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PWR Primary-to-Secondary Leak Guidelines

Prepared by
PWR Primary-to-Secondary Leak Guidelines Committee

REPORT SUMMARY

PWR Primary-to-Secondary Leak Guidelines

A standardized program for managing primary-to-secondary steam generator tube leakage will help minimize the likelihood of tube ruptures. These guidelines contain recommended operating actions in response to primary-to-secondary leakage of varying magnitude, appropriate methods of calculating leakage rates from secondary system sample points, and methods of monitoring leakage once detected. The guidelines should serve as a pattern for development of a station-specific program for meeting the challenge of primary-to-secondary leakage.

INTEREST CATEGORIES

Steam generators

KEYWORDS

PWR
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BACKGROUND The nuclear industry considers the frequency of steam generator tube rupture events in the United States unacceptable. Thus, it was decided the industry could benefit from guidelines that present standardized station actions to initiate prompt plant shutdown before rapidly propagating leaks can progress to tube rupture. As with other EPRI-sponsored guidelines, it is recommended that station personnel use the guidelines as a template for development of station-specific programs.

OBJECTIVE To develop industrywide guidelines on primary-to-secondary steam generator tube leakage to help reduce the probability of tube rupture.

APPROACH A committee of industry experts collaborated in reviewing the available data on primary-to-secondary steam generator tube leakage and plant design as well as operating features available to monitor leakage. Based on this information, the committee developed recommended operational actions, including a description of four plant primary-to-secondary leak rate conditions to ensure proper monitoring/response. These recommendations have been designed to minimize the probability of tube rupture events and should help utilities manage small primary-to-secondary leakage.

RESULTS These guidelines follow the format of other industry guides and address four operating conditions with respect to primary-to-secondary steam generator tube leakage. For two of these conditions, the guidelines contain recommended actions that can result in rapid, controlled plant shutdown if primary-to-secondary leakage displays evidence of rapid propagation.

The guidelines also include sections on leak rate calculations and monitoring methods. The leak rate calculation section presents standardized approaches for calculating primary-to-secondary leakage rates from various secondary system grab sample locations. The monitoring methods section discusses how to use the leak rate determinations to calibrate station radiation monitors for continuous monitoring. In specific, the guidelines focus on properly using existing monitors rather than attempting to specify additional monitoring hardware.

The fundamental goal of these guidelines is to present a complete, technically justified program that can be used to develop station-specific operating programs.

The committee believes that a station program developed in accordance with these guidelines should help plant personnel manage small leaks and thus reduce the likelihood of tube ruptures.

EPRI PERSPECTIVE This document provides a series of industrywide recommendations for station management of primary-to-secondary steam generator tube leakage. Included is a detailed description of leak characteristics that justify rapid, controlled plant shutdown to minimize the likelihood of tube rupture. The guidelines also provide technical information on standardized approaches for calculation of primary-to-secondary leak rates using a variety of secondary system radiochemical data. As in the case of other EPRI-sponsored guidelines, these recommendations will be reviewed after implementation by the industry. If warranted, a revised guidelines document will be issued based on these evaluations.

PROJECT
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ABSTRACT

Primary-to-secondary leakage can result from mechanisms that propagate slowly or rapidly. The frequency of tube ruptures from rapidly propagating leaks has been considered unacceptable by the industry. An effective station program for monitoring primary-to-secondary leakage is essential to ensure necessary operational actions are taken before a rapidly propagating leak results in a tube rupture. An industry wide approach for development of standardized primary-to-secondary leak actions has been prepared by the industry and presented in these *PWR Primary-to-Secondary Leak Guidelines.* These guidelines contain recommended operating actions in response to primary-to-secondary leakage of varying magnitudes, appropriate methods of calculating leak rates from various secondary system sample points, and various methods of monitoring leakage once detected. These guidelines should serve as a pattern for development of a station-specific program for primary-to-secondary leakage.

