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Vol. 2

Research Program Plan

Steam Generators

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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FOREWORD

This document presents a plan for research in Steam Generators 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.

Charles Z. Serpan, Jr., Chief
Materials Engineering Branch

Approved by:

Guy A. Arlotto, Director
Division of Engineering Technology
Office of Nuclear Regulatory Research

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Steam Generators

Introduction

Degradation of steam generators is caused by corrosion, stress-corrosion cracking, intergranular attack, denting, wastage, and thinning, all of which are long-term, time-related effects. The plan is that tube integrity must be determined both for leak and for burst, as caused by these degradation factors. The measured tube integrity must then be correlated back to the nondestructive examination signals so that accurate predictive methods can be established and validated, and tube inspection and tube plugging schemes can be established for use.

The secondary side of steam generators is sometimes cleaned with the result that large clearances are formed between tubes and supports. The lack of support can cause vibrations at operating conditions which can quickly damage or break tubes.

1.0 Definition of Issues and Needs

Valid data is needed on the integrity and remaining margin of safety of tubing having cracks, dents, wastage, and other forms of degradation, and the correlation of nondestructive examination signals with tube integrity. The rationale for this need is that steam generator tubes have been and are degrading in the form of cracks and general wastage, and the regulatory staff must know the potential remaining integrity in tubes having various degrees and types of degradation, cracks, etc., in order to set the requirements on tube plugging and additional inspection of tubes. If inspection "indications" translate to potential cracking and leakage, plugging or augmented inspections would be required; if indications are benign, the plant can be returned to service. Furthermore, the only way to predict tube integrity is from knowledge of the signal taken from inspection. Thus, signal evaluation errors must be reduced or eliminated, and signals must be carefully correlated to exact defect size, as well as to measurements of tube burst strength.

Evaluation of decontamination, cleaning operations, and repairs on tube integrity and on tube vibrations is needed. The rationale for this need is that processes may be proposed or are in use for decontaminating the primary side (to reduce man-rems), for cleaning the secondary side (to help reduce corrosion problems), and for repairs. The chemical or mechanical means employed can possibly damage the tubes, induce large residual stresses, or leave corrosive residues that can continue to attack the tubing, negate cleaning, and hasten future cracking. In addition, the increased clearance between supports and tubes as a result of chemical cleaning may induce additional vibration and cause unacceptable fretting and wear of the tubes during operation. These evaluations are needed so that informed decisions can be made on applications from utilities.

Valid data is needed to confirm and evaluate industry proposals for the influence of coolant chemistry and stress factors on corrosion and cracking in primary systems and in PWR secondaries. The rationale for this need is that an independent body of data is needed on the relationships among water chemistry, metallurgy, and stress factors, including geometric details, for the NRC to evaluate industry positions to mitigate corrosion.

2.0 Research Program Description

In order to answer the questions posed in the previous section, the Steam Generator Program has been organized with the three elements of Non-Destructive Examination; Mechanical Integrity Testing; and Corrosion, Cleaning and Decontamination. A description of the research activities in each of the elements is given below; these activities are then reflected in the summary schedule of research by fiscal year, which is in the following section of this plan. The primary steam generator research described in this program element is conducted as part of the Steam Generator Group Project (SGGP) at Battelle-Northwest Laboratories, Richland, Washington. Although NRC is the prime sponsor of this work, four other co-sponsors also each contribute 10% of the program's cost, over the five year period of the program. These sponsors are Italy, France, Japan, and EPRI.

2.1 Non-Destructive Examination

To improve detectability of defects, several new generation eddy current techniques such as multifrequency, multiparameter units and new probe designs are available. These units need to be tested in a manner that will allow NRC to qualify their use. In addition, NRC is planning to upgrade inspection criteria for steam generator ISI. In order to establish a statistically valid sampling of tubes as a basis of examination, the measurement error and confidence limits of the NDE inspection must be established. Only then can a statistical evaluation of in-service inspections provide valid information on tube degradation rate and defect distribution. A large percentage of the generator tubes will be examined by as many NDT systems as can be obtained. A direct validation of NDE results will then be conducted by metallographic sectioning of a statistically valid number of generator tubes. This will provide comparison data between instruments and techniques. It will also establish a large validated statistical basis on which to evaluate inspection requirements proposed for Regulatory Guides. Highly characterized sections of the generator will also be maintained for future NDT development work and validation testing. The identified NDE task areas include:

