure that this signal is not important or harmful.

The 3150 C/s signal could not be explained at first. After careful scrutin of the construction of the component it appeared that the evaporator had no part that could generate this signal. It was suggested that a loose part was somewhere in the component. The TPD* that carried out these measurements suggested that a loose metal bar on rod of roughly 0.25 m was in the unit.

After more than 3000 hrs of testing the evaporator was disassembled by the manufacturer. In the lower part of the sodium entry a stainless steel tube of 0.19 m length and 0.0105 m diameter was found; photo 1. Apparently the weight was such that this tube floated on the incoming sodium like a ball on a fountain.
The rod was, at load conditions, always in the lower parts of the sodium entry header that is the conical part, as the slightly dented surface can testify; see photo 2.

3.2. Tests internals

3.2.1. Equipment

After inspection of the internals at the manufacturer the evaporator was fitted with new transducers before being reassembled. A accelerometer** was fitted at the outside of a tube in the sodium inlet area.
Also three straingauges were spot welded on to the tubes. The evaporator was recently put in operation again.

3.2.2. Results

The evaporator has, at the time of writing, logged only few hours. One result we have is that only one straingauge is in operation.

The first one was faulted just after assembly of the unit, number two succumbed after the first few hours of operation.

*) Technische Physische Dienst/Delft, Holland.
**) made available to us by Interatom/Bensberg.

4. CONCLUSIONS

4.1. Both calculations/model tests and measurements in situ show that there is no need for vibration/acceleration transducers on the SNR-300 steam generators. The amplitudes that very found were extremely small. The lifetime of the steam generators will not be limited by vibrations.

4.2. Quality, reliability and behaviour with time are rather uncertain quantities for the accelerometers.
This makes vibration measurements not viable for non testing purposes at this moment.

4.3. Thru-shell fittings for the cables are a source for trouble and the same goes for the cables itself.

4.4. The straingauges proved unreliable and the influence of spot welding on the gauges used is not yet known.

4.5. Lack of space for transducers and the like, as a result of designing for sodium, is an obstacle which cannot be easily by passed.

4.6. The vibration measurements indicated that no wear on account of vibrations would occur.
This is in accordance with the inspection results obtained by disassembling the helicoil evaporator and a straight tube evaporator which is identical to the straight tube superheater.

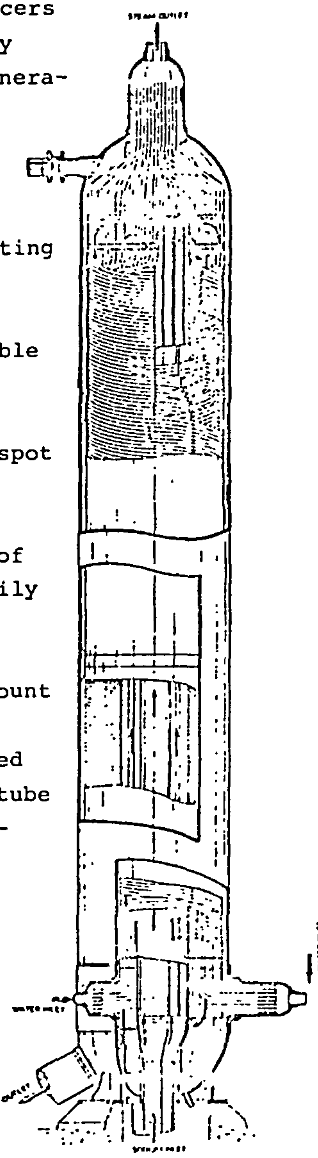


fig. I
PROTOTYPE 50 MW
HELICOIL EVAPORATOR

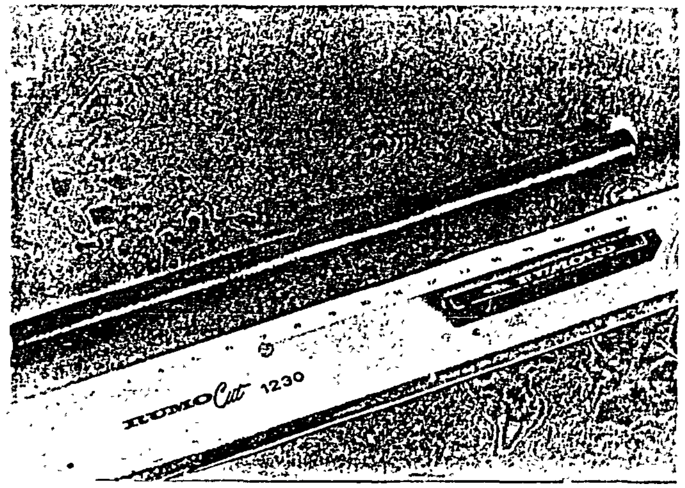


PHOTO 1:STAINLESS STEEL TUBE

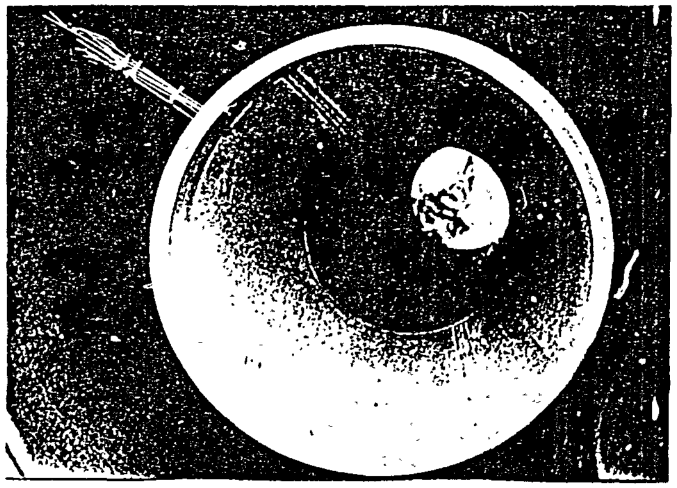


PHOTO 2:SODIUM INLET

Y. Tigeot, M. Livolant, "Vibrational Studies and Measurements on the Phenix Reactor". (France)

In the sodium cooled fast reactors of pool type, the internal shells are relatively thin. Consequently since the beginning of the Phenix Project, a special attention has been devoted to the flow induced vibration of those shells.

The main parts of the tests have been:

- Tests on models
- Tests in air on the reactor shells with determination of the modal shapes and frequencies of the main components during the construction
- Measurements during the hot flow tests

The aim of these tests was to verify that the vibratory level of the different components was acceptable before the operation at full power, and for the future to check the theoretical and experimental methods used to predict and verify the vibrational levels in the sodium cooled reactors.

The main results of all the tests are presented and analysed in the paper

1- Introduction

Dans les réacteurs rapides refroidis au sodium, du type intégré, les différentes cuves intérieures sont relativement minces. Aussi, dès le début du projet PHENIX, une attention particulière a été portée au risque de vibrations de ces coques, et tout particulièrement, aux vibrations induites par les écoulements.

Une série d'études et d'essais a donc été lancée pour s'assurer que la marche du réacteur ne serait pas perturbée par des incidents vibratoires importants comme cela s'est produit pour les réacteurs à eau pressurisée, et dans certains cas, pour les réacteurs à gaz.

Les trois principales phases de ces études ont été :

- Essais sur modèles
- Mesures des modes propres et des fréquences propres des différents composants du réacteur au cours de la construction, en l'absence de sodium, par excitation mécanique
- Mesures des vibrations au moment des essais de démarrage en fonctionnement isotherme, et ensuite à la valeur nominale

2- Essais sur modèles et mesures vibratoires en air sur le réacteur en cours de construction

Les premiers essais ont été effectués sur deux types de maquettes :

a- des maquettes hydrauliques sans similitude mécanique permettant la mesure du champ des pressions fluctuantes induites par l'écoulement (Société Alsthom-Techniques des Fluides-anciennement Sogreah à Grenoble).

b- des maquettes en similitude mécanique permettant la détermination des modes propres (INSA Lyon et BVS Grenoble)

L'application du champ de pressions fluctuantes mesuré en a), sur les différents modes propres mesurés en b), avec les corrections nécessaires pour tenir compte de la masse ajoutée de sodium, a permis d'estimer l'écart type de l'amplitude vibratoire moyenne de la virole supérieure de cuve primaire à quelques dixièmes de millimètre [1].

Toutefois, compte tenu de la mauvaise connaissance des longueurs de corrélations des fluctuations de pression, et de la représentativité insuffisante des essais mécaniques, cette valeur a été considérée comme peu sûre, et une campagne d'essais sur le réacteur lui-même a été décidée (figure 1) .

La détermination des fréquences propres, le relevé des déformées et des coefficients de masse et d'amortissement généralisés associés, ont été effectués en air à l'aide de forces d'excitation ponctuelle aléatoire du type "bruit blanc" ou sinusoïdale, de fréquence variable [2][3]. Les relevés ont été effectués sur toutes les structures présentant des résonances inférieures à 15 Hz, et qui seront les seules pouvant être excitées éventuellement par les fluctuations de pression aléatoire dues à l'écoulement turbulent du sodium. Les principaux résultats sont présentés sur le tableau 1.

En plus des structures importantes, toutes les structures annexes ont été testées aux vibrations au cours de cette phase par des méthodes simples (choc, lâcher). A la suite de ces tests, certaines ont été raidies.

Ces résultats expérimentaux ont été confirmés par un code de calcul : REVOMODE, permettant de déterminer les fréquences propres, les masses généralisées et les déformées axiales de coques minces de révolution. Les résultats sont indiqués sur le tableau 1 .