EPRI FOREWORD

Under the auspices of EPRI, the electric power industry has developed operating guidelines for various station activities, including secondary cycle chemistry control and steam generator inspection. Industry wide guidelines have been useful in helping utilities develop and implement station-specific programs. Primary-to-secondary leakage has been experienced by many U.S. PWRs; some have experienced a tube rupture due to rapidly propagating leakage mechanisms, since primary-to-secondary leakage can result from mechanisms that propagate slowly or rapidly.

Tube ruptures can significantly challenge reactor safety systems and a controlled shutdown prior to rupture is the preferred response to rapidly propagating primary-to-secondary leakage. An effective station program for monitoring primary-to-secondary leakage is essential to ensure necessary operational actions are taken before a rapidly propagating leak results in a tube rupture. These *PWR Primary-to-Secondary Leak Guidelines* contain recommended operating actions in response to primary-to-secondary leakage of varying magnitudes, appropriate methods of calculating leak rates from various secondary system locations, and various methods of monitoring leakage once detected. Additional supporting information is presented in Appendices.

These guidelines represent a major step in developing a proactive operational program to ensure proper response to primary-to-secondary leakage. It should serve as a pattern for development of a station-specific program for primary-to-secondary leakage, with exceptions taken based on evaluation by station personnel.

R. C. Thomas
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INTRODUCTION AND MANAGEMENT RESPONSIBILITIES

1.1 BACKGROUND

Over the last 20 years, steam generator tubes in PWRs have experienced various types of degradation from both the primary and secondary sides of the tubes. Corrosion mechanisms of concern include wastage, pitting, secondary side stress corrosion cracking (ODSCC), intergranular attack (IGA) and primary water stress corrosion cracking (PWSCC). Mechanical damage from fretting, fatigue and loose parts has also resulted in tube degradation.

Utility inspection and diagnostic operational programs are designed to detect incipient conditions before steam generator tube corrosion or mechanical damage leads to through-wall failure. In most cases, tube degradation mechanisms that result in primary-to-secondary leakage propagate slowly and lead to operational difficulties, but do not diminish any safety margins. Some damage mechanisms can progress rapidly and can result in a tube rupture, resulting in significant secondary system contamination and potential actuation of reactor safety systems.

Technical Specifications for most US plants dictate the frequency and sample size of nondestructive examinations (NDE) of the tubes to ensure their integrity as a primary system boundary. An industry-developed approach, presented in the *PWR Steam Generator Examination Guidelines - Rev. 3*, establishes a recommended practice for NDE that reflects utility operating experience. Tubes are repaired or removed from service when inspection data indicate that their integrity is no longer assured.

Despite preventive efforts by utility personnel, primary-to-secondary leakage still occurs. Therefore, each utility should develop a plant-specific plan to manage such leakage to ensure that the likelihood of propagation to tube rupture is minimized.

1.2 GUIDELINES OBJECTIVES

These guidelines address management considerations, monitoring methods and equipment, leak rate calculations, operational response and data evaluation. The document presents industry experience with and recommendations for operation of pressurized water reactors (PWRs) with small (less than Technical Specifications limits) steam generator tube leakage.

Utility personnel should use this document to ensure their program provides adequate details, so operators can respond to changes in steam generator tube leakage in a safe, reliable and cost-effective manner. Implementation of these guidelines will improve management of small leaks and reduce the potential of steam generator tube ruptures.

These guidelines present an industry-developed approach for calculating and monitoring primary-to-secondary leak rates. Recognizing the variations in plant designs and resources, deviation from these guidelines is acceptable following plant-specific evaluations. A plant-specific primary-to-secondary leak monitoring program should be developed based on these recommendations, retaining the philosophy presented herein.

1.3 PRIMARY-TO-SECONDARY LEAK PROGRAM CONSIDERATIONS

This section lists and discusses the considerations which are common to most utilities, including the elements of organizations which are needed to carry out the primary-to-secondary leak monitoring program effectively. Since utility organizations and resources vary significantly, actions are identified without specifying responsibility for completing them. Utility-specific implementation policies and procedures should assign the responsibilities to specific positions within the organization. One major element of these guidelines is the need for every level of management to understand the importance of the actions presented in Section 2 and the potential impact on, and benefits to, the utility company.