- Examine all available data tapes, analog records and service notebooks of past inservice inspections of the removed from service steam generator, to help establish a statistical program plan.
- Conduct baseline eddy current examinations of all accessible tubes in the steam generator. This examination will be conducted after the unplugging of all tubes where it has been determined, from the historical ISI data base, that potential useful nondestructive examination information can be obtained. The baseline examinations will determine possible changes in indications since the last ISI due to service or transport damage. They will also provide information for statistical determination of specimen matrices for later tasks.
- Conduct nondestructive examinations of the generator using all obtainable technologies by teams from PNL and from inspection agencies from the USA and abroad. This will create a comprehensive bank of comparable NDE data for the various techniques. Included would be the current code inspection method for reference and the new generation eddy current techniques (multifrequency, adaptive

learning, new probe designs) as well as other NDE techniques (ultrasonics, fiber optics, vibration devices, pressure tests, etc.).

- o Establish a small-scale tube bundle that will contain a collection of defects encompassing the type found in the degraded generator. This mock-up will be used in qualifying future NDT equipment, inspection procedures and repair methods.

Another programmatic area utilizing nondestructive techniques will concern the comprehensive examination of the secondary side of the generator. This effort will necessitate the cutting of several holes in the generator shell to facilitate sampling and detailed study by visual inspection, boroscopes, special miniaturized cameras and fiber optics. The object is to establish as comprehensive a picture as possible of crud/corrosion product distribution, condition of tube support plates, and location of defects which may or may not be detected by eddy current tests. Secondary side characterization efforts will continue in detail as sample removal provides additional access penetrations.

Analysis of location, extent and type of corrosion products can provide useful input to several questions. Defects in tubing can possibly be associated with specific corrosion processes. More knowledge about the processes and where they occur will lead to a better understanding of how to prevent further deterioration or eliminate the problem in new units. Detailed information of corrosion product location will also provide insight into the thermal hydraulic aspects of generator function. Hot spots and steam blanketing regions could be identified leading to design improvements.

2.2 Mechanical Property Testing

Mechanical testing of defected tubing specimens is conducted to determine remaining tube strength and to determine the effects of defects such as leaks on reactor operation. Included also is the testing necessary to determine tube integrity under the vibration resulting from loss of tube support material following chemical cleaning; they will be discussed under the Corrosion, Cleaning and Decontamination section, below.

Mechanical testing including burst and collapse testing under simulated operating and accident conditions will confirm the predictive models of tube failure developed in the NRC Steam Generator Tube Integrity Program. These models were based on tests conducted on mechanically and chemically simulated generator tubing defects. The predictive models are used to establish a basis for tube plugging criteria. Service defected tubing is necessary to prove that appropriate defect simulations were used in developing the predictive failure models and to improve or modify these models as necessary. Certain defect combinations may be present in the generator that could result in tube failure at pressures below the lower bound predicted from defect combinations examined in the Steam Generator Tube Integrity Program.

The association of leak rate data with various defect types and severity will provide guidance on allowable defect degradation for safe operation. An ability to provide length and depth information and to distinguish more clearly between defect types may allow use of different plugging criteria for different defects. These criteria will have to be based on the consequences of tube

failure with the various defects. Specimens will be removed from the generator that will allow separate leak rate determinations. These specimens will be either identified thru-wall defects, or defects that can be extended thru-wall.

Of particular interest will be tubes from inner-row U-bends, tubes with potential cracking under dented areas, and tubes showing leakage from the tube sheet crevice region. Specific tasks include the following:

- O Burst and collapse strengths will be determined for specimens having a range of service induced wastage and/or cracks.

- O Leak rate, primary side conditions to ambient air, will be determined on tubes with inservice thru-wall or extended to thru-wall defects. This will allow a correlation of typical leak rates to type and extent of defect.

- O Tubes will be metallographically sectioned to provide information on service induced thinning, cracks, and cracks possibly masked by the tube support plates and support plate corrosion products. This task will serve to validate accuracy and reliability of previous NDE tasks.

- O Examine U-bend sections to provide strain characterization. This information will show the extent of plastic deformation in different U-bend regions. The strain information will be valuable to determine areas subject to eventual failure, hence requiring closer monitoring. Correlation of the presence of inner diameter nucleated cracking with U-bend strain will be attempted. Information on the uniformity of strain characterization between numerous similar samples will establish if it is possible to generalize findings about U-bend condition in a unit from removal of a few specimens.

