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Research Program Plan

Non-Destructive Examination

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

J. Muscara

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FOREWORD

This document presents a plan for research in Non-Destructive Examination to be performed by the Materials Engineering Branch, MEBR, Division of Engineering Technology, (DET), Office of Nuclear Regulatory Research. It is one of four plans describing the ongoing research in the corresponding areas of MEBR activity, which are being published simultaneously in four volumes as follows: Vol. 1 Reactor Vessels, Vol. 2 Steam Generators, Vol. 3 Piping, and Vol. 4 Non-Destructive Examination. These plans have been updated and are more detailed expansions of those originally published as part of the Long Range Research Plan for the Office of Nuclear Regulatory Research in NUREG-1080 Vol. 1; for more complete information on background, interfaces, and utilization, the above cited report should be consulted.

These plans were originally written as internal NRC working documents to cover the five year period from FY 1985 through FY 1989, to foster better coordination between the offices of Nuclear Regulatory Research and Nuclear Reactor Regulation, and improve the understanding of the derivation, approach and scope of the research programs. The plans have also been very useful for expanding that circle of understanding of the programs to other parts of the NRC staff, to the ACRS, and to contractors as an important information source and planning base. It is therefore hoped that the readers will benefit from these more clearly delineated objectives, needs, programmatic activities, and interfaces together with the overall logical structure within which these exist.

Publication of these plans will make visible to industry and other interested individuals what our objectives are and how we are approaching the work in these important areas. It is noted that reports of progress in all the areas of MEBR research are published annually in the series of reports "Compilation of Contract Research for the Materials Engineering Branch, Division of Engineering Technology," NUREG-0975 (Vol. 3 Annual Report for FY 1984). It is intended that these plans will periodically be updated; therefore, comments on these plans are welcomed from all quarters. Comments need not be restricted to activities for the five year period covered, but may include comments on omissions or what might be considered for the longer term. Please address comments directly to me.

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Nondestructive Examination

Introduction

Nondestructive examination/evaluation (NDE) of nuclear reactor components is required during fabrication, before service, and at regularly scheduled shutdowns for periodic inservice inspection (ISI). Any flaws produced during fabrication should be detected by the fabrication and preservice baseline examinations and components containing rejectable flaws should be repaired before the reactor enters service. The purpose of ISI is to ensure that any flaws which develop during service can be detected and evaluated and that unacceptable components are repaired or replaced to maintain safety, as well as to identify possible generic-type defects that may be present or developing in the remainder of the system or other similar systems so that timely corrective actions can be taken. Section XI of the ASME Boiler and Pressure Vessel Code, "Rules for Inservice Inspection of Nuclear Power Plant Components," defines inspection criteria for ISI and allowable flaw sizes based on fracture mechanics for various locations within reactor components. If a flaw is found that exceeds the allowable size, the component must be repaired or a safety analysis must be conducted, using fracture mechanics, to show that the flaw will not grow to an extent that will impair the integrity of the component. To conduct reliable safety evaluations using fracture mechanics, accurate information on flaw characteristics--with respect to size, shape, orientation, and location within the component--is required. In the present ultrasonic inspection procedures, the pulse-echo amplitude and search-unit position are evaluated as a basis for flaw detection and sizing. Although ultrasonic testing is the presently accepted and most useful volumetric inspection technique, its reliability for flaw detection and sizing (using the code procedure) is questionable and often inadequate. The major thrusts of the research in ultrasonic testing for ISI are (1) to define the influence of inspection variables and procedures on inspection reliability and to determine the impact of inspection unreliability on system safety and (2) to study and evaluate improved techniques for reliable and accurate flaw detection and characterization. This research, therefore, has direct impact on evaluations of and improvements in reactor safety.

Cracks which have developed during service have not always been detected using the currently required inservice inspections. Sometimes these cracks can grow through the component wall as for example the intergranular stress corrosion cracking (IGSCC) in BWR piping. Detection of certain types of cracks (e.g., IGSCC) using ISI is difficult; further, some degradation mechanisms may be too rapid for timely detection at scheduled ISI intervals. Therefore, effective development and implementation of continuous monitoring technology for crack growth in the entire reactor coolant pressure boundary can result in improved reactor safety through elimination of leakage due to crack growth, even in systems where degradation could not have been predicted on the basis of prior knowledge. Improved methods for continuous monitoring of pressure boundary leakage should provide an additional margin of safety should the growth of cracks not be identified by other means. The research for continuous online monitoring using Acoustic Emission (AE) is aimed at developing and evaluating technology for the continuous detection and evaluation of crack initiation and growth during reactor operation and for sensitive leak detection, location and quantification.

1.0 Definition of Issues and Needs

1.1 Periodic Inservice Inspection

Nondestructive examination for inservice inspection of nuclear power reactors is both a requirement and a key factor in establishing the safety and integrity of operating reactors. ISI is depended upon for identifying inservice induced degradation and/or possible generic degradation problems. Only when one knows with a high degree of assurance of the absence of flaws, --or the exact size, shape, and location of flaws that are present, --can one make intelligent decisions about operating conditions which will influence the continuing integrity of primary system components. The volumetric inspection method used for the required ISI of most reactor components including the pressure vessel, piping and nozzles is the ultrasonic testing (UT) method. ISI of steam generator tubing is conducted with the Eddy Current (EC) test method.

Field experience and laboratory results have shown that the current NDE techniques do not always give the results required with respect to reliability and accuracy of flaw detection and evaluation. At issue then are the capabilities of the currently practiced and available NDE techniques to perform their required functions with respect to both flaw detection and characterization (size, shape, orientation, location). The degree of the problem depends on the material and the component to be inspected and on the types of flaws present. With respect to flaw detection, the picture is variable. Detection was found (PNL) to be reliable for ferritic piping, less reliable for stainless steel piping containing intergranular stress corrosion cracking (IGSCC) and not at all reliable for cast stainless steels. Inspection effectiveness of pressure vessels using code procedures for detection of flaws is similarly variable. In general, sizing capabilities using code techniques (based on amplitude) for most materials and components have been found by field experience, laboratory testing and round robin inspections to be inadequate. However, improved procedures and new advanced techniques show more promise.