On peut constater que pour un nombre d'ondes circonférentielles donné sur la virole supérieure de cuve primaire, on obtient systématiquement deux fréquences de vibrations par l'expérience, les modes correspondants étant décalés d'un quart d'onde .

Par contre, sur les baffles et contre-baffles hydrauliques qui sont parfaitement de révolution, ce phénomène n'a pas été observé.

Pour les essais en vraie grandeur sur un site de réacteur, il est difficile de se livrer à une isolation des modes très soignée du fait du nombre limité d'excitateurs et de points de mesure, et de la nécessité de travailler rapidement. La connaissance préalable d'une bonne approximation par le calcul s'est révélée extrêmement précieuse pour mener à bien de tels essais.

3- Mesures effectuées pendant les essais isothermes (450°C)

Une instrumentation vibration a été mise en place sur les structures du bloc réacteur. Ce sont, soit des jauges de contrainte soudables fonctionnant à haute température, soit des accéléromètres piézoélectriques et des capteurs de fluctuation de pression. Tous ces capteurs fonctionnant en sodium sont sensibles aux parasites électriques induits par le secteur (50 Hz et multiples) ainsi qu'aux fréquences de glissement des moteurs asynchrones des pompes primaires et secondaires. Les signaux sont alors inexploitables sous forme brute, et il est indispensable de travailler sur les densités spectrales de puissance obtenues en temps réel, ou par traitement numérique à partir d'enregistrements dépouillés sur "Transformée de Fourier Rapide" permettant d'obtenir les fonctions de cohérence à partir des densités interspectrales.

Le mouvement de la dalle et des principaux composants fixés ou posés sur celle-ci a été mesuré par des accéléromètres ultra sensibles (Servo accéléromètres) généralement montés sur des supports triaxiaux permettant de suivre en un point les mouvements horizontaux suivant les directions radiale et tangentielle du réacteur, ainsi que suivant la direction verticale.

Les mesures vibratoires ont montré essentiellement la présence de deux types de phénomènes vibratoires :

- la réponse des structures à leurs fréquences propres sous l'influence des fluctuations de l'écoulement
- la présence de fréquences pulsatoires correspondant aux vitesses de rotation des pompes et à leurs multiplos .

TABLEAU 1

Valeurs expérimentales			Nature et position du mode	Valeurs calculées par REVOMODE	
fréquence Hz	masse généralisée 10^3kg	taux d'amortissement généralisé 10^{-3}	axe Nord-Sud	fréquence Hz	masse généralisée 10^3kg
3.1 4.3	4 non mesurée	2	n=2 cuve primaire Ventre Noeud	4.2	3.7
5.8 6.5	3.1 3.1	1.2 2	n=3 cuve primaire Ventre Noeud	5.9	2
6	non mesurée		n=3 baffles hydrauliques	6.9	5.5
8.2	non mesurée		n=4 "	8.9	6.7
9	non mesurée		n=2 "	11	6.5
12.1 12.6	1.2 1.2	1.8 5.8	n=4 cuve primaire Ventre Noeud	12.1	1.4
13	non mesurée		n=5 baffles hydrauliques	13.6	5.1

Ce phénomène provient du fait que les cuves étudiées ne sont pas strictement de révolution à cause des traversées d'échangeurs, de pompes,et de la rampe de chargement.Le calcul REVOMODE ne peut évidemment pas retrouver ce phénomène et la fréquence calculée se situe en général entre les deux fréquences expérimentales.

3.1 -Résultats - Cuve primaire

En basse fréquence (inférieure à 10 Hz), seules les jauges d'élongation donnent des résultats utilisables. On observe une résonance très amortie(taux d'amortissement égal à 10%)pour la fréquence de 0,3 Hz. L'élongation maximale obtenue est de 0,4 $\mu\varepsilon_{eff}$(écart type) au voisinage du redan. Compte tenu du nombre limité de points de mesure, il n'a pas été possible de déterminer la nature de la déformée. Le spectre de bruit autour de cette résonance varie comme l'inverse de la fréquence (figure 2) .

A plus haute fréquence, on observe sur les jauges d'élongation, les accéléromètres et les capteurs de fluctuation de pression, les harmoniques de la vitesse de rotation des pompes à des niveaux très faibles . Les déformations ne dépassent pas 0,12 $\mu\varepsilon$,et les déplacements absolus 3 µm.

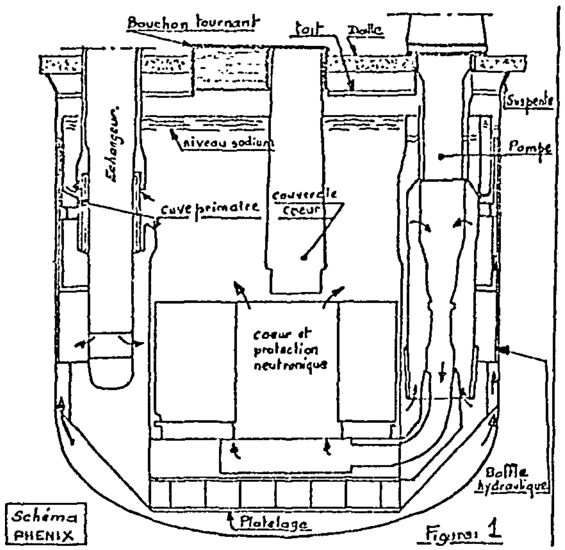


Figure 1

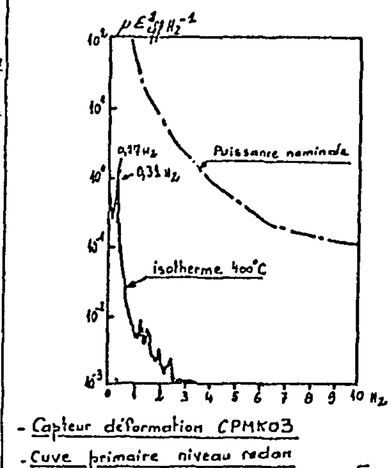


Figure: 2

3-2 Résultats- Structures plongeantes -Jupes de pompe

Sur une jupe,on observe des résonances à 1,7 1,95 et 7,15 Hz correspondant à celles mesurées en air. Sur le couvercle coeur apparaissent des fréquences à 7,3 8,5 et 10 Hz dont les fréquences sont liées à celles observées en air à 18 21 et 13,5 Hz.

Sur les cloches d'échangeur, on observe une résonance à 9 Hz qui correspond à la fréquence de 15 Hz mesurée en air.Les amplitudes de ces résonances sont très faibles (0,1 $\mu\varepsilon$). La déformation maximale est observée sur le bras de manutention 1,3 $\mu\varepsilon$ au débit maximal pour la fréquence de 2,3 Hz.

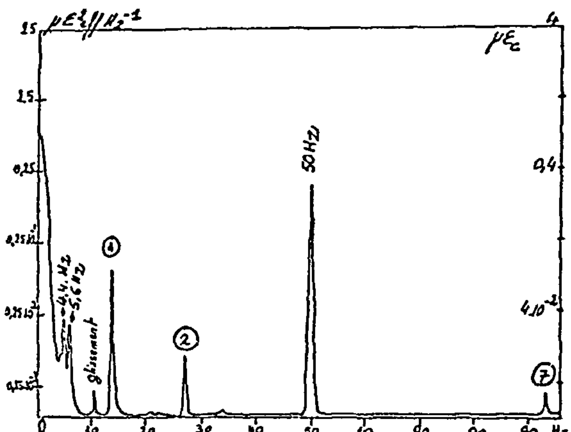
Les autres résonances correspondent aux harmoniques de la vitesse de rotation.

3-3 Résultats -Dalle et cuve principale

Les brides supports des trois pompes primaires et des six échangeurs intermédiaires sont posées sur la dalle avec la possibilité de translation sur celle-ci. La cuve principale est reliée à la dalle par l'intermédiaire de 21 suspentes permettant les dilatations radiales.

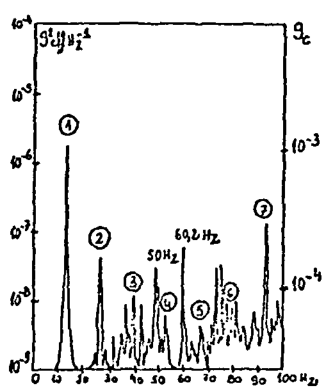
La raideur de ces suspentes introduit deux modes de vibration d'ensemble de la cuve principale par rapport à la dalle. On observe ces fréquences sur une jauge d'élongation soudée sur une suspente pour les valeurs 4,4 et 5,6 Hz (figure 3). On ne les observe pas sur la cuve principale .

On constate partout la présence des harmoniques de la vitesse de rotation 1-2-3 et 7 principalement(le nombre 7 correspond au nombre d'aubes du rouet des pompes). Les fonctions de cohérence entre les capteurs d'un montage triaxial d'accéléromètres fixé sur la dalle et les autres mesures disponibles ont des valeurs supérieures à 0,6 pour ces fréquences. La présence de ces harmoniques est donc due à une transmission mécanique du mouvement de la dalle à l'ensemble des structures, la dalle elle-même étant mise en mouvement par l'intermédiaire des brides d'appui des pompes primaires. L'amplitude maximale du mouvement de la dalle est observée en vertical à 13,3Hz avec une amplitude de 1mg soit 3.10^{-6}m de déplacement crête à crête(figure 4)



-Capteur déformation TWMKOS
-Suspente - P.N. P.P: 800k/mm. P.S: 760k/mm.