- O A statistical cross section of tubes will be destructively examined to provide data to correlate with eddy current information. Examination will be by sectioning and metallography.

- O Remove a section of the tube sheet for detailed destructive assay of the crevice region between tube and tube sheet. Correlate the destructive assay with prior NDT work and leak rate experiments, and postulated defect mechanisms.

2.3 Corrosion and Chemical Cleaning

This section is concerned with the analysis of corrosion products in steam generators and their implication on corrosion mechanisms and the possible correlation of coolant composition on the corrosion and integrity of materials and components on the primary and secondary side of steam generators.

Chemical cleaning processes must not seriously affect future serviceability and inspectability of steam generators. As input to formulating the regulatory guides on the acceptable extent of cleaning procedures, information must be developed on the effect of cleaning on future serviceability and safety. In order to provide for this, the effect of increased clearance between the support plate and tube on increased vibration and wear will be studied.

Further, the effect of chemical cleaning on eddy current signals will be evaluated. Specifc tasks include the following:

- o Conduct a comprehensive optical examination of the secondary side of the steam generator.

- o Analyze sludge profiles and chemical species present at different levels. This analysis should provide information of how operating chemistries affect sludge generation and could provide input for development of water chemistry control guidelines. Correlations between sludge profiles and areas of corrosive attack on tubing will be established.

- o Perform decontamination of the channel head and evaluate metal losses and determine effects on the structural integrity of weldments and stressed and unstressed primary and secondary system materials.

- o Using the present state of the generator condition, reconstruct thermal-hydraulic characteristics relevant to degradation patterns, e.g., steam blanketing regions compared to areas of chemical concentration and generator flow profiles.

- o Conduct flow tests of an experimental tube bundle to measure the vibrations and loads imposed on tubes from the increased clearance between tubes and support plates following chemical cleaning.

- o Perform wear tests to evaluate the integrity of tubes following chemical cleaning as a function of additonal service life.

- o Conduct pre- and post-cleaning experiment NDT on service degraded steam generator tubes to determine changes in tubing defect indications and the effects on NDT ability to characterize defects.

Research is now concluding on development of the relationship of coolant chemistry parameters, stresses, temperature and metallurgical factors that are responsible for initiation and propagation of stress corrosion cracking in Inconel 600 steam generator tubing. The coolant environments include pure water, AVT ingredients, and those species expected during intrusions, especially chlorides and sulfates. The tubes, representing as-received, annealed and cold-worked material conditions, are also subjected to strains representing those expected from denting and from residual stresses, as well as to strain rates that could be expected during accident sequences.

Repairs of steam generator tubing, primarily by sleeving and by welding are relatively new procedures. Such processes will be reviewed to determine if regulatory, confirmatory research is needed to verify the resulting integrity claimed. The retired-from-service steam generator provides an ideal test bed for tests to verify the adequacy of repairs. Included in the studies would be NDE of the tubes before and after repair, as well as detailed stress and other metallographic measurements made on repaired tubes which were then removed from the generator.

2.4 Basis for Selection of the Specified Test Program

Statistical interpretation of the large amounts of data to be provided by the SGGP will form the basis for much of the scientific analysis. Therefore, the earliest task in this area was the establishment of an information storage and retrieval system. Next a statistical analysis was to determine a valid sample of various defects necessary for confirmatory evaluation of NDT techniques. This analysis, coupled with historical ISI data, determined which plugged tubes in the generator were to be unplugged to provide a good defect sample. Tubes that had their plugs removed were examined by eddy current inspection during the baseline examinations to determine if the defect as characterized prior to plugging had changed. This input will serve to modify as necessary the statistical defect analysis for NDT validation studies.

The measurement error and confidence limits of any nondestructive technique allowed for ISIs must be determined. Also there is need to know what constitutes a statistically valid sample of steam generator tubes to examine. A concentration of defects in certain tubes or tube locations would certainly influence the choice of how many tubes from certain areas would constitute a statistically valid sample. Only with a statistically valid model of generator defects can a reliable analysis be made of the distribution of defects, the historical rate of degradation and the probability for unscheduled outage due to tube failure. This model is what is needed to improve and/or confirm the safety analysis associated with postulated reactor accidents. It is realized that a model based on defects in the Surry generator is not going to be universally applicable to all other nuclear steam generators. On the other hand, with such a defect model used wisely, selected aspects should be widely applicable.