Following is a description of the problems related to ultrasonic inservice inspection:

o At present, the main inspection problems in piping relate to detection and characterization of IGSCC in stainless steel weldments. The problems can be attributed to the properties of the material, the properties of the crack itself and its location. The tightness of the IGSCC can reduce the UT signal reflected back to the transducer and, if tight enough, can even allow the signal to propagate through the crack without a return reflection. The branching nature of the IGSCC can diffuse the UT signal and can screen the main portion of the crack. Further, IGSCC occurs close to the weld fusion line making it difficult to distinguish signals produced by cracks from those produced by the weld root, the fusion line or the pipe counterbore; as a consequence, crack signals are often misinterpreted and ignored. Also if access is limited from only one side of the weld and the crack lies on the far side, so that the UT beam must pass through the weld metal, then those cracks are virtually undetectable with currently used techniques because of the highly attenuative and beam distortion properties of

the weld metal result in loss of signal. Cast stainless steel piping (and other cast stainless steel components) has been found to be virtually uninspectable by Code or other currently used techniques. The same problems inherent in the inspection of stainless steel through weld metal are present for the inspection of cast stainless steel. The inspection of cast stainless steel is even more difficult since it is more attenuative then stainless steel weld metal and the large grain structure of the cast stainless steel produces grain boundary reflections during the UT, thereby increasing the general background noise level rendering it difficult to detect and distinguish flaw signals. Further, the ultrasonic behavior of cast stainless steel differs as a function of grain morphology which can vary from pipe-to-pipe (or casting-to-casting) and thereby complicating the ISI problem. The sizing difficulty is due to the tightness of cracks, branching nature of IGSCC, location and orientation of cracks and most significantly the current Code sizing techniques (amplitude drop) are not based on physical principles.

o The main problems for ISI of pressure vessels relate to both flaw detection and characterization. For many years the near surface zone of the vessel for approximately 1-inch depth (inside layer for vessel inspections performed from inside the vessel as in PWRs) was not inspected. The techniques and instrumentation/transducers used for the ISI produce large front surface ring-down noise, thus masking any flaw signals that might be present in the near surface zone and rendering it uninspectable. Thus, many of the procedures simply "gated-out" all the signals originating in this zone of material. Recent evaluations of pressurized thermal shock for older PWRs have shown the need to detect small cracks 1/4-inch in depth and larger in the near-surface zone; i.e., surface cracks, cracks in the clad, or cracks underclad. Under certain pressurized thermal shock scenarios, these flaws could grow a considerable distance into the pressure vessel wall. As just discussed, because of the properties of the instrumentation/transducers, this is precisely the zone that has been gated-out during standard UT Code inspections. A most important problem when attempting to inspect for cladding and underclad flaws is brought about by the presence and properties of the clad metal itself. It is due most significantly to the roughness of the clad. The severity of the problem increases with clad roughness and rough clad weldments are virtually uninspectable by currently practiced techniques. The rough clad scatters, breaks-up, and distorts the ultrasonic beam. To a lesser degree, the scalloped clad-base metal interface also affects the ultrasonic beam. The stainless steel cladding material is highly attenuative. Reflections from the grain boundaries of the cladding material and imperfections in the cladding contribute to a relatively large general background noise level. All of these factors contribute to the unreliability of inspection for small cracks in or under the clad. Smooth strip cladding can be more reliably inspected using 70° longitudal dual beam zone focused transducers. As with the case for piping, sizing of flaws in pressure vessels can be unreliable if code techniques which rely on

amplitude drop are used since these have no physical basis. However, new practices based on other signal processing techniques have been developed which seem reliable for characterizing fatigue cracks.

Code inspection of steam generator tubing has not always been reliable especially as the flaw signals are affected by and sometimes masked by signals from inspection variables other than flaws as for example, the presence of tube supports, tube sheets, denting, probe wobble, etc. This situation has been improved somewhat in the last several years by the use of multifrequency EC systems. However, the sensitivity and reliability for flaw detection and characterization still needs improvement. One additional problem that surfaced recently was the inadequacy of the standard probes and techniques in use to detect and characterize circumferential type flaws such as intergranular cracks and general intergranular attack in the tubes in a narrow band at and within the tube sheet crevice.

The MEBR research program in NDE for ISI addresses the significant questions and problems discussed above.

1.2 Continuous On-Line Monitoring

The availability and application of reliable continuous on-line monitoring of reactors for crack growth and leak detection could be used to assure continuing integrity of the pressure boundary and improve safety. Some questions need to be resolved to develop and apply such reliable and effective techniques. The two main questions are a) can AE be used to detect growing cracks and/or leaks that are present without excessive false alarms and b) can the AE information be used to obtain an estimate of flaw severity. The first of these is important because false alarms could cause unnecessary shutdown of reactors. The second is also important because AE can detect the presence of small cracks which would not impair the safety of an operating reactor. One, therefore, must also know from the AE data the severity of the growing cracks so that reasonable decisions can be made for the operation of a reactor (i.e., continue operation; operate until the next scheduled shutdown then perform additional inspection and repair as necessary; shutdown immediately, inspect and repair -- of course this last situation should not or rarely occur since the stable growth of a crack would have been detected and followed long before the crack would reach a critical size and proper corrective actions would have been taken at some previous scheduled shutdown). To address these questions, instrumentation must be developed which can operate for long periods in the reactor environment, techniques and analyses are needed to be able to detect and locate AE signals originating from cracks or from leaks within the noisy reactor environment and distinguish crack signals from innocuous noise signals originating from other sources. Further, techniques, analyses and a data base must be developed to correlate AE signal properties to fracture mechanics parameters and leak rates which will allow evaluation of crack growth and severity from the AE monitoring. Instrumentation, techniques, and analyses models have been developed and evaluated under laboratory and intermediate scale test conditions. These can be used under reactor operating conditions for the on-line detection and location of cracks and leaks, their discrimination from other sources and for estimation of flaw severity. The current MEBR research program in this area deals with final optimization and validation of the technology developed so far by performing tests and continuous on-line monitoring of a commercial nuclear power reactor.

2.0 Research Program Description

A research program in NDE has been underway in order to improve NDE capabilities and to answer the questions posed in the previous section. The program can be divided into two major areas: (1) Periodic ISI and (2) Continuous On-Line Monitoring. In the ISI area, the disciplines of UT and EC testing are studied and in the continuous on-line monitoring area, AE is being developed and evaluated and evaluated both for monitoring of crack growth and for leak detection. The following subsections give more detailed descriptions and status of projects in these program areas.