Figure: 3



Capteur accélération . Dalle "vertical."

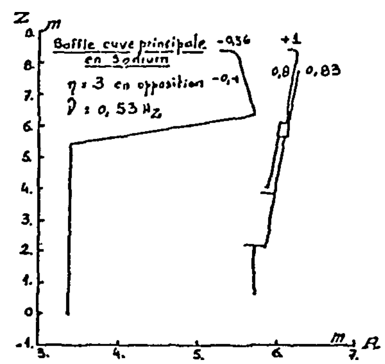
Figure : 4

3-4 Analyse des résultats concernant la cuve primaire

Il est intéressant de comparer ces résultats expérimentaux aux fréquences et amplitudes calculées pour la cuve primaire. Avec le programme REVOMODE, on trouve en air des fréquences propres mesurées expérimentalement sur la cuve primaire et les baffles hydrauliques. Le programme AQUAMODE prenant en compte les lames de liquides entre les coques, permet la transposition des fréquences de vibration en présence de sodium et l'estimation des amplitudes vibratoires à partir des spectres de pression mesurés sur les maquettes hydrauliques.Rappelons que l'effet du fluide sur les vibrations de respiration des coques réduit la valeur des fréquences propres et introduit des couplages avec, pour un indice n caractéristique d'une vibration de respiration,l'existence de modes en phase et en opposition de phase. Les résultats obtenus, pour un amortissement supposé de 1% et une surface de corrélation de 1m², sont: (figures 5-6-)

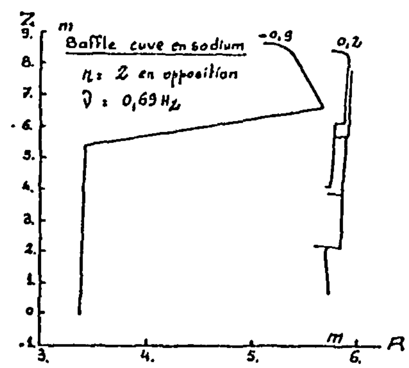
-fréquences de vibration	0,53 Hz	0,69 Hz
-amplitude de déplacement en mm	0,043	0,32
-élongation correspondante	$0,050.10^{-6}$	$1,8.10^{-6}$

La comparaison de ces valeurs avec les mesures montre que l'effet du sodium est sousestimé par le calcul: fréquence calculée la plus basse 0,53 Hz-fréquence mesurée : 0,3 Hz.



Déformée : ν = 0,53 Hz

Figure: 5



Déformée : ν = 0,69 Hz

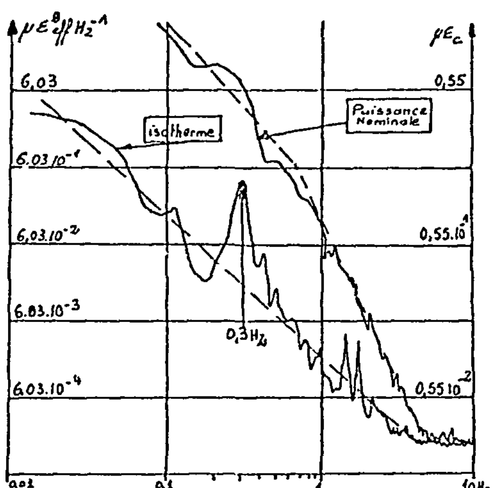
Figure: 6

L'amplitude calculée (1,8 µε) est plus forte que l'amplitude mesurée (0,4 µε).Mais,si l'on introduit dans le calcul l'amortissement de 10% mesuré, la valeur calculée devient 0,6 µε qui est proche du résultat mesuré. Ce résultat est encourageant en ce qui concerne la validité de la méthode de prévision utilisée pour PHENIX, mais il faudrait évidemment un nombre plus important de telles mesures pour confirmer l'efficacité de cette méthode. Des études systématiques de l'amortissement en présence de fluides en mouvement apparaissent aussi nécessaires pour affiner la précision .

4- Mesures effectuées à la puissance nominale

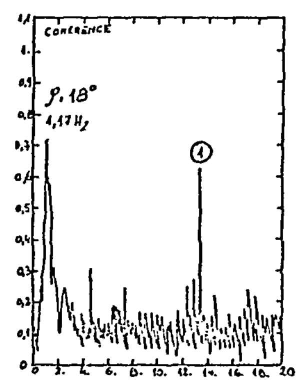
Compte tenu de l'élévation de température,les seules mesures en sodium exploitables ont été celles obtenues à partir des jauges d'élongation,et en air celles de la dalle et de ces composants. La mise en évidence de la raisonance à 0,3 Hz de la cuve primaire n'est plus possible car il se superpose au spectre précédent un bruit d'origine thermique variant comme l'inverse de la fréquence jusqu'à 1 Hz et ensuite comme l'inverse du carré de la fréquence, cette évolution étant analogue à celle de l'analyse spectrale des mesures de température des cuves (figure 7 -Jauge à la base de la cuve primaire).

Les résultats les plus intéressants sont obtenus en puissance par l'analyse simultanée de tous les signaux vibratoires disponibles avec la mesure de la puissance neutronique utilisée actuellement pour le suivi vibratoire de PHENIX. On a ainsi confirmé l'influence du mouvement de la dalle support à la fréquence fondamentale de rotation des pompes. De même, à l'aide d'accéléromètres placés sur les carters des mécanismes de commande des barres de contrôle on a mis en évidence l'effet de la vibration d'une des barres de contrôle sur la puissance neutronique (cohérence égale à 0,72 -figure 8).



Capteur déformation: CPMK01
Cuve primaire niveau bas.

Figure: 7



Cohérence barre contrôle N° 14

Puissance neutronique et barre contrôle N° 14

Figure: 8

5- Conclusions

L'ensemble de ces essais et études vibratoires a permis de vérifier que pour les principales structures de PHENIX, le niveau des vibrations mesurées était plus faible, les deux sources de vibrations principales étant l'écoulement lui-même, et les vibrations mécaniques des pompes.

La mesure des fluctuations de pression de l'écoulement sur maquette hydraulique, associée à un calcul aussi précis que possible des fréquences propres et des modes propres de vibration des coques, permet d'obtenir une bonne estimation du niveau des vibrations dues à l'écoulement. Une incertitude subsiste en ce qui concerne l'amortissement à prendre en compte.

L'estimation des vibrations dues aux pompes est plus incertaine actuellement, et pour SUPERPHENIX, un ensemble de mesures assez complètes sera effectué dans ce but.

Le test vibratoire à l'air de toutes les structures internes s'est revélé très utile: d'une part, il a permis de vérifier les résultats de calcul, et , d'autre part, de détecter les structures annexes trop souples et de les raidir

En ce qui concerne les mesures, les meilleurs résultats ont été obtenus avec les jauges d'élongation. Les accéléromètres et les capteurs de presssion piézoélectriques ont été inexploitables aux basses fréquences du fait du bruit de fond de l'électronique.

La plus importante constatation est que les déformations mesurées sont très faibles, ce qui est rassurant pour l'avenir de la filière quant aux risques de vibrations, à condition bien entendu de continuer à prêter une grande attention à ce risque au cours du projet et de la réalisation .

Compte tenu des résultats satisfaisants obtenus, l'ensemble de ces études et essais sera vraisemblablement reconduit pour SUPERPHENIX, en tenant compte de l'expérience acquise.

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[2] Y.TIGEOT, G.PAYAN and J.M.GAMA- Study of vibration riks in the structures of the Reactor Block PHENIX - Paper n°526 International Symposium Vibration Problems in Industry 10-12 April 1973 Keswick, England

[3] Y.TIGEOT, M.LIVOLANT, F.JEANPIERRE -Vibrations des structures internes de réacteurs, Comparaison, expériences, calculs. Paper E4/2 Second SMIRT Berlin 10-14 September 1973

W. Haesen,* G. F. Klinkert,* Th. J. Tromp,* "Radiographic and Ultrasonic *Inspection of an Austenitic Pump Barrel*". (The Netherlands)

1 INTRODUCTION

Periodic inspection is compulsory for the SNR-300 sodium pumps. The licensing authorities require a visual inspection of the rotating parts, visual inspection of the inner surfaces of the pump barrel and volumetric inspection of all highly stressed welds.
At this moment these tests are envisaged every four years.

Volumetric testing of the welds of a radio-active pump barrel poses quite a few problems. Therefore we made a series of preliminary tests on an austenitic pump barrel in order to ascertain the problems one may encounter. The tests involved were:

1. Ultrasonic
2. Radiografic

*) NERATOOM, the Hague/Holland.

The radiografic tests were made in order to verify the signals obtained by the ultrasonic tests.
Fortunately the barrel of a prototype sodium pump was available for testing (see figure 1). This is the barrel of the 5000 m^3/h STORK pump which was tested by Interatom/Bensberg. The prototype pump is approximately the same size as the SNR-300 pump barrel. Although the welds are not exactly the same as in the SNR barrels the shape however can be considered sufficiently representative for the SNR-pump welds.
The pump barrel material is: austenitic steel Werkstoffnr. 1.4948. One should bear in mind that this vessel has small radii which means strongly curved surfaces; see photo 12.

At the time of writing the investigations and tests are not yet finished. Nevertheless the results obtained are such that we feel it is worthwhile to discuss them in this meeting.