An effective primary-to-secondary leakage monitoring program should designate operational responses for each of the following scenarios:

- Low level and/or slowly increasing primary-to-secondary leakage;
- Rapidly increasing primary-to-secondary leakage; and
- Steam generator tube rupture (no leak before break).

1.3.1 Program

An important ingredient of a successful plan for primary-to-secondary leak monitoring program is a set of procedures which implement these guidelines. The written procedures which carry out the program should:

a. State the need for the program;

b. Highlight corporate management support for the program; and

c. Assign responsibility for:

- Preparation and approval of procedures to implement the program,
- Surveillance, analysis, and data evaluation for the monitoring program,
- Establishing priorities for equipment/instrument maintenance,
- Program review functions,
- Corrective actions prescribed by the program,
- Ensure continued operation with small leaks is consistent with the recommendations contained in these guidelines and with plant Technical Specifications, and
- Conducting walk-throughs or drills to test effectiveness of program response and coordination.

d. Establish the authority to:

- Carry out procedures,
- Implement corrective actions,
- Initiate requests for modifications to plant systems as required to meet the program needs,
- Complete economic analyses,
- Resolve disagreements, and
- Initiate plant shutdown if limits are exceeded.

Procedures implementing this program should, when taken together, contain the level of detail necessary for personnel at all levels to understand and carry out their responsibilities.

1.4 TRAINING

A program for periodic (continuing) training of personnel involved with the program commitments should be established. Some indoctrination in the basics of the program should be considered for all employees who, by virtue of their job responsibilities, may identify and need to respond to symptoms of primary-to-secondary leakage.

Training programs should be designed for the level and qualifications of personnel being trained. The following elements should be included:

- A clear statement of the primary-to-secondary leak policy, including clarification of the impact of this policy upon the various responsibility areas,
- Identification of the relationship between primary-to-secondary leakage monitoring and commitments to primary system integrity and off-site dose calculations,
- Techniques for identifying leak mechanisms based on secondary cycle radioactivity, and
- The interaction/communication required between station personnel to ensure the commitments of the program are satisfied.

1.5 PROCEDURE IMPLEMENTATION (EXAMPLE)

This subsection is provided to give one example of how a specific utility might implement the administrative portion of the guidelines.

1.5.1 Definitions

The following definitions will be used in the discussion:

a. Corporate Management: Utility management responsible for nuclear plant power production but with offices which may be remote from the plant site. This includes personnel having line responsibilities to the chief operating officer of the utility.

b. Station Management and Operating Staff: On-site management responsible for overall station performance and plant personnel responsible for the day-to-day operation of a nuclear unit.

c. Plant Chemistry Staff: Plant personnel responsible for implementing the day-to-day chemistry control program, including on-line monitoring, and for the accuracy and timeliness of the analytical results obtained in the plant's laboratory.

d. Plant Maintenance Staff: Plant personnel responsible for repair and modification of plant equipment, especially those responsible for calibration and repair of radiation monitoring system (RMS) equipment. This definition also includes those personnel responsible for prioritizing and planning of station maintenance.

e. Engineering/Technical Support: Plant personnel responsible for evaluation of steam generator and balance-of-plant material condition, plant inspection programs and component life estimations.

f. Training Staff: Training personnel responsible for ensuring pertinent individuals are qualified to implement appropriate plant responses to primary-to-secondary leakage.