An additional aspect of the statistics program will utilize the large amounts of eddy current data to be acquired in the nondestructive examination efforts as an input for research in advanced automated signal evaluation utilizing pattern recognition techniques.

3.0 Schedule

A network showing major milestones and tasks to be completed by fiscal year is enclosed as Table 1. A Milestone chart for the Surry SGGP Program, which contains all these same elements but in different tasks, is enclosed as Table 2.

4.0 Coordination

Coordination domestically and with foreign countries is relatively easy in this program because of the co-sponsorship agreements signed with three foreign countries and with EPRI. The EPRI connection is especially beneficial in this regard because it connects the program into all the work underway with the Steam Generator Owner's Groups. A feature of the SGGP management is bi-annual meetings at the laboratories of the program sponsors, wherein detailed presentations are made of the work underway in those countries, or in the case of EPRI, under their cognizance in the owners group.

5.0 Capabilities of NRC Staff and Contractors

NRC staff members who are program managers for this area are:

Joseph Muscara, PhD, Metallurgical Engineering, U. of Michigan, 1971

Dr. Muscara is the Program Manager for the contracts. He has been a program manager in AEC and in NRC for ten years; for one 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. He has been named as a member of the Pipe Crack Study Groups in NRC, and as a member of the EPRI Corrosion Advisory Group. He is currently manager of the Steam Generator Group Project and of the program on Tube Vibration Studies, both of which are at PNL.

Alfred Taboada, M.Met.Eng., Renssalaer Polytechnic Institute
B.Chem.Eng., Newark College of Engineering

He has worked in the NRC for the past 9 years as a Program Manager, Standards Development staff, and Operating Reactor Reviewer, and in the AEC for 9 years as a Senior Materials Engineer managing engineering materials development work for advance reactors. Prior to that, he worked at ORNL for 12 years as a Group Leader and Project Metallurgist in the design, development, fabrication, and NDE of the following Reactor Programs: ANP, MSRP, HFIR, HRP and SNAP-8. He is a member of the ASME B&PV Code Committee, Subgroup on Materials and ASTM E-10 Executive Committee and has been a member of the NRC Pipe Crack Study Groups and Piping Review Committee. He is currently managing the SCC of PWR Steam Generator Tubing Program at BNL, the Materials Engineering Program at ORNL, the RV Thermal Annealing Program at INEL and Dosimetry Programs at HEDL, NBS and ORNL.

The primary RES contractor for steam generator related work is Battelle Northwest Laboratories, at Richland, Washington. They were selected for this work because of their breadth of experience in steam generators from the NDE phases through corrosion to mechanical property testing. PNL also has access to a remote site for the placement of the containment building to house the retired-from-service generator; accessibility for transport of the generator was also an important factor. (By contrast, INEL has the remote site but is inaccessible for practical transport of the generator.)

Research on the stress corrosion cracking of tubing is conducted for RES at Brookhaven National Laboratory. The capabilities for this work at BNL reside in the Metallurgy Division which has much consultation service to NRR over the years in the area of corrosion and steam generator tube service performance. Within this division, there reside personnel who were formerly associated with the Navy program on SCC in steam generator tubing; there is also a good relationship with the INCO research activities located in nearby upstate New York, all of which contribute to an excellent capability for conducting this work.

6.0 Closure of Technical Issues

The research validation of technical issues in this area will be completed in the FY 1986-87 time frame as a result of the completion of the Surry Steam Generator Group Project. The key issue to be closed is that of validation of NDE methods for detection and characterization of cracks, flaws, dents, etc., in the tubes. Currently, a great deal of variation exists in the methods and regulatory decisions on the acceptance of the methods and their results from inspections at plants wherein degradation of tubes is occurring. A parallel issue that will be closed, is that of the integrity of cracked and otherwise degraded tubing when subjected to operating or accident loadings. For this issue to be successfully resolved, it is necessary for the previous one on accuracy of NDE methods to be firmly in place because predictions of tube integrity are based on the correlation between NDE signals and test-to-failure of tubes having a wide range of cracks, flaws and defects. Such a background of information will allow the staff to evaluate licensee applications for inspection, and for disposition of results leading to a return to service. Further, an optimum inservice inspection plan will give the number and location of tubes to be inspected and the frequency of inspections to resolve the issue of the proper minimum inservice inspection requirements to avoid inservice tubing failure which could result in unacceptable loss of coolant inventory.