2.1 Periodic Inservice Inspection Techniques

2.1.1 Reliability of Ultrasonic Inservice Inspection

Experience from inservice inspection of reactors and from round-robin tests has shown that the ultrasonic test techniques being used often have poor reliability for flaw detection and are inadequate for flaw sizing. Therefore, confirmatory research began in late FY 1978 at Pacific Northwest Laboratory (PNL) to quantify the reliability of current ultrasonic ISI techniques, to identify the inspection parameters that contribute to unreliability, and to establish the changes required in these parameters to obtain, in the short-term, considerable improvement in the reliability of current ISI. Further, the reliability of new, improved commercially available techniques will be quantified to ensure that new systems give inspection reliabilities consistent with the establishment of a high assurance of safety in inspected components. Specific objectives of this project are:

- o Determine the effectiveness and reliability of ultrasonic inservice inspection (ISI) performed on commercial, light water reactor pressure vessels and piping. Recommend Code changes to the inspection procedures to improve the reliability of ISI.
- o Using probabilistic fracture mechanics analysis, determine the impact of NDE unreliability on system safety and determine the level of inspection reliability required to assure a suitably low failure probability.
- o Evaluate the degree of reliability improvement which could be achieved using improved NDE techniques.
- o Based on material properties, service conditions and NDE uncertainties, formulate recommended revisions to ASME Section XI and regulatory requirements needed to assure suitably low failure probabilities.

The project consists of several major tasks related to both piping and pressure vessel inspection. The initial work on the project concentrated on piping inspection reliability. An important objective of the project is to develop data on the reliability and probability of flaw detection for ISI of reactor components using the current code techniques (as a baseline), state-of-the-art techniques and new advanced techniques. This data can then be used in probabilistic fracture mechanics evaluations to determine the probability of component failure given certain inspection techniques, material properties and service conditions. In this way one can establish the improvements (if any)

that are required in the current techniques to keep the probabilities of failure at acceptably low levels. To develop a proper data base on the reliability and probability of flaw detection would require extensive testing of many mock-ups containing many flaw types and sizes using many inspection teams under field ISI conditions. Obviously, to do this for all the required ISIs would be very expensive and time consuming. It was decided that a predictive model was needed to relate variations in inspection parameters to UT signal response. Thus inspection reliability and probability of flaw detection under different conditions could be estimated. Some models are available in the literature, however, they need to be expanded and validated. A series of parametric tests were performed to evaluate effects of UT inspection, flaw and material parameters on the ultrasonic response. One purpose for these tests was to expand and evaluate the predictive models available. The data from a fairly extensive round-robin could then be used to establish the probability of detection curves for given cases and to validate the predictive model and thereby allow extension of results from the one round-robin to other cases using fewer tests and less extensive trials.

The parametric study was completed in FY 1980. The accomplishments of this task include evaluation of the impact of inspection variables on UT response variability and estimates of current ISI reliability. A RIL was prepared summarizing these results and making recommendations for changes in code requirements and inspection parameters that could be immediately implemented to improve markedly ISI sensitivity and reliability. Most of these recommendations were adopted by the ASME Code in Section XI, Div. 1 as Code Case N-335, "Rules for Ultrasonic Examination of Similar and Dissimilar Metal Piping Welds" approved April 2, 1982. This Code Case is being prepared for incorporation into the ASME Section XI.

Another major task was the conduct in 1982 of a pipe inspection round-robin (PIRR) to establish the reliability of crack detection and sizing using currently practiced UT procedures for reactor primary piping systems. Six teams from commercial ISI agencies performed 1500 manual pipe inspections on about 80 specimens. The teams used their own field inspection procedures which are Code acceptable and an improved procedure for crack detection written by PNL. This improved procedure optimized UT test parameters as determined from the previous parametric study and is similar to Code Case N-335 which was based on and followed these studies. The test samples contained pipe-to-pipe welds in materials commonly used in LWRs i.e., cast stainless steel stainless clad ferritic steel and wrought stainless steel. All pipe materials contained thermal fatigue cracks and a set of wrought stainless steel specimens contained stress corrosion cracks. All cracks were laboratory induced and some specimens contained no defects. The inspections simulated important field conditions: a) pipes were inspected from one direction as is usually the case for pipe-to-component welds, b) cracks were located both on the near side where the sound beam passes only through the base metal and on the far side where the beam must pass through the weld metal to the flaw, c) the specimens and operators were placed in an easy-to-inspect position and in a difficult position with respect to scanning, viewing of scope, clothing and access, d) a time limit of 30 minutes was imposed for scanning by the levels I or II inspectors, and e) the level III inspector was not allowed to discover new indications but only to evaluate those indications identified by levels I and II as requiring further evaluations as is usually done in field ISI.

A great quantity of data was collected during the PIRR, these data were checked, reduced, analyzed and evaluated during 1983. Plots of probability of detection as a function of crack size for the different piping materials and flaw types were developed. Major conclusions from this work are:

- o UT flaw detection in clad ferritic main coolant pipe can be 100% effective, if adequate sensitivity is used per ASME Code CASE N-335. Section XI minimum sensitivity (50% of the notch amplitude) is not adequate.

- o Flaw detection in clad ferritic pipe is almost equally effective with and without weld metal in the sound path.

- o UT inspection of centrifugally cast stainless steel is ineffective using conventional manual techniques currently in field use.

- o Section XI minimum requirements do not provide effective inspection of wrought stainless steel pipe welds containing either thermal fatigue or intergranular stress corrosion cracks. Increased sensitivity and selection of optimized transducers improves detection reliability.

- o When the sound beam must pass through the butt weld in wrought stainless pipe, UT inspection using current field techniques is ineffective.

- o Even when using identical equipment and procedures, variability in flaw detection reliability is significant.

- o Crack detection reliability in UT inspection of stainless steel pipe welds should be qualified by test.

- o Crack length measurements were in general quite good. There was a trend to oversize very small cracks and to undersize very long cracks. A conservative approach would be to record length based on signal reduction to background noise level.

- o Crack depth measurements in both ferritic and stainless steel piping using Code techniques based on probe motion are unreliable.

Continuing work in this area will use a number of commercial ISI teams using their current demonstrated techniques to conduct mini-round-robin testing. This mini-round-robin will incorporate IGSCC in stainless steel piping of different thicknesses. The pipes will contain single cracks and multiple cracks of varying lengths and depths and some service induced cracks. The purpose of these tests is to expand the data base from the PIRR to include larger diameter/thickness pipes, larger cracks and crack combinations to more closely represent the conditions of interest for field ISI. Also improvements in performance due to required training and performance demonstration since the PIRR will be measured, individual performance will be compared to team performance and variabilities between individuals and between teams will be evaluated. Results from the parametric studies, the PIRR, and the mini-round-robin will be used to extend and validate a model to describe ISI performance. This model will then be applied to parametric data obtained from flawed piping specimens of other diameters and wall thickness and from

dissimilar metal welds in order to predict the performance of field ISI practice on piping not included in the experimental studies. Additional extensive round-robin testing will not be necessary; the performance of the PIRR and mini-round-robin inspection teams will be extrapolated.