1.5.2 Individual Group Responsibilities

The specific responsibilities of the various groups used in this example for implementation of primary-to-secondary leak guidelines are as follows:

a. Corporate Management

Corporate management is responsible for establishing the policies and providing the resources necessary to support and enforce the program. The roles of corporate management may include:

- Participating in establishing plant-specific responses to primary-to-secondary leakage and

- Maintaining oversight to identify and assess needed changes and providing direction as needed to improve the program.

b. Station Management and Operating Staff

The responsibility of station management and the plant operating staff is to establish leak rate monitoring and response procedures and to assure the appropriate corrective actions are taken based upon the program. Station management and the plant operating staff should be aware of the following:

- Plant-specific steam generator degradation mechanisms,

- The importance of minimizing the occurrence of steam generator tube ruptures and of plant operating responses to reduce the likelihood of tube ruptures, and

- The impact of primary-to-secondary leakage on other operational concerns, such as operating/shutdown radiation fields, contamination of the secondary system, radioactive waste generation, off-site radiological consequences and waste disposal costs.

c. Plant Chemistry Staff

The plant chemistry staff is responsible for implementation of the chemistry control program. One component of the chemistry program will be to perform radiochemical sampling and analysis that will be used to quantify the leak rates, though subsequent leak trending will be performed via the RMS monitors and supplemented by grab samples. Interpretation of radiochemical data may also provide additional information regarding the leak mechanism.

To fulfill this obligation, the plant chemistry staff should have adequate training, personnel, experience, and process monitoring and laboratory instrumentation to obtain data required. Chemistry personnel should:

- Understand the goals and requirements of the program,
- Understand the plant-specific degradation mechanisms,
- Perform timely data review and evaluations to quantify leak rates, and
- Perform thorough assessments to characterize leakage.

d. Plant Maintenance Staff

Plant maintenance personnel are responsible for one of the most important parts of the program implementation, i.e., to assure timely and effective maintenance and repair of plant equipment and instrumentation. The plant maintenance staff should be aware of the following:

- The impact of out-of-service or out-of-calibration radiation monitors on leak monitoring program and
- The need for timely correction of monitor and instrument problems.

e. Engineering/Technical Support

Engineering/Technical Support staff should ensure that qualified personnel are assigned the responsibility for predicting and verifying the material condition of steam generator tubing. These individuals should be aware of the following:

- History of steam generator tube degradation phenomena and rates of degradation;
- Relevant industry experience on tube degradation;

- Reliability and accuracy of steam generator inspection data;

- Regulatory commitments relative to steam generator tube plugging; and

- Bases for assignment of Action Levels for primary-to-secondary leak rates.

f. Training Staff

The Training staff should ensure that personnel on shifts are qualified to implement the plant primary-to-secondary leak program. These individuals should be aware of the following:

- Technical basis and definitions of plant primary-to-secondary leak actions;

- Program requirements for monitoring primary-to-secondary leak rates;

- Individual group responsibilities for primary-to-secondary leak program implementation.

1.6 GENERAL GUIDELINES FOR DEVELOPMENT OF A PRIMARY-TO-SECONDARY LEAK ADMINISTRATIVE PROGRAM

The following general guidelines are offered to show an acceptable approach for development of an administrative program for management of primary-to-secondary leakage. It is emphasized that these general guidelines are to improve continued operation when small primary-to-secondary leakage is being experienced. These should not be confused with the recommended operational actions presented in Section 2.

1. Perform an evaluation of the plant regulatory effluent requirements for instantaneous concentrations (10CFR20 requirements) and the off-site accumulative activity/dose for all pathways. This evaluation should incorporate station ALARA goals to maintain off-site doses well below those required by 10CFR20.

2. Evaluate the present plant holdup and processing capabilities (conventional waste systems) for contaminated secondary system water and demineralizer resins, if applicable, for various primary-to-secondary leak scenarios to assess the plant's ability to meet the regulatory effluent requirements. These scenarios should include various leak sizes (small, slowly propagating/steady leaks up to a tube rupture) for various RCS activity source terms.

3. Consider administrative leak rate limits to minimize the likelihood of exceeding effluent radioactivity release rates and plant contamination and to provide prompt identification of leakage that requires compensatory actions.

4. Develop an action plan to upgrade the waste system holdup and/or treatment capabilities, as necessary, to meet the plant effluent requirements and management goals. Develop an administrative program to accommodate the (new) plant holdup and treatment capabilities, and to meet the effluent requirements.