TABLE 1: STEAM GENERATORS

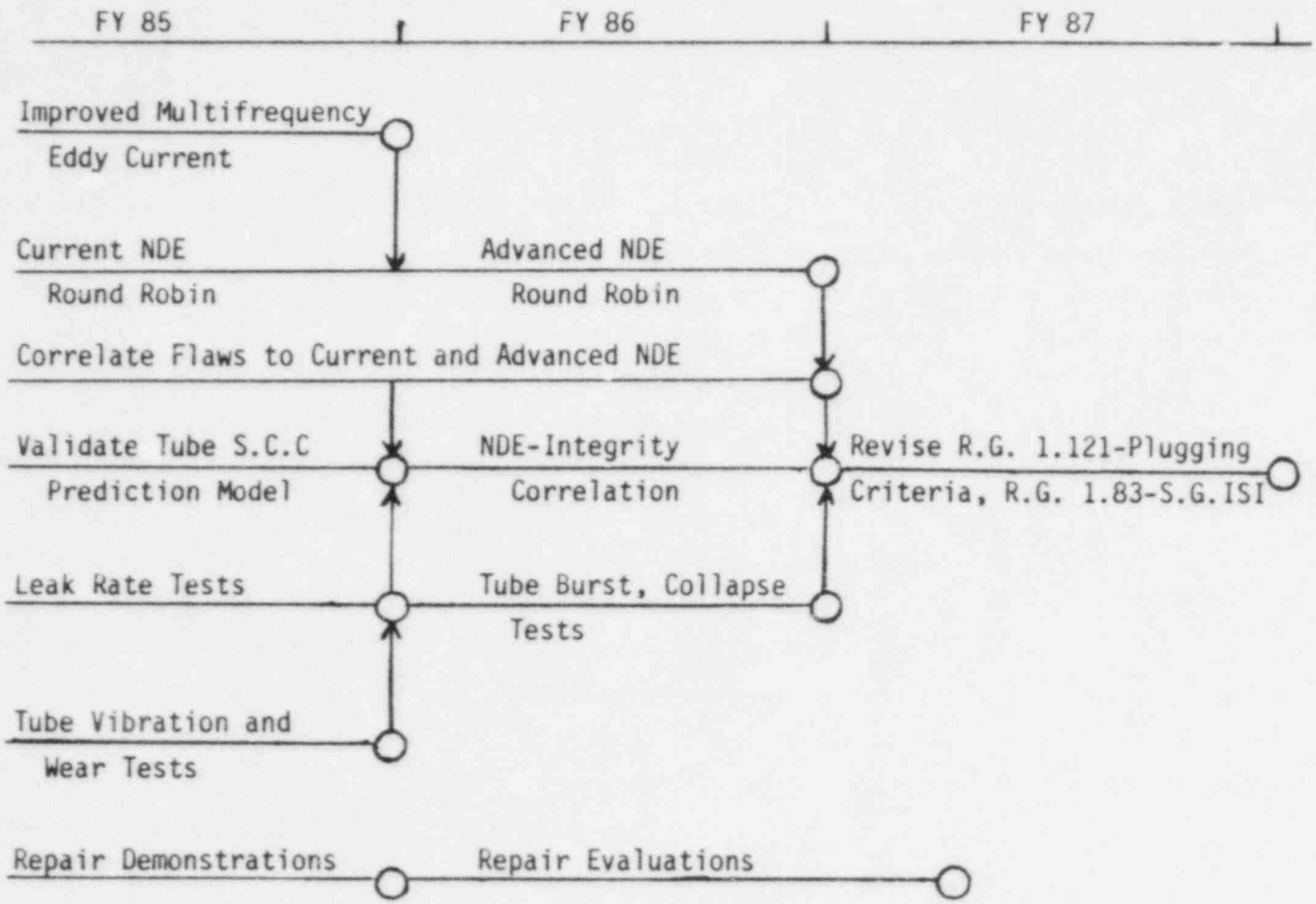
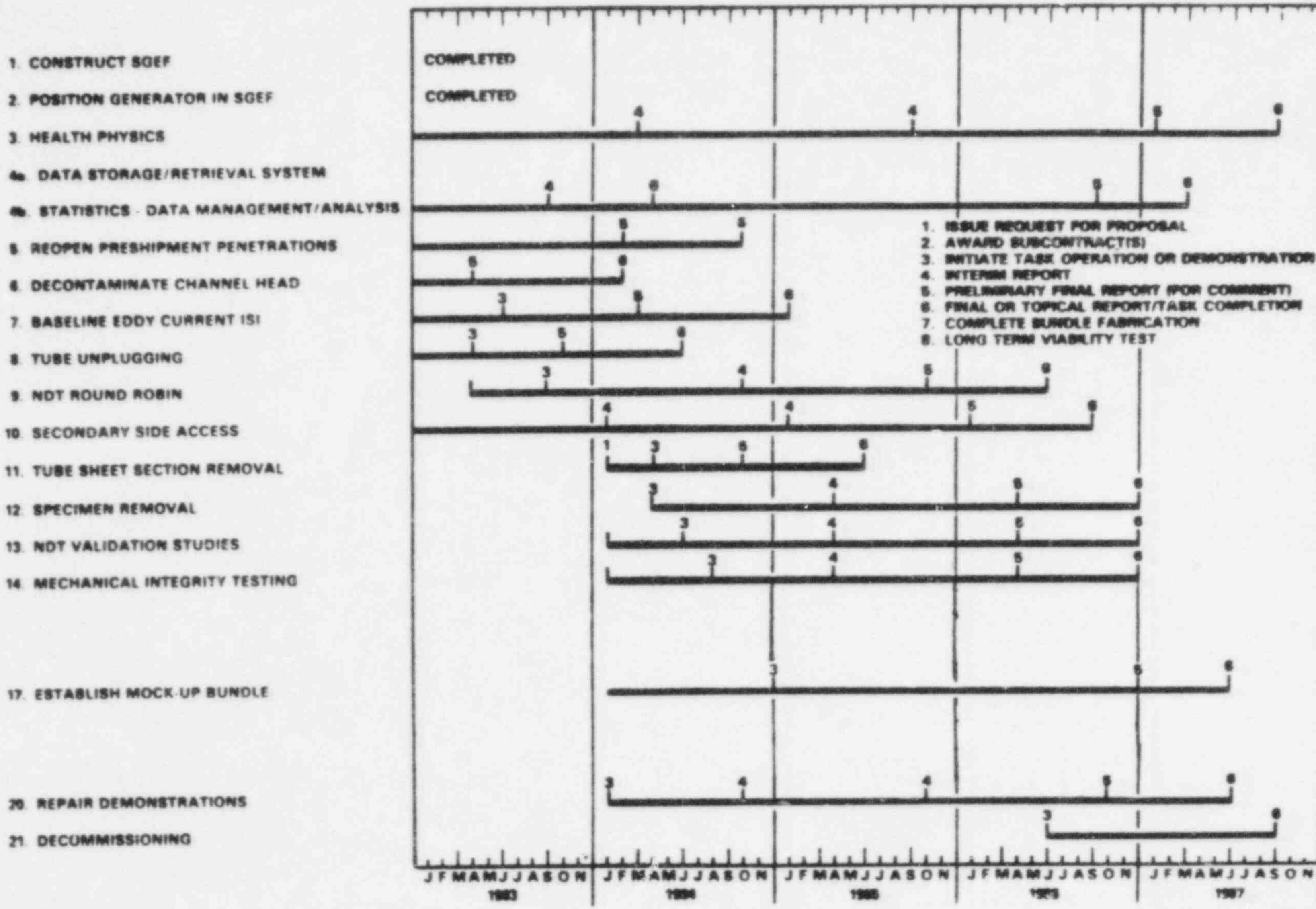


TABLE 2

MILESTONE CHART
SURRY STEAM GENERATOR GROUP PROJECT



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14. ABSTRACT (200 words or less)

This report describes the NRC's research program related to steam generators. Mainly it discusses the program for evaluation of a removed-from-service degraded steam generator. Also discussed are projects to evaluate the vibration and wear that could result from chemical cleaning and NDE tasks for inservice inspection of steam generators.

15a. KEY WORDS AND DOCUMENT ANALYSIS

Steam Generators
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Degradation
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Vibration
Wear
Tube Integrity
Secondary NDE Examination
Plugging Criteria
Inspection Criteria
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