Other ongoing work is evaluating state-of-the-art and advanced UT techniques to determine the reliability of those techniques and how they can be used to improve reliability of inspection in those areas found to be inadequate by the PIRR. Some of the same pipe specimens used in the PIRR will be inspected but not by as many teams or by commercial teams. The probability of detection model will be used to predict field performance for the techniques. The techniques to be evaluated are: SUTARS, FLAWSORT, AUTS, SAFT-UT, and Acoustical Holography.

Results from the PIRR and parametric studies indicated the need to qualify the inservice inspection process including personnel, equipment and procedures for those inspections required by Code and NRC. A qualification criteria document is under development for this purpose. The experience, procedures used and results from the PIRR will form the basis for this document. Included will be requirements on equipment based on results from ongoing parametric studies of the effects of changing equipment parameters on UT signal response and inspection reliability. A first draft of a general qualification document was written and reviewed with industry including representatives from ASME, ASNT, EPRI, utilities, ISI vendors and architect engineers. A second and third more specific draft criteria document is written and the third draft was reviewed with the NRC staff and subsequently with industry. This third draft is being prepared for publication as a NUREG/CR report. Some of the key aspects of the document are:

- o All the main aspects of the inspection process - personnel, equipment, procedures - will be addressed,
- o Practical demonstrations will be required and will use realistic specimens and flaws from a statistically significant sampling plan,
- o Nationally uniform written examination requirements,
- o Maintenance of a national registry of qualified personnel,
- o Guidance for industry to develop their own qualification program for plant-specific problems.

During the industry review, it was recommended that the ASME Code should evaluate/modify the document for possible code implementation. The ASME Code Section XI Subgroup on NDE has established a task group for evaluating the document, developing implementation mechanisms and incorporating into the Code the proper ISI qualification requirements.

Most of the project description covered so far under this section has related mainly to piping and the experimental program has used materials and techniques representative of same. However, some of the work such as the parametric studies, probability of detection predictive modelling and qualification criteria applies equally well to pressure vessel inspection. Specific work

applicable to pressure vessel inspection has concentrated on the evaluation of UT techniques for the detection and sizing of near surface flaws which are of interest for evaluations of vessel integrity under various pressurized thermal shock transients. These efforts have emphasized underclad crack detection and sizing. An initial quick response evaluation was performed using a 70° longitudinal wave dual-beam zone-focused transducer. The results have been published in NUREG/CR-2878. It was concluded that the technique is effective for smooth clad surfaces and not very effective for the rough surfaces produced by manual shielded metal arc welding (SMAW). However a large improvement in inspectability was achievable after light polishing of this surface. By smoothing the as clad surface from 12.6×10^{-3} inches RMS to 5.6×10^{-3} inches RMS an effective inspection condition was achieved.

Following and continuing work is evaluating different techniques, inspection angles and wave propagation modes on the inspectability and sizing capability of small near surface and underclad cracks as a function of clad type and roughness, and flaw size. Three clad types are investigated - SMAW, three-wire submerged arc, and two-inch strip clad. Further, the effects of cladding surfaces and of clad-base metal dilution interface on the sound beam propagation are being quantified. Conclusions from this work so far are:

- o Detection and sizing of underclad cracks is ineffective for SMAW clad surfaces and reliable for three-wire submerged arc and strip cladding,
- o Shear waves are distorted by the clad-base metal interface and are not effective for inspection,
- o 70° longitudinal waves at frequencies in the range of 2.25 to 5 MHZ should be used with dual element probes; single element probes are not effective,
- o The calibration reflector should be 1/16 inch side drilled hole (SDH) at the clad-base metal interface.

Evaluation of ISI reliability for pressure vessels and nozzles requires the use of very large heavy section specimens. Round-robin inspection and destructive confirmation of flaws would be prohibitively expensive. Nevertheless information on the reliability of pressure vessel inspection is needed for safety evaluations. Therefore, we are cooperating with several groups to obtain data on the reliability of pressure vessel inspection. From the UK we are obtaining the raw data from their defect detection trials (DDT) where a number of large section pressure vessel steel plates and nozzles containing various flaws and artificial reflectors were inspected by several teams using conventional and advanced techniques. We are also cooperating with the Pressure Vessel Research Committee (PVRC) and with the multinational PISC II (program for the inspection of steel components) program to obtain data from other large section pressure vessel and nozzle inspection samples, again containing different flaws and inspected by many teams using different techniques. These data will be supplemented with our own inspection trials, if needed, and combined with probability of detection predictive models to quantify the reliability and probability of flaw detection for pressure vessel and nozzle ISIs when using either Code minimum or improved procedures. Further, the reliability of flaw sizing for these components will be established from the data supplied and or gathered in the program.

Fracture mechanics calculations have been and will be conducted throughout the project to guide the NDE studies and development of ISI requirements. Important factors being evaluated are UT sensitivity requirements, inspection intervals and inspection sampling plans. Based on probabilistic fracture mechanics, service conditions, material properties and UT reliability, a unified set of inspection requirements will be developed to keep the probability of failure of primary system components (pip ng, nozzles, pressure vessels) at acceptably low levels. Recommendations for . de modifications to improve ISI reliability will be made throughout the prog am and will culminate in the unified set of inspection requirements just discussed.

2.1.2 Improved Ultrasonic Inspection for Flaw Detection and Characterization

The basic functions of ISI in primary system components are: 1) to detect important flaws with high sensitivity and reliability, and 2) to characterize detected flaws on terms of their type, size (length, depth), shape, orientation and location so that informed assessments can be made regarding reactor safety. It has been clear for many years that a major improvement is needed over the currently practiced NDE techniques to adequately meet the above basic functions for crack detection and characterization. A research project was started in FY 1975 aimed at dramatically improving the sensitivity and resolution capabilities of ultrasonic testing to obtain the reliable detection and accurate characterization of flaws needed for safety evalutions. An entirely new technology has been developed for ultrasonic testing which uses the phase and amplitude information of signals and search unit position to form a highly accurate image of flaws. This signal-processing technique has been named the synthetic aperture focusing technique for ultrasonic testing (SAFT-UT).