2. WELDS INSPECTED

The highly stressed welds were inspected, these are number 1,3 and 4 Weld no. 2 although not highly stressed, was also checked. Details of the weld geometry is shown in fig.2-4. Both the ultrasonic tests and the radiographic tests were carried out by the Röntgen Technische Dienst B.V.*. The X-ray photographs that were made during the manufacture of the pump vessel were available for comparison.

3. TRANSDUCERS USED

For the ultrasonic tests prism transducers of the focused transmitter/receiver type were employed.
These transducers are based on [1] but are of an advanced type. As a result of our interest in this field these transducers were further optimized, size was reduced and matching of the ultrasonic equipment was improved by the RTD.

4. ULTRASONIC TESTS

Technical data is given in tables I and II.
The tests were carried out manually.

*) Rotterdam/Holland

4.1. Test 1

Attenuation-tests were done at 4 and 2 MC/s. A difference of 1 dB was observed for 2 MC/s per mm weld material so transducers of the 2 MC/s-type were chosen.

4.2. Test 2

Runs were made on welds no. 1,2,3 and 4. In all welds wave-transformations were observed. Further investigations indicated that the scource of trouble originated in the change-over basematerial/weldmaterial.

This gave misleading echo's in case of long focus transducers; see foto 1,2 and 3.
Also the highly curved surfaces were of great influence since small variations in transducer positioning were possible. The variations caused substantial changes in signal. Only one conspicuous indication in weld no.2 was observed. Defects near the weld surface could not be inspected due to weld shape and the chosen direct beam method.

4.3. Test 3

This test was made on weld no.2 as a result of test 2.
The signal we now obtained is shown on photo 4.
One of the echo's should be due to the shape of the root weld. Thus grinding of the inner surface should have resulted in the disappearing of one echo.
However the result differs from what was expected as can be seen in foto 5. This implies that grinding of the ground or root weld at the inner surface is highly desirable.

4.4. Test 4

This run was made in order to detect "near-surface" inperfections. Here were special transducers of the S.E.T.* type used. Since the focus of this transducer type lies under the transducer surface only the portions of the welds that were grinded flat for these tests were checked for flaws.
This run was not very succesful since the curvature of the barrel and the weld surface caused coupling problems.

*) transmitter/receiver; transverse mode.

4.5. Interim conclusions

After the first four series of tests so many signals were obtained that radiographic testing seemed necessary. These tests are dealt with separately in 5. The radiographic tests did not confirm the signals obtained by ultrasonic testing. So we decided on a new series of ultrasonic tests.

4.6. Test 5

In both acceptance X-ray photographs and the new made X-ray photographs showed some small volumetric imperfections in weld no.1. On account of this we tried to find the flaw with ultrasonic equipment. However a clear correlation between both tests could not be found.

4.7. Test 6

Sensitivity settings were checked via drilling of two flat-bottom holes; see fig. 5. The full depth of these holes was reached in respectively 6 and 3 steps. The first hole was drilled in the direction of the beam. At a sound distance of 75 mm no clear signal was obtained. With the transducer in a fixed position the depth of the hole was increased and a phantom signal was observed; see photo 6. The flat bottom echo appeared in the phantom signal, photo 7 With increased depth the two signals came apart, photo 8. The second flat bottom hole made an angle of 68° with the beam axis. This hole gave no clear echo's.

4.8. Test 7

Calibration test on weld no.1. The flat bottom hole in the beam axis was used to obtain the correct sensitivity setting. The echo of the flat bottom hole was set at 5 scale divisions on the C.R.T.. Weld no.1 was reinspected with this sensitivity. With this setting no clear correlation between ultrasonic test and radiographic information was obtained.

5. RADIOGRAPHIC TESTS

5.1. Introduction

Because of the ambiguous ultrasonic test results a great number of X-ray photographs were made. Here we tried to get the best possible photographs of the vessel welds; see photo 12. During manufacture and licensing tests the X-ray equipment was positioned outside the barrel. In the recent tests the equipment was positioned in the centerline of the vessel; photo 13.

5.2. Equipment used:

- Self rectifying X-ray tube.
- Max. tension 300 kV.
- Max. tube current 5 mA
- Focal spot dimension 2.5 mm
- Film: Gevaert D-4; size: 10 x 48 cm.
- Double film technique.
- Lead intensifier sheets, thickness 0.125 mm.
- Packing: lead/film/lead/film/lead.
- Copperscreen of 0.25 mm thickness to prevent scatter radiation
- Filmcassette: vacuum type.
- Film/weld spacing:approx.2 cm (see fig.6).

With this a density of D=2.5-3.0 was reached.

5.3. Radiographic tests

5.3.1. Test 1 (see photo 14)

Weld no.1 was inspected by means of 12 photo's. The exposure time was 8 min.; focus-film distance 47 cm; material thickness: 35-43 mm. Results: some small inclusions were observed, two somewhat larger imperfections were visible. These imperfections could also be seen on the original manufacturing photographs. On account of the ultrasonic signals more effort was invested in the radiographic investigations than one would normally require.

The techniques employed yielded a better quality photograph however essentially the same imperfections were observed as were visible on the manufacturing X-rays.
After manufacture of the vessel and after the accepture X-ray shots had been made the inner surface was finished in this weld area by means of milling (or turning).
Thus for the new X-ray shots a better situation was available.

5.3.2. Test 2

Weld no.2, again 12 shots were made. Exposure times 12 min; focus/film distance 80 cm; material thickness: 34 mm.
Nothing serious was observed, only very small indications visible.

5.3.3. Test 3

Weld no.3, 12 photo's were made.
Exposure time 3 min; focus/film distance 40 cm; material thickness: 35/40 mm. Some gas inclusions were found. One indication was visible which is may be a small crack of approx. 3 mm.

5.3.4. Test 4

Weld no.4, 12 photographs.
Exposure time 10 min.; focus/film distance 70 cm; material thickness: 35/40 mm. No flaws were found only some indications that the weld, at various places, had been repaired during manufacturing of the vessel.

5.4. Gamma-graphic test

For completeness sake three shots were made by means of an Iridium 192 source.
No useful data was obtained by this technique. The exposures were made at weld no.1. The source strength was: 17 Ci; exposure time 30 min.; focus/film distance 47 cm; material thickness 35-40 mm.

5.5. Evaluation of the results

- The photographs obtained were of a higher quality than the original ones however essentially no significant difference in the inspection quality was found. For the relevant data was visible in the original photo's. A higher number of small inclusions and imperfections were found.

- Weld preparation is an important item.

- Gammagraphic test is not recommended.

- Interpretation of the X-rays by two skilled persons is highly advisable.

- Double film technique and the use of vacuumcassettes is recommended.

6. CONCLUSIONS

As mentioned the investigations on the pump barrel are not yet finished, but some conclusions can be drawn.

6.1. The first results obtained by ultrasonic testing were disappointing.
The S.E.L.* technique proved to be very susceptible to direction variations in the austenitic weld material

6.2. No clear correlation between the ultrasonic signals and X-ray photographs was observed.

6.3. With techniques used, wave transformations were found.

6.4. A curious cumulative effect of "phantom echo" and "flaw echo" is very disturbing and makes evaluation very difficult.

6.5. Transverse flaws/defects can not be detected.

6.6. The texture of the weld material is such that ultrasonic testing is not yet a viable inspection method.

*) S.E.L. (Transmitter, Receiver, longitudinal wave)

All this does not mean that we reject ultrasonic testing of austenitic material, for new transducers are under development and improvements are possible. However the pump barrel supplied us with a clear benchmark. The pump barrel is centainly representative for what is going to be used in the SNR-300. It is sensible to admit that ultrasonic testing of austenitic welds, whether for production of inservice inspection is at this moment not a reliable inspection method.

[1] Ultrasonic testing of austenitic steel weld joints.
B.Kuhlow, E.Neumann, H.Wüstenberg, E.Nabel, E.Mundry.

TABLE II ULTRASONIC DATA

Test nr.	Weld nr.	Remarks
1	2	at 4 MC/s attenuation 1,8 - 2,0 dB/mm " 2 " " 0,6 - 1,0 " " with 70° transducers wavetransformations were observed.
2	1,2,3,4	test piece used Type V2 thickness 40 mm material: 1.4948
3	2	sensitivity setting: cylindrical drilled flat bottom hole, dia. 3 mm.; 20 mm below surface
4	1,2,3,4	———
5	1	see test nr.3; 10 dB additional amplifying
6	1	10 dB additional amplifying
7	1	see test nr.6

TABLE I ULTRASONIC DATA

Test nr.	Weld nr.	Position from zero in cm	Transducer	Freq.MHZ /mode	Angle & focal length in mm	Coupling	Receiver-*) matching unit
1	2	0,100,200	miniature prism	2&4 trans.	70&60°/-	water + wettingagent	-
2	1,2,3,4	complete circum	prism transmitter/ receiver	2/long.	68°/55 52°/60 60°/40 72°/23 60°/37	" " " " "	+ + + + +
3	2	63	prism transmitter/ receiver	2/long.	52°/60	"	+
4	1,2,3,4	at random	prism transmitter/ receiver	2/trans.	90°/16	"	-
5	1	80 to 130	prism transmitter/ receiver	2/long.	68°/55 60°/40 52°/60	min.oil " "	+ + +
6	1	40 and 42	prism transmitter/ receiver	2/long.	68°/55	"	+
7	1	80 to 130	prism transmitter/ receiver	2/long.	68°/55	"	+

*) RTD 750901
50 Ω amplifier
interface E-tuned
U.S.I.P 11 2MHz.