During the previous years many technical achievements have established the SAFT-UT technology. SAFT-UT has evolved into a very robust methodology for flaw imaging which can be adapted to many different types of materials, specimen geometries, and propagation modes. SAFT-UT processing increases the signal-to- noise ratio above that obtained from any conventional ultrasonic testing due to the inherent spatial averaging in SAFT-UT. This property also helps to eliminate or minimize the spurious grain boundary reflection noise in large grained stainless steels. The enhanced signal-to-noise aids in the reliable detection of small defects and in the inspection of noisy materials, such as cast stainless steel, through-weld inspection of stainless steels, and in inspection for underclad cracking. SAFT-UT processing provides high resolution images of defects. These images are volumetric in nature; i.e., they provide a three dimensional map of the defect and surrounding region. The characteristics, flexibility and robustness of the SAFT-UT processing make this technique ideal for all required reactor ISIs including the difficult cases of inspection mentioned above.

Many technical areas and issues relating to SAFT-UT have already been addressed and resolved. Some of the more important of these are:

- o SAFT-UT on regular and arbitrary surface geometry
- o effects of surface distortion upon image quality
- o effective display techniques

- o basic algorithm improvements to increase speed; i.e., lookup tables, "software machining," etc.

- o analyses of real-time SAFT-UT processing and design and construction of a prototype real-time hardware processor.

Much of this earlier work involved analyses and development of SAFT-UT processing theory, ideas and procedures and computer implementation of the evolved SAFT-UT algorithms. Evaluation of these developments has been through computer simulations and laboratory testing on simple specimens containing artificial reflectors and some laboratory produced cracks.

The main purpose of these developments is to make available greatly advanced techniques for the detection and characterization of flaws during reactor ISI. Further, these techniques should be validated and incorporated in Code and/or regulatory requirements. At this stage, two factors relating to SAFT-UT performance must be demonstrated before a real-time SAFT-UT field rated system for all the required ISIs can become a reality. First, SAFT-UT must reliably detect and image vertically oriented flaws that could be present in reactor components. Second, it needs to be demonstrated that the large number of mathematical operations required in SAFT-UT signal processing can be achieved in real-time. Currently the SAFT-UT processing is conducted in software which is time consuming and not a drawback for post inspection, off-line flaw characterization of identified flaws. However, real-time processing must be achieved if the technique is to be useful also for general component scanning for flaw detection and characterization during the actual ISI. Both of these issues are being addressed in the current SAFT-UT program which is aimed at final development, optimization, field validation and Code acceptance of SAFT-UT.

Past demonstrations of SAFT-UT in laboratory specimens have been performed using longitudinal, normal beam ultrasound as the predominant mode of propagation. These demonstrations have been quite successful at illustrating the superior resolution improvements which can be achieved with SAFT-UT. Normal beam ultrasonic inspection, however, does not provide the best detection reliability or the best signal-to-noise ratio from vertically oriented defects. Angled beam SAFT-UT, using either longitudinal or shear waves, appears to provide the means necessary for detecting and imaging vertically oriented defects. Some initial efforts to demonstrate this capability have already been undertaken and improvements in image quality and detecting reliability are expected to be forthcoming from work which is ongoing.

Much effort and analysis has been directed toward the achievement in real-time of the processing required for SAFT-UT. This work has indicated that real-time processing is not possible using general purpose computer equipment; however, real-time processing rates can be achieved using special purpose hardware designed specifically for this purpose. The design for such a processor has been developed which takes advantage of a parallel processing architecture. A prototype processor has been developed and is being evaluated.

The objectives of the current program on SAFT-UT are to:

- o Design, fabricate, and evaluate a real-time flaw detection and characterization system based on SAFT-UT for inservice inspection of all required LWR components.
- o Establish calibration and field test procedures.
- o Demonstrate and validate the system through actual field reactor inspections.
- o Generate an engineering data base to support Code and/or regulatory acceptance of the real-time SAFT-UT technique.

The program involves three major phases. The first includes a) laboratory tests to optimize both ultrasonic parameters and SAFT-UT processing parameters for inspection of important components and flaw types and b) developing the requirements and specifications for a field system. The second phase will concentrate on building the field system, optimizing the display technology, and laboratory testing the field system. The third phase will validate the technology by performing field ISIs and will make a case for Code/regulatory acceptance of SAFT-UT.

2.1.3 Distinguishing IGSCC from Geometrical Reflectors

A particular insidious problem is the detection and recognition of intergranular stress corrosion cracking (IGSCC) in stainless steel piping. The nature of IGSCC renders it difficult to detect because of its tightness, branching nature and orientation. Complicating the detection and proper identification of these cracks is the fact that IGSCC occurs in the heat affected zone very close to the weld fusion line, to the weld root and to geometrical discontinuities of the "weld-prep." As a consequence, during the normal UT inspection of the stainless steel pipe weldments, many geometrical reflectors are produced from these other sources in the same area that an IGSCC might exist. Because many more of these geometrical reflectors exist than do cracks, and because the IGSCC signals are so close to these other signals and are difficult to separate, the operators very often miscall the crack signals and classify them as geometrical reflectors and cracks, therefore, are not detected. In theory, since geometrical reflectors and IGSCC are morphologically different they should also scatter sound differently.

Because IGSCC has an irregular geometry of a stepped nature (crack follows grain boundary) and it usually has several branches besides the "main" crack, it is expected that IGSCC would produce a broader scattering pattern than a geometrical reflector. The dependence of the echo amplitude on the angle of beam incidence to the reflector surface could then be used as a way to distinguish IGSCC from geometrical reflectors.

To evaluate this concept seven IGSCC and four geometrical reflectors in stainless steel piping were examined using a miniature (1/4 inch) 45° sheer wave transducer at 2.25 MHZ in the pulse-echo mode. The echo amplitudes were measured as a function of skew angle (with respect to reflector surface) for all the specimens. The results showed that the change in signal amplitude as a

function of skew angle was sharper for geometrical reflectors than for IGSCC. This indicates that as expected the signal is scattered over a wider angle for IGSCC as compared to geometrical reflectors. For the IGSCCs significant signals were obtained over included angles ranging from a minimum value of 50° to a maximum of 70° depending on the particular crack. Contrasted to this the geometrical reflectors scattered signals over a range of from 26° to 38°. Based on these encouraging results a multielement skew angle (MESA) probe was designed and constructed to evaluate its capability for discriminating IGSCC from geometrical reflectors. This probe contains seven interlocking miniature 45° angle shear wave probes (at different skew angles) in a rubber frame suitable for inspection of 28-inch diameter pipe. This probe and associated multiscanner UT equipment will be further evaluated on a greater number of specimens and on actual field produced cracks and components. The successful validation and use of this probe will greatly help in improving the reliability of IGSCC detection by helping the operator determine if a signal is due to IGSCC or a geometrical reflector.

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2.1.4 Eddy Current ISI of Steam Generator Tubes

As an integral part of the primary system pressure boundary, ISI of steam generator tubing is required; while most other primary system components are inspected by ultrasonic testing, eddy current testing is normally used for steam generator tube inspection. The presently used ASME-code eddy current inspection techniques are fast, but they can produce unreliable inspection results because of the many independent variables that affect the signals. For example, it is extremely difficult to detect flaws in a dented tube region surrounded by corrosion products and the tube support plate. Two research projects are and have been active to evaluate and develop improved eddy current inspection techniques for steam generator tube ISI.

One of these projects is covered more fully in the detailed program plan for Steam Generators. A summary description only of this effort follows. The project uses a retired-from-service steam generator as a test bed for various studies including NDE. The generator contains many degraded tubes and is positioned vertically in the research facility similarly to positioning of generators in operation. The main objectives of the NDE related tasks are to evaluate current state-of-the-art eddy current techniques and improved techniques, to develop improved plugging criteria and to develop a statistically based inservice inspection plan. Three baseline eddy current examinations have been conducted. One of these was a limited examination using single frequency EC similar to the ISIs that were conducted on the unit while it was in operation. The other two baselines used two different multifrequency EC systems and inspected a majority of the tubes in the generator. Using the data from these inspections in conjunction with the results from destructive evaluations of selected tubes that will be removed from the generator, the reliability of these NDE techniques (which are currently used in the field) will be established. Burst tests, collapse tests and leak rate tests will be performed on degraded tubes removed from the generator; these tubes will have been inspected in situ before removal for testing. A comparison of the EC characterization of the defects with their actual nature and with their burst and collapse pressure holding capability will allow validation of predictive models developed previously and the development of improved tube plugging criteria based on inspection results. EC data and inspection reliability will be used in conjunction with secondary side inspection results which characterize flaw types and distribution throughout the generator and with expected flaw propagation rates to develop a statistically based ISI plan for the frequency of inspection and the particular sampling during inspection necessary to keep the maximum possible number of tubes failing in between ISI periods at given levels. Further, round- robin inspections will be conducted in-situ on a statistically valid set of tubes to evaluate standard and improved inspection techniques and to determine their reliability by comparing NDE results to destructive characterization of the tubes. Finally a number of tubes with varying flaws will be placed in mock-up to be reserved for future use in validating new techniques.

In the other project, a three-frequency instrument was constructed and laboratory-evaluated with the capability for either separating and measuring or discrimi- nation against variations in each of the following parameters: (a) tube diameter, including denting at the supports; (b) probe wobble; (c) the presence of supports around the tube; (d) tube wall thickness; (e) location (radial and axial) of defects in the tube wall; and (f) the size of wall defects. Preliminary field tests of the equipment were conducted in FY 1981 for inspection of flaws in the tubesheet region of several operating steam generators. The instrument was upgraded to take into account the effects of copper deposits on tube surface and prepared for additional field tests.

Because the commonly practiced EC techniques had missed detecting circumferentially oriented cracking and intergranular attack using differential or absolute encircling coils, analyses and calculations were conducted to determine the optimum coil design to detect circumferentially oriented flaws as well as axial and other orientations. It was found that small pancake coils would be most effective and the optimum size of each element was calculated.

An optimum circumferential probe was designed which would incorporate 16 of the pancake coils in two staggered bands around its periphery. In this manner the probe would be sensitive to all orientations of flaws and none would be missed regardless of their location. Because a 16 element probe could be excessively complicated electronically, an 8-element probe was constructed first and used with the 3-frequency EC instrument to evaluate the concept. The 16-element probe is currently undergoing laboratory evaluation. The probe and three-frequency EC system for both flaw detection and characterization will then be validated by performing field inspections including exhaustive characterization of the Surry steam generator removed from service. Upon completion of this validation the improved techniques wil' be implemented by incorporation into the Code or through a regulatory guide.

2.2 Continuous On-line Monitoring

2.2.1 Acoustic Emission Surveillance of Operating Reactors

Techniques are being developed for the continuous on-line monitoring for flaw growth and for leak detection. Detection of flaws- and the monitoring of flaw growth during reactor operation - can be one of the most powerful means of preventing unexpected failure of primary system components during service. Ongoing research projects will develop acoustic emission (AE) technology for on-line detection and evaluation of crack growth and for leak surveillance.

A research project was started in FY 1977 to determine the feasibility of and develop the technology for (1) the on-line detection of flaws in nuclear reactors and (2) the evaluation of their significance on a continuous basis by measuring and analyzing the AE information. The project is structured along three main phases. The objectives of the first phase were to develop empirically based analysis models for characterization of crack severity from the AE data, to develop models for the discrimination of AE produced from crack growth vs. that produced from innocuous noise sources, to develop procedures for AE monitoring in the noisy environment of an operating reactor, and to assess the feasibility for continuous on-line monitoring. The objectives for this first phase have been met and on-line monitoring of reactors was determined feasible. The research conducted during this phase used laboratory scale testing and performed analytical evaluations. A laboratory baseline of data has been developed using a variety of specimens and testing conditions, representative of what might be expected during reactor operation, to characterize AE signals and crack growth. Pressure vessel and piping materials have been tested under cyclic and monotonic loading conditions at room temperature and at 550F in a variety of specimen types and sizes for both base metals and welds. These data have been used in the development of a model for estimation of flaw severity. This model correlates fracture mechanics parameters to the AE characteristics produced from the growing cracks. Detailed evaluations of the AE signal waveforms have produced a model for distinguishing the AE from cracks from that produced by noise sources through pattern recognition analysis. Transducers, coupling methods, and equipment have been evaluated and optimized for long term use in the reactor operating environment. Finally, the methodology for operating in the noisy environment has been established through evaluation of reactor noise and by tuning the sensors to operate and monitor at frequencies above the noise (above 350 KHZ). These higher frequencies have been found appropriate for detection of crack growth.