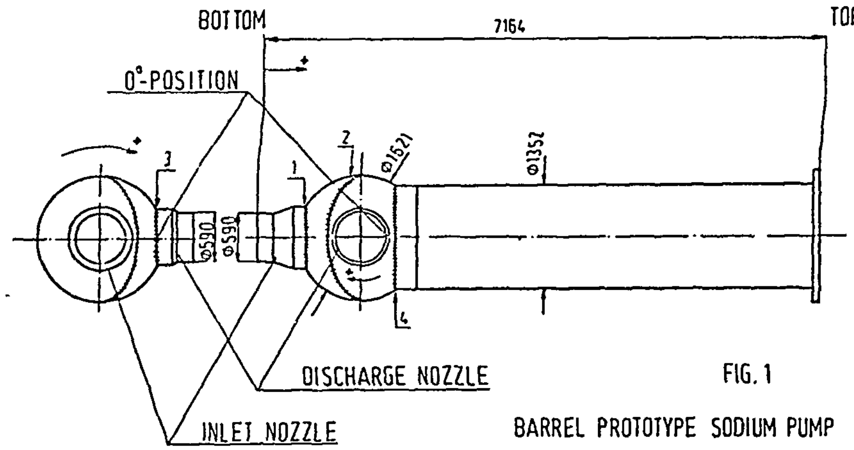


FIG. 1
BARREL PROTOTYPE SODIUM PUMP

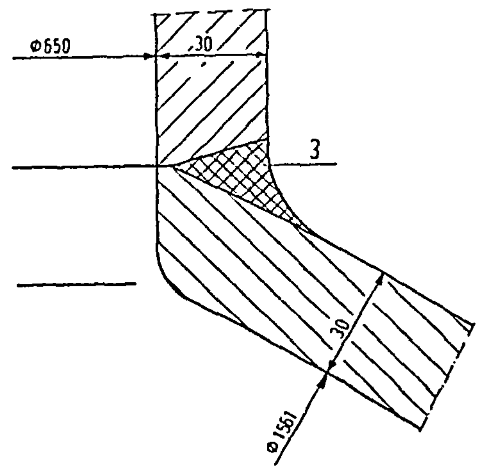


FIG. 4
WELD Nr. 3
DISCHARGE NOZZLE

FIG. 5 WELD Nr.1

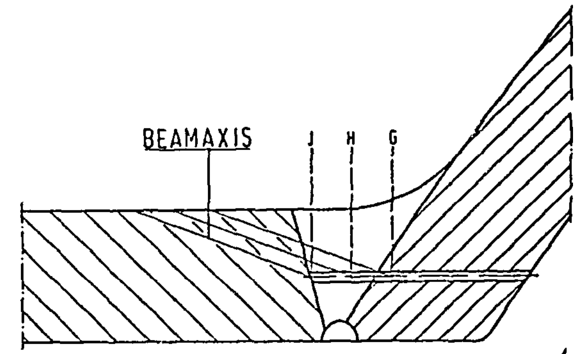
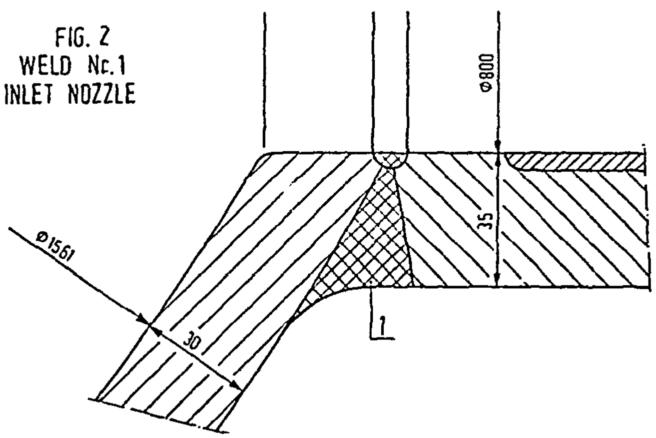
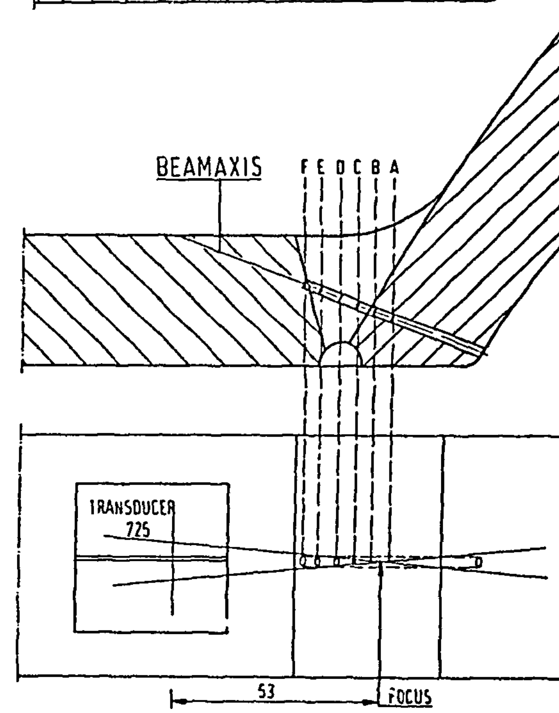
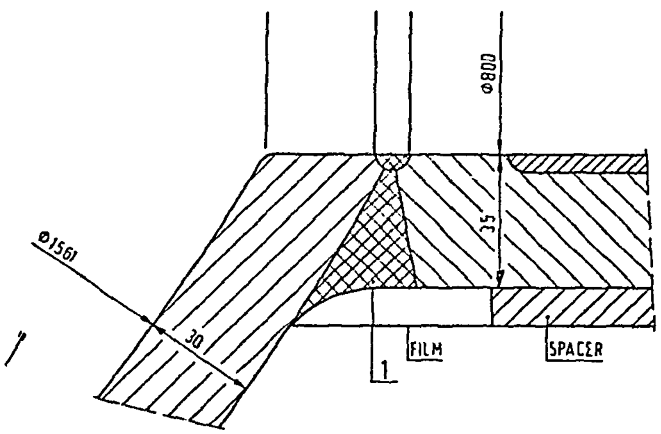