The objective of Phase II was to evaluate and improve the methods and models developed in Phase I by performing larger scale tests using intermediate size specimens and pressure vessels. A number of intermediate size vessels (ITV) tested at ORNL under the HSST program for validation of fracture mechanics have been monitored using AE. The experimental work under this phase culminated in 1983 with the completion of a 12-month pressure vessel test conducted in the FRG in cooperation with MPA. This test consisted of monitoring cracks growing in a 5-inch thick intermediate scale pressure vessel which was tested in fatigue under simulated reactor operating conditions of varying stresses, temperatures, noise sources, electrical transients, and so forth. The vessel contained three fatigue presharpened flaws of varying sizes which were implanted before testing. The vessel was subjected to cyclic loading and to hydrostatic testing. The cracks were instrumented and their growth was followed by crack opening displacement measurements, periodic UT and by continuous AE monitoring. The tests were monitored using AE equipment and methodology developed earlier in the program. The monitoring equipment incorporated both flaw severity and the noise discrimination models to characterize flaw growth and to distinguish crack growth AE from other noise signals generated during the test. Much data was gathered during the 12-month test and is being evaluated. The flaw severity model worked reasonably well; the AE noise/flaw discrimination model needs refinement. Besides the implanted flaws, several naturally occurring cracks developed at different places of the pressure vessel during the testing. These cracks were properly detected, located and characterized before their detection by the periodic UT. These tests showed the high potential for reliable on-line monitoring of reactors using AE.

The third and final phase of the program is currently underway. The objective of this phase is to validate the techniques, procedures, equipment and evaluation models developed for continuous on-line monitoring using AE by conducting reactor monitor during service. In conjunction with this work a new nuclear power reactor was monitored during hydrotesting and hot functional testing. Further, the reactor is now instrumented and will be monitored during its operation beginning in 1984 for a period of two years. During this time the techniques will be improved as required and the entire methodology validated. Upon successful completion of this monitoring, a case will be made for acceptance of the technology by the Code and Regulatory authorities.

2.2.2 Leak Surveillance by AE Monitoring

Using AE methods to detect coolant leaks during nuclear reactor operation offers potential improvement in sensitivity, response time, location accuracy, leak- source characterization, and leak quantification over present methods. Leak surveillance by AE methods detects the noise generated by leak flow to the atmosphere from the high-pressure, high-temperature coolant system. This noise is propagated through the material; it is detectable remotely by piezoelectric sensors which are mounted on the system. A project to develop and improve the technology for application of acoustic emission to leak surveillance began in FY 1982. The research will (a) define and improve the sensitivity of the method for detecting leaks from actual cracks under reactor operating conditions, (b) evaluate and develop sensing systems for effective leak detection compatible with the reactor environment, (c) develop improved methods for accurate leak location, (d) develop methods for discriminating the AE from

different leak types (crack versus pump and seal, and so forth), and (e) develop methods and correlations for relating the AE to leak quantity and possibly to the through- wall crack size. Several tests have been conducted using pipe samples with stress corrosion cracks and with fatigue cracks. The signal levels obtained even from very small leaks are adequate for detection in a plant environment. A correlation is being developed between the AE levels and the leak rate. Techniques are under development for the location and classification of leaks. Additional testing will continue to finalize these correlations. Emphasis is being placed on assuring that the equipment and methodologies are compatible with that being developed for continuous on-line monitoring for crack growth. Equipment will be assembled incorporating the features and analyses being developed for reliable on-line leak monitoring of operating reactors. This technology will be validated by actual monitoring of an operating reactor and a case will be made for code acceptance.

2.3 Basis for Selection of the Specified Test Program

The tests being conducted were described in the previous section. The philosophy of the testing centers around determining the state-of-the-art in ISI to evaluate the reliability of detecting and to decide if improvements were required. Therefore, reviews and interviews were conducted to find out what techniques are practiced in the field and how they are performing. The parametric testing and round-robin inspections of real flaws in reactor materials usi · commonly practiced field techniques were conducted to quantify the reliabil ․y and adequacy of the current Code techniques. Current state-of-the-art techniques were also evaluated on real flaws and material conditions to determine the improvements achievable from these already developed techniques.

In those projects where a great deal of improvement was sought and for the continuous monitoring research the philosophy of the projects and testing is as follows:

- Perform analytical evaluations of the concepts which will lead to improvements and conduct laboratory tests to establish the feasibility;

- Perform additional testing using larger scale, more realistic specimens containing actual flaws to establish that techniques are reasonable under these conditions - if not improve techniques;

- Perform tests and analyses to establish procedures, calibrations, environmental performance, etc., to assure that techniques can work under field conditions, that they can be reasonably carried out and interpreted by operators and that equipment can survive for the length of time necessary; and

- Finally, perform testing and validation on actual reactors and reactor components to establish final improvements and validation of the technologies developed and to be able to make a case for Code acceptance.

3.0 Schedule

Most of the projects in the current NDE program will be completed by 1986; during 1987 will concentrate on getting the improved techniques accepted by Code. If the current programs are successful as the results indicate now, then major improvements will have been made both for ISI and for continuous monitoring. This situation would indicate that no further research is needed in this area. A network showing major milestones and tasks to be completed by fiscal year is given in Figure 1.

4.0 Coordination

The NDE program is routinely reviewed by NRR and IE. Further, coordination is conducted with EPRI. The NDE projects are coordinated among each other. For example, the AE techniques for crack growth monitoring and for leak detection are conducted in different laboratories but the work is coordinated to assure that the systems are compatible. Complimentary and coordinated work is going on at different laboratories in the areas of inspection of stainless steel and eddy current inspection. Test specimens are shared between projects. Coordination and cooperation is also conducted with foreign countries. For example, cooperative efforts in SAFT-UT, in ISI reliability and in Acoustic Emission have been underway with the UK and the FRG. Other cooperation and coordination is conducted with the OECD in the areas of ISI reliability and UT inspection of stainless steels.

5.0 Capabilities of NRC Staff and Contractors

The NRC staff member who manages the NDE program is Joseph Muscara, PhD, Metallurgical Engineering, U. of Michigan, 1971. He has been a Research program manager in AEC and NRC for 9 years; for 1 year prior, he was on the Standards Development staff. He has foreseen the need for many research programs, and has guided them through the review and approval process. Some of the research programs on NDE are producing major breakthroughs in materials and components very difficult-to impossible to inspect previously. He has been named as a member of the Pipe Crack Study Group in NRC, and a member of the international group for review and coordination of NDE research under the CSNI committee of OECD.