FIG. 2
WELD Nr. 1
INLET NOZZLE







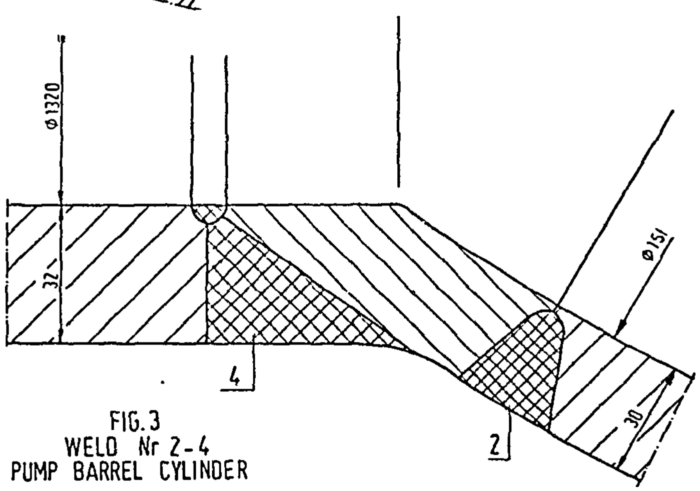


FIG. 3
WELD Nr 2-4
PUMP BARREL CYLINDER

FIG. 6
WELD Nr. 1
INLET NOZZLE

R 50 80 % + 32 dB

WELD NR. 2

R 50 80% + 22 dB

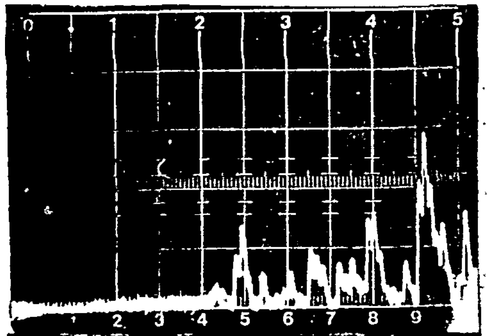


Photo 1

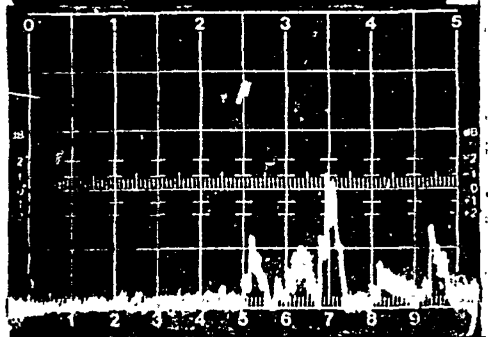


Photo 2

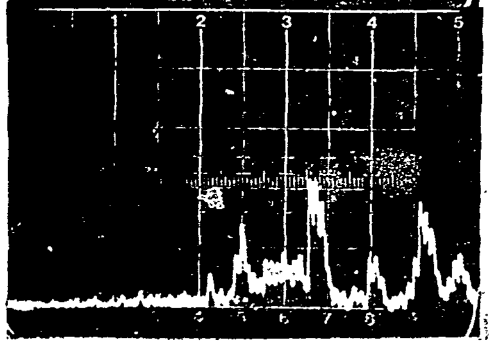


Photo 3

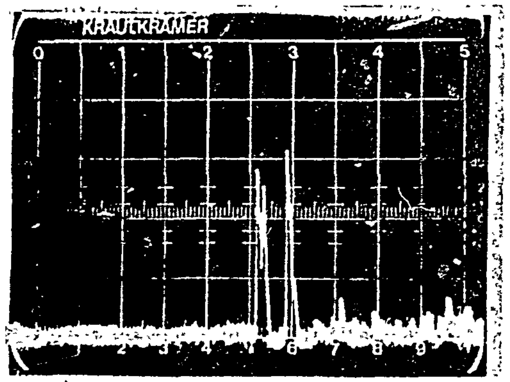


PHOTO 4

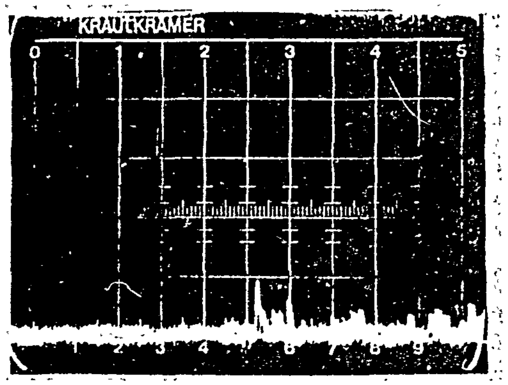


PHOTO 5

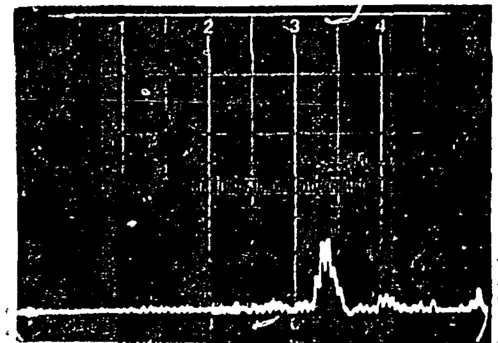


Photo 6

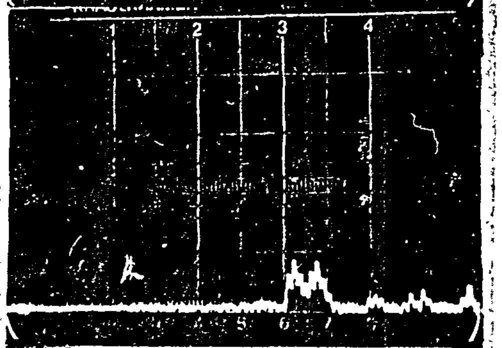


Photo 7

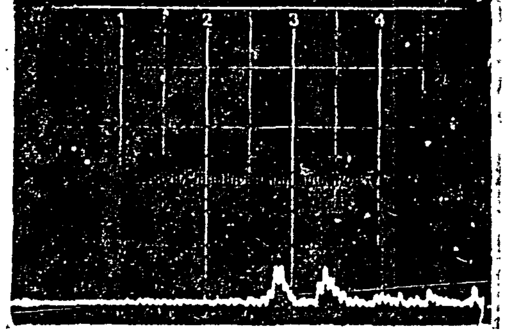


Photo 8

CALIBRATION TESTS ON TEST PIECE

TESTBLOK AK 10
TEK. Vs 585. 09 A1

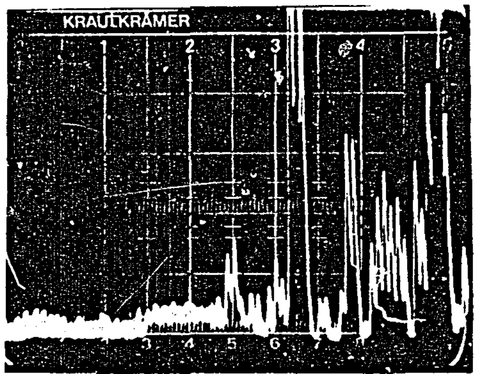
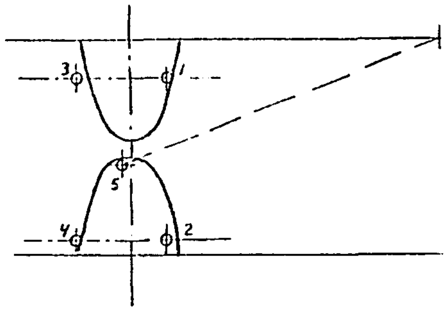


PHOTO 9

TASTER N: 725
GEVOELIGHEIDS INSTELLING
5 SCH D + 6 dB



TASTER N: 729

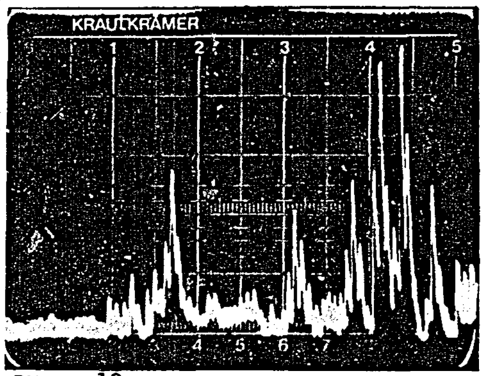
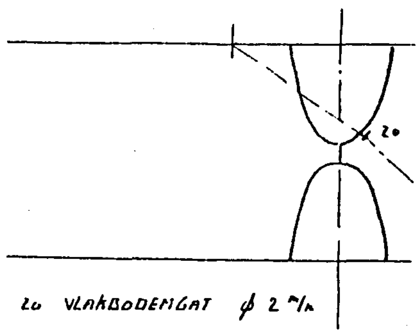


PHOTO 10



2o VLAKBODEMGAT ø 2 m/m

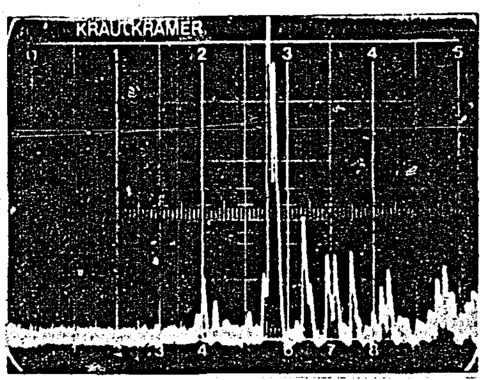
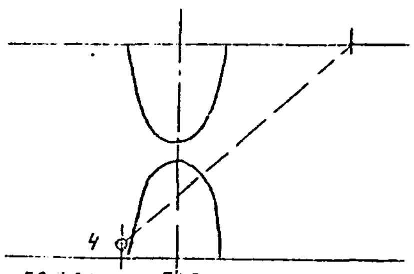


PHOTO 11



TASTER N: 729
GEVOELIGHEIDS INSTELLING
5 SCH D + 3 dB

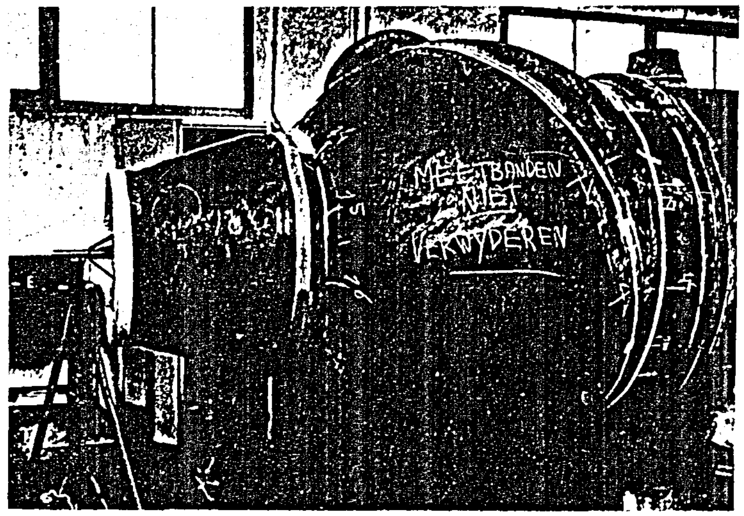


PHOTO 12

PHOTO 13.

PHOTO 14.

H. J. Plewden, K. S. Probert, "In Sodium Materials Monitoring for LMFBR". (United Kingdom).

INTRODUCTION

Experience in the U.K. with the CO_2-cooled Magnox reactor system has shown the necessity for monitoring materials and components from within the coolant circuit. It has also demonstrated the need to know more precisely the materials used in construction.

Knowledge of materials behaviour in the unique environment of the sodium cooled fast reactor is far more limited than in the CO_2 coolant previously used and predictions of long term behaviour need to be based on regular inspection and monitoring of materials exposed to the same environment as the reactor components. Extrapolation from laboratory experiments and prototype reactor experience are not in themselves considered sufficient, although providing valuable guidance.

The information derived from solid phase monitoring in the first commercial LMFBR will provide guidelines for future operation of the station and also for the design of subsequent stations, highlighting any problem areas. It will be a firm requirement of the CEGB that adequate facilities are provided for monitoring materials behaviour of all critical components in both the primary and secondary sodium circuits. The purpose of this paper is to outline the essential features of a suitable monitoring scheme, and thus encourage fast reactor designers to incorporate the necessary facilities into the reactor design at an early stage.

MATERIAL SUPPLY

It has become apparent from the Magnox stations currently operating and the AGR's under construction that there is a need to characterise the materials in the reactor more closely than in the past with respect to chemical composition, mechanical properties, corrosion properties and fabrication history. This approach is being adopted in the U.K. with the SGHWR and will be essential for the LMFBR. Specifications should be drawn up only after taking into account known data and mechanisims of mass transport and corrosion in sodium, and it should be an objective at this stage to restrict scatter in materials properties as far as possible.

All monitoring specimens, whether in the form of coupons or components, should be taken from the same casts of material as those used in the fabrication of components for reactor use and should include extremes in materials scatter. Where small items such as bolts, washers, etc., are concerned, samples should be taken from the batches of materials supplied for construction. Larger monitoring specimens such as bolted assemblies and weld details, should be manufactured at the same time as the actual reactor components and under the same conditions. Additional samples of material (at least 10% of the total requirement) should be retained as archive material in case of subsequent need to repeat any experimental work.

Specimens should essentially reporduce the composition and metallurgical condition of permanent and semi-permanent circuit materials. They should as far as possible simulate fabrication condition, heat treatment, degree of cold work, surface finish and weld effects. The supply of monitoring specimens and of additional archive material should be part of the Tender Submission.

SPECIMENT REQUIREMENTS

Numbers of specimens (excluding archive material) should be sufficient to permit removal of at least duplicate specimens after commissioning and annually for the first five years of operation and biennially thereafter, with a small contingency allowance. There will be some variation in the type of specimen within the monitoring scheme, depending on the environment. The general requirement for all areas should include corrosion coupons and mechanical test specimens. In high flux regions, dimensional and geometry change specimens may be required, and for areas such as the diagrid that may be liable to shock loading, impact test specimens would be desirable.

Equivalent numbers of large components such as bolted assemblies are probably not feasible and detailed consideration of the optimum numbers of such components is required. The most obvious solution to a limitation in numbers is to remove specimens for non-destructive examination and then return them to their original location. There should however be a sufficient number to permit the destructive examination of one or perhaps two specimens during the reactor lifetime, without defeating the long term purpose of the scheme, if the non-destructive examinations should warrant such a step. Certainly one should aim for the inclusion of the maximum number of small components which can be removed for destructive examination at regular intervals, to supplement the information from coupon specimens.

SPECIMEN LOCATION

Materials in the reactor experience a variety of environments and all conditions which can lead to significant material deterioration under operational or fault conditions should be monitored, e.g. areas susceptible to corrosion, deposition, carburisation or decarburisation, high and low flux. Regions at the sodium cover gas interface which may be subject to intermittent wetting must be monitored. Additionally, particular attention should be given to locating specimens on or near to components which cannot be inspected, repaired or removed without major engineering work.

Ideally it would be desirable to expose the specimens under the precise conditions of temperature, flux, coolant chemistry and flow, and stress as the actual components. It may be possible to locate specimens in areas in which the first four conditions are met, but simulating the applied steady and fluctuating stresses might involve a degree of complication which may not be possible with any in-reactor scheme. Exploration of stress effects may have to be restricted to laboratory work, but their simulation in reactor must be given serious consideration. The introduction of some measure of redundancy into various structural items might serve as a source of monitoring or inspection of stressed specimens.

Where problems of access restrict the placing of specimens directly into the reactor coolant, by-pass loops may have to be considered to give an adequate monitoring coverage.

Removal and insertion of specimens must not interfere with the economic and safe operation of the reactor. Thus, there must be minimum loss of availability and minimum disturbance of sodium chemistry.

REACTOR COOLANT CHEMISTRY

It is clear that a materials monitoring scheme must be accompanied by an equally comprehensive scheme for the monitoring of the chemistry of the reactor coolant. It is important to ensure that the location and frequency of sodium sampling will give adequate definition of the coolant chemistry at all specimen locations in the materials monitoring scheme.

CONCLUSIONS

A monitoring scheme is essential to the economic, safe and reliable operation of a commercial LMFBR. To achieve this aim it should be considered as an integral part of the evolving design and the construction of the station and not incorporated with resultant difficulties and compromise at a late stage of construction.

The precise numbers of specimens and components involved in any monitoring scheme cannot be clearly defined until the overall reactor design and materials of construction are known. Even when these are agreed a measure of flexibility in the scheme should be retained for as long as possible.

Early attention to the need for a comprehensive materials monitoring scheme should enable the provision of suitable specimens at suitable locations, which will be representative of the varying environmental conditions without seriously influencing sodium chemistry or flow paths.

Acknowledgement

This paper is published by permission of the Central Electricity Generating Board.

F. Papezyk, R. Saglio, M. T. Destribats, *"Ameliorations Apportees, par les Transducteurs Focalises, au Controle des Soudures Mixtes Entre Acier Ferritique et Austenitique"

R E S U M E

Le contrôle par ultrasons des soudures mixtes en acier austéno-ferritique est difficile avec les méthodes classiques. La structure métallurgique de certaines zones de la soudure crée des échos parasites. L'utilisation de transducteurs focalisés spécifiques apporte une amélioration notable et rend le contrôle possible.

I - INTRODUCTION

Le Commissariat à l'Energie Atomique a développé une méthode de contrôle par ultrasons en immersion totale pour les soudures mixtes des anneaux de sécurité des réacteurs P.W.R. L'utilisation des transducteurs focalisés, étudiés au C.E.A., a permis de résoudre correctement les problèmes de contrôle relatifs à ces soudures.

Le contrôle par ultrasons de la soudure de l'anneau se pratique par l'intérieur de la tubulure d'entrée ou de sortie de fluide.

2 - DESCRIPTION DU SPECIMEN D'ESSAI

Les essais ont notamment été effectués sur un échantillon représentatif de diamètre 698 mm et d'épaisseur 77 mm.
La zone soudée est constituée (fig 1) :
- côté piquage : par de l'acier faiblement allié au Mn - Mo - Ni
- côté embout : par de l'acier inoxydable : 20 Cr - 10 Ni - 3 Mo

Le beurrage de liaison est en acier inoxydable : 20 Cr 10 Ni 3 Mo et la soudure réalisée manuellement avec électrodes enrobées, en acier inoxydable de la même nuance que celle du beurrage.

Dans cet échantillon, divers défauts artificiels ont été réalisés. A savoir :

- 4 trous et 1 entaille dans la zone soudée de diamètre 3 mm aux profondeurs respectives de 25 - 50 - 65 - 77 mm et de longueur ≃ 50 mm,
- 2 fentes de profondeur 2 mm et largeur 10 mm situées en bordure et au centre de la zone soudée,
- 1 trou dans l'acier noir de diamètre 3 mm à 57 mm de profondeur.

3 - MODE OPERATOIRE

L'utilisation de palpeurs focalisés a conduit à procéder à l'examen de la soudure en la divisant en 2 tranches d'épaisseur différentes de façon à obtenir une réponse ultrasonore constante dans toute l'épaisseur. A chaque tranche d'épaisseur correspond un transducteur spécial. L'emploi de transducteurs focalisés minimise les interactions du faisceau ultrasonore et de la structure métallurgique. Il s'en suit un accroissement du rapport signal sur bruit.

4 - ESSAIS

Tous les essais entrepris l'ont été dans le but de connaître la dimension des défauts et d'augmenter le rapport signal sur bruit.
Deux séries d'essais ont été effectuées :
- l'une en ondes transversales à 45°,
- l'autre en ondes longitudinales à 45°

en faisant varier la fréquence et le diamètre de la pastille piézoélectrique.

La principale difficulté rencontrée a été la présence d'échos parasites de forte amplitude réfléchis au niveau de la jonction acier noir-beurrage. Les résultats obtenus en ondes transversales de 500 kHz à 2 MHz n'ont pas permis d'éliminer les signaux parasites, ni d'avoir une représentation fidèle, en forme et dimensions, des défauts artificiels. Malgré ces imperfections, les signaux ultrasonores des défauts artificiels étaient nettement définis.

5 - RESULTATS - CONCLUSION

Les images C-Scan obtenues sur la pièce d'essai constituent, dans l'état actuel du développement de cette étude, une amélioration sensible des résultats du contrôle par ultrasons des soudures mixtes.

La figure 2 montre l'image obtenue par examen en ondes longitudinales à 45° à l'échelle 1/2 correspondant à la zone d'épaisseur 30-77 mm sur laquelle on observe les trois trous de Ø 3 mm ainsi que l'entaille et les deux fentes à la limite acier noire-soudure.
La figure 3 montre l'image C-Scan en ondes longitudinales de la tranche d'épaisseur 0-30 mm dans laquelle subsiste une zone morte de 0 à 10 mm.
Cette zone morte est très dépendante de l'état de surface.
Ces résultats sont significatifs des améliorations apportées par l'emploi de palpeurs focalisés adaptés à l'épaisseur et à la géométrie de la pièce à contrôler, tant pour la détection des défauts que pour leur dimensionnement.