One of the major contractors for the projects is Pacific Northwest Laboratories (PNL). They were selected for their excellent and varied staff who have performed pioneering research in all areas of NDE and further have taken their research to the final stages of field validation and application Some work on the inspection of stainless steel is conducted at Argonne National Laboratory where Dr. D. Kupperman is a foremost expert and has conducted unique research in the areas of the effects of stainless steel structure and isotropy on Ultrasonic Response. Work at Oak Ridge National Laboratory on Eddy Current is performed by Dr. C. Dodd who has worked in this field for many years including work on his PhD thesis. Dr. Dodd's theories and modeling of Eddy Currents is the standard work and acts as a benchmark for work conducted by other researchers worldwide.

6.0 Closure of Technical Issues

A series of issues will be closed over the next several years, all dealing with the detection and sizing of flaws in primary system components, using ultrasonic test methods as the basis. Closure will be achieved, from the research standpoint, through development or validation of techniques and equipment that will reliably find and size flaws in the field in the stated components. Specific issues to be closed include carbon steel pipe in FY 1985-86, carbon steel pressure vessels in FY 1986-87, wrought stainless steel pipe and welds in FY 1987-88, and multi-metal safe-end welds and cast stainless steel in FY 1988-89. Although techniques and equipment may be validated as acceptable for reliable inspections, it is only when these two plus the operator have jointly been qualified to act in concert that reliable inspection can be achieved. Thus, a necessary prerequisite for closing the detection and sizing issues is that of qualification of the entire inspection system: personnel, procedures and equipment.

Requirements for qualification should result in a national center for NDE qualification during the FY 1985-87 time frame, whose operation will be of great benefit to NRC because of the assurance it will give to the reliability of test results from inservice inspections of plants. Finally, the technology will be validated and in place by FY 1986-87 for routine use of continuous monitoring by acoustic emission for detection of leaks (for example from BWR piping that had been cracked and repaired by weld clad overlay) and for detection, location and characterization of crack initiation and subsequent growth (for example from fatigue cracking or from IGSCC). The availability of these techniques will allow the staff to more readily accept repairs for continuing service because such continuous surveillance would assure immediate detection of crack growth and/or a leak if break-through of a repair should occur.

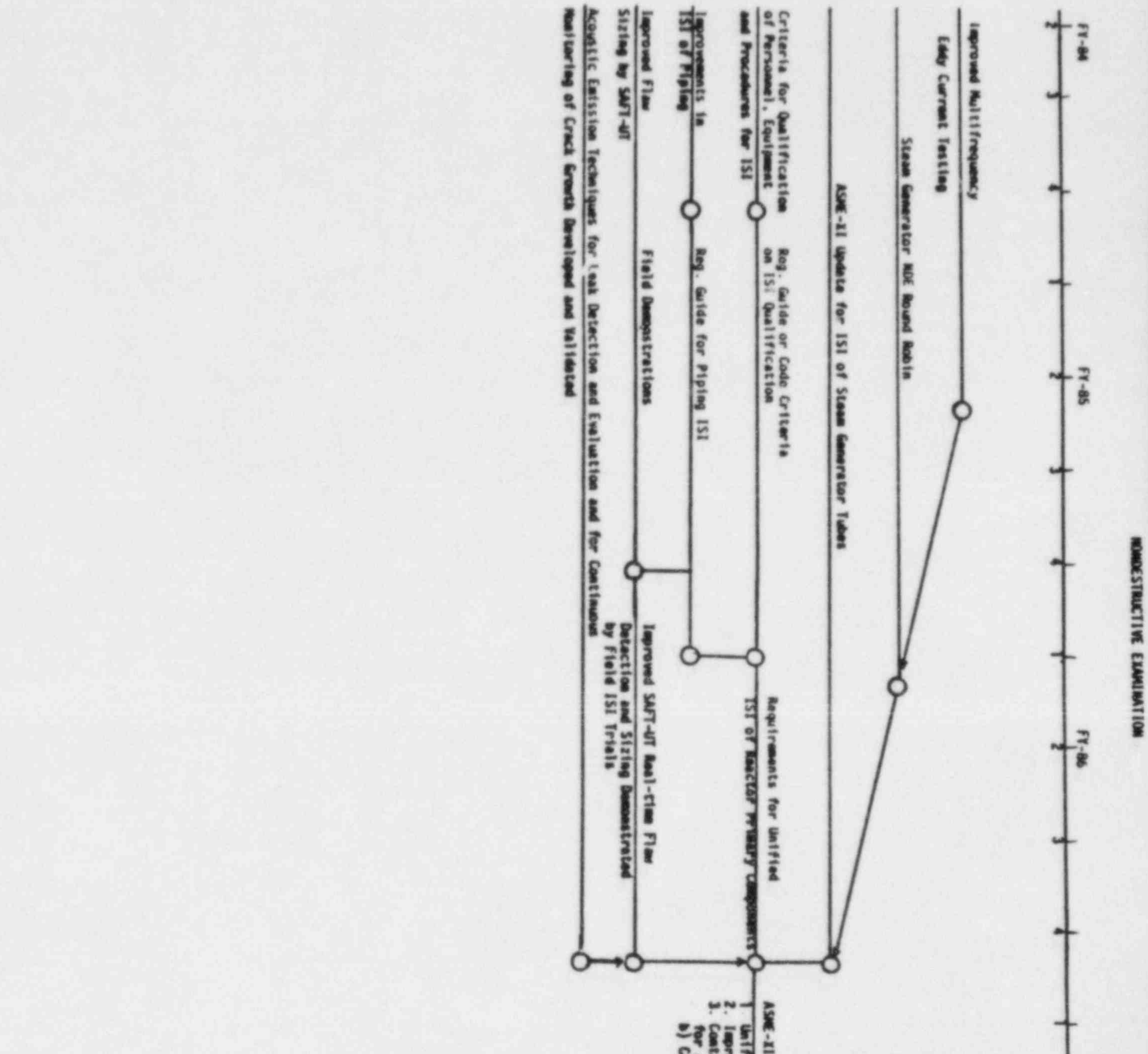

FIGURE 1
NONDESTRUCTIVE EXAMINATION

NRC FORM 335 U.S. NUCLEAR REGULATORY COMMISSION

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14. ABSTRACT (200 words or less)

This report describes the NRC research program in non-destructive evaluation. Projects are described for the development and evaluation of techniques for periodic inservice inspection of reactor components and for the continuous online monitoring of reactors. The areas of study described are ultrasonics, eddy current testing and acoustic emmission.

15a. KEY WORDS AND DOCUMENT ANALYSIS

Ultrasonics
Eddy Current
Acoustic Emmission
Reliability
Leak Detection
Continuous Monitoring
Nondestructive Evaluation
Inservice Inspection
Reliability of Inspection
Reactor Inspections
Leak Detection

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