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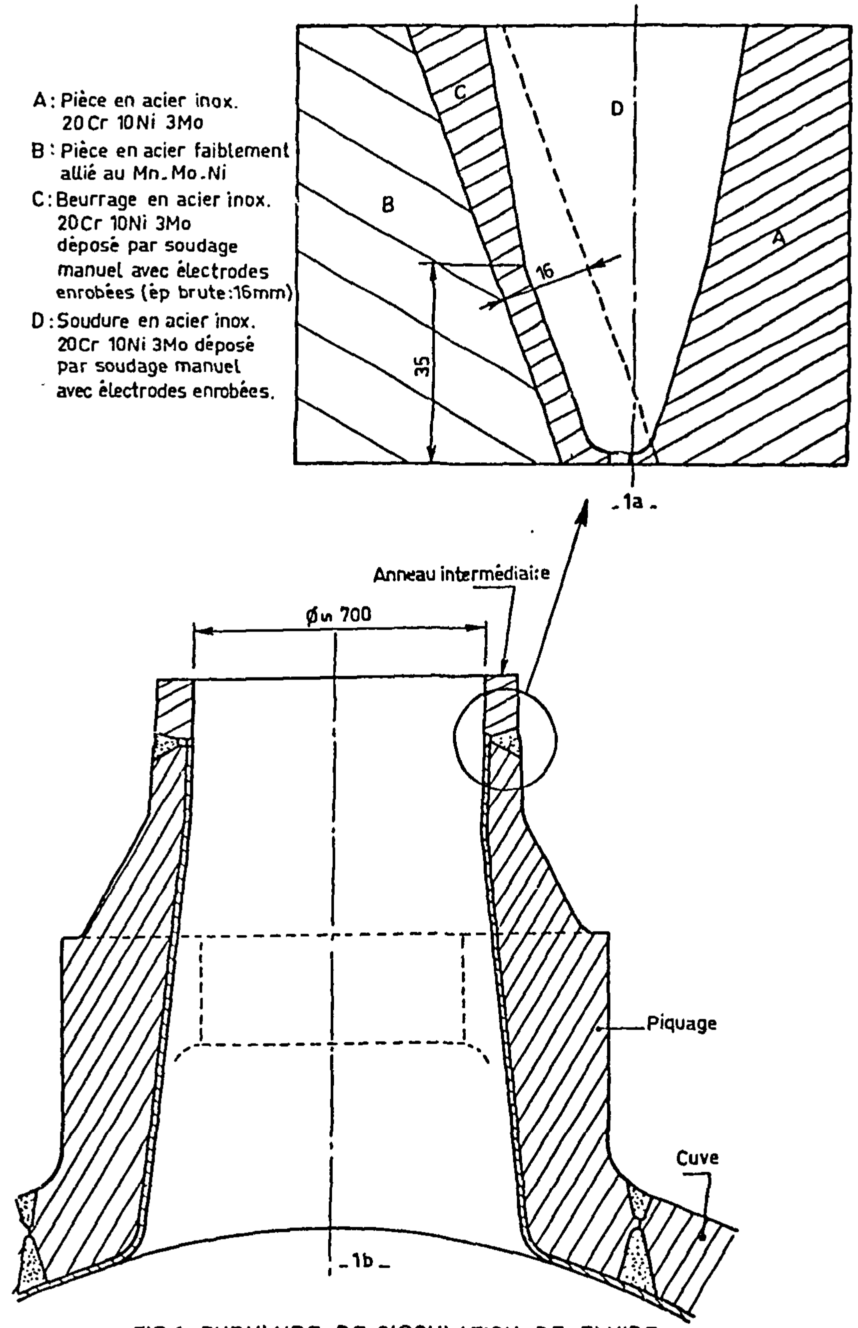

FIG.1_TUBULURE DE CIRCULATION DE FLUIDE.

FIG 2 - EMBOUT DE SECURITE - Echelle 1/2

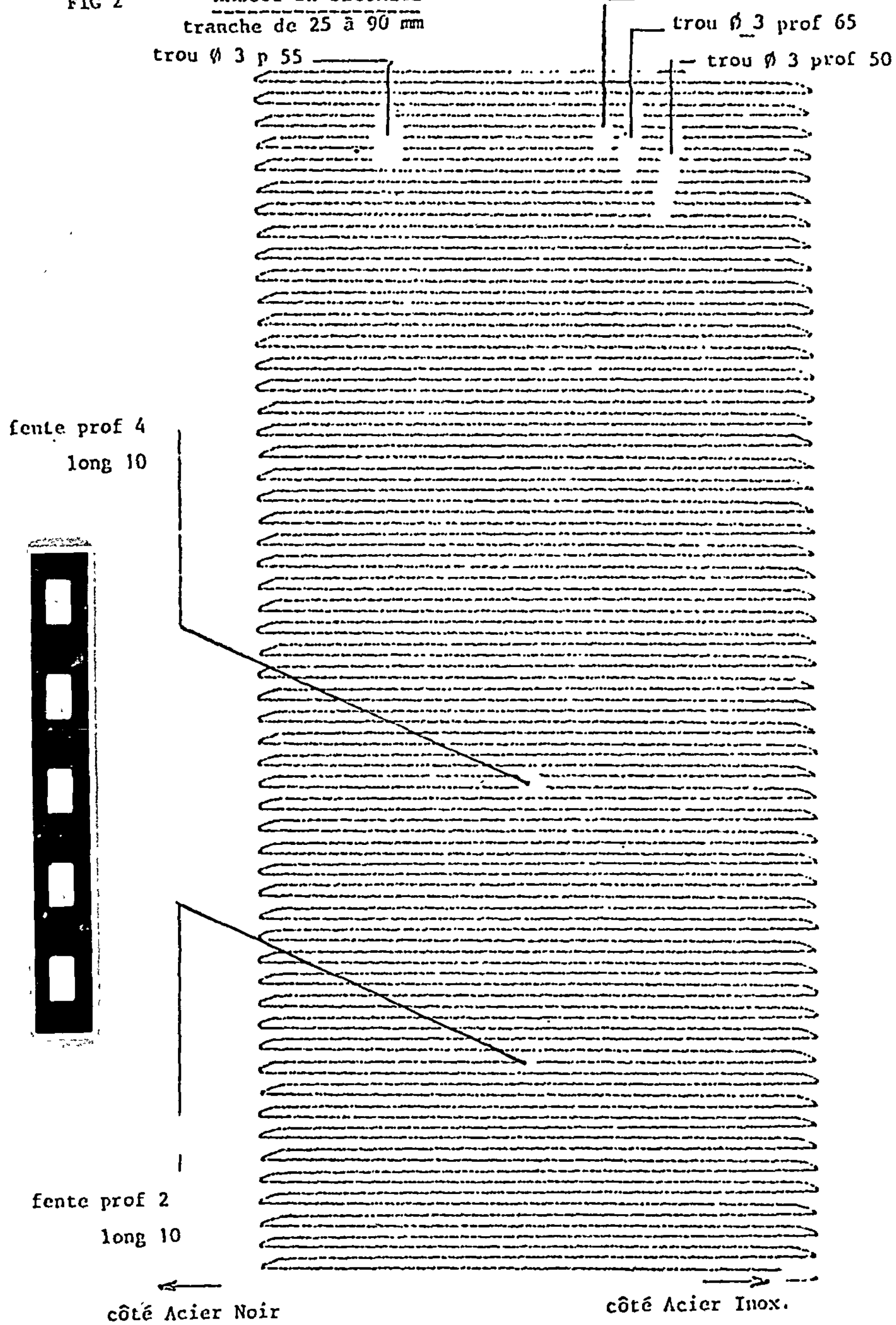

FIG 3 - EMBOUT DE SECURITE - Echelle 1/2

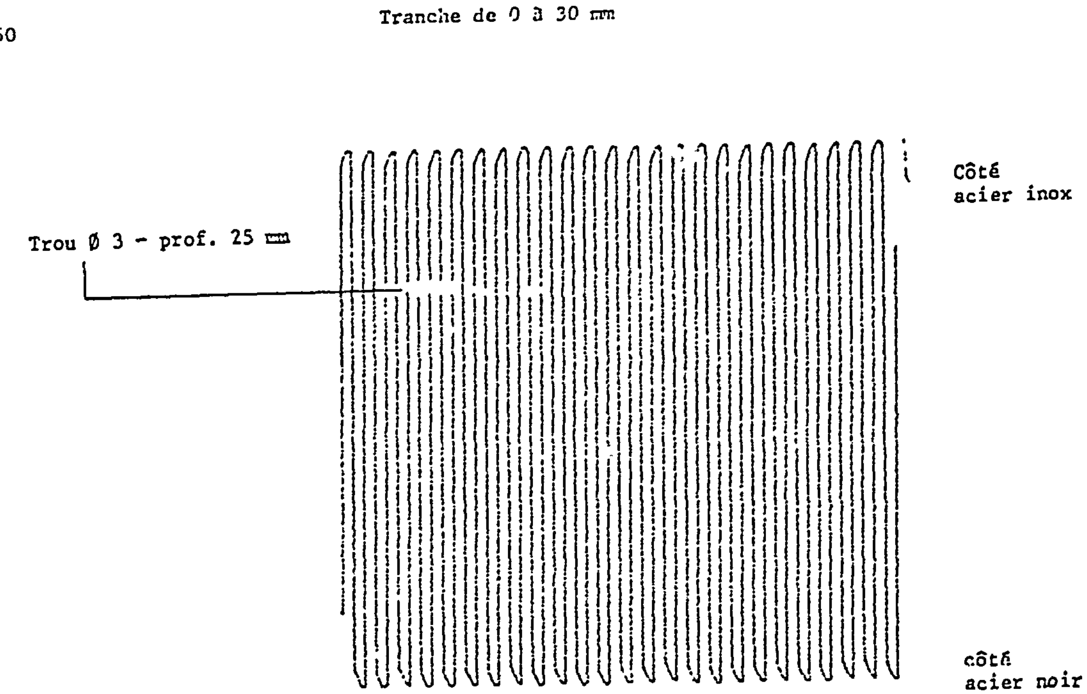

Fig 1 - Tubulure de circulation de fluide

Fig 2 - Embout de sécurité - Tranche DE 25 à 90 mm

Fig 3 - Embout de sécurité - Tranche de 0 à 30 mm