1.7 SUMMARY

This document presents a generic program for managing primary-to-secondary leakage. Plant-specific programs should consider plant design, materials, steam generator corrosion experience, management structure, and operating philosophy and may deviate from the specific recommendations contained herein. However, all plant-specific requirements should be defined in accordance with the philosophy of these recommendations. This program should help plant personnel manage small leaks and will reduce the likelihood of tube ruptures. To meet this goal, an effective corporate policy and monitoring program are essential and should be based on the following:

- Clear management support for operating procedures designed to ensure that primary-to-secondary leakage does not progress to tube ruptures, as provided in Section 2;

- Adequate staff, equipment and organizational resources to implement an effective leak monitoring program, using a combination of radiation monitors and laboratory radiochemical analyses;

- A sound leak rate monitoring program that incorporates existing plant equipment/radiation monitors and proceduralized actions;

- Management agreement at all levels, prior to implementing the program, on the actions to be taken in response to primary-to-secondary leakage and the methods for resolution of situations not covered by the guidelines; and

- Continuing review of plant and industry experience and research results to revise the program as warranted.

2

OPERATING GUIDELINES FOR PRIMARY-TO-SECONDARY LEAKAGE

2.1 PURPOSE

The recommendations contained in this section are designed so that appropriate actions can be taken early enough to preclude a tube leak from propagating to rupture. Consistent with other industry-developed guidelines, the recommendations are presented in a series of defined operating conditions that reflect increasing primary-to-secondary leakage. Accordingly, the recommended plant actions become more severe when leak rates accelerate. Immediate plant shutdown is recommended if leakage trends suggest that a leak is rapidly propagating.

This section presents the operating conditions that define plant action levels. It then presents the recommended station actions that coincide with these action levels. The recommendations contained in this section and supported by other sections describe a program that is capable of responding to rapidly propagating steam generator tube defects without relying on time-consuming chemistry grab samples. Following discussions of the actions, the technical basis for selection of the Action Level 2 implementing criteria is presented. It is recognized that integration of these recommendations may vary in detail from site to site, due to differences in design, operation, etc. It is important, however, that the philosophy contained in this section be retained in all station programs.

Section 2.4 addresses other components of a primary-to-secondary leak program. These items should be considered for implementation in advance of primary-to-secondary leakage.

2.2 ACTION LEVEL CRITERIA AND RECOMMENDATIONS

Four operating conditions including two Action Levels have been defined for initiation of station actions based on primary-to-secondary leakage rates and action thresholds. These are:

- **Normal Operation**: The plant condition in which no primary-to-secondary leakage is detected in routine surveillance.

- **Increased Monitoring:** This describes the condition in which leakage has been detected and quantified but is not in a range that can be accurately monitored by most radiation monitors.

- **Action Level 1:** Action Level 1 defines a plant condition in which leakage has increased to a condition that can and should be frequently monitored by the RMS with periodic benchmarking by laboratory analyses.

- **Action Level 2:** This action level describes a condition that suggests the leak is propagating rapidly and the unit should be shut down.

The Action Levels presented are considered to be a significant line of defense against tube ruptures. The criteria presented have been evaluated against some of the tube ruptures previously experienced by the industry. These evaluations suggest that plant shutdown would have been initiated, based on the Action Level recommendations, prior to tube rupture.

Normal Operation

Definition: Normal Operation describes the period of operation when normal radiochemical grab sampling and process radiation monitors indicate no primary-to-secondary leakage. Due to the lack of analytical certainty at very low radiochemical concentrations, it is assumed that the leak rate is ≤5 gpd.

Recommended Actions: Since this operating condition suggests that no primary-to-secondary leakage is present, no specific actions are recommended. However, it is recommended that station procedures contain a prescribed grab sample and radiation monitor surveillance program which is designed to detect and quantify leakage.

Increased Monitoring:

Definition: Increased Monitoring describes the plant condition where primary-to-secondary leakage has been quantified to be >5 gpd but <30 gpd.

Recommended Actions: The presence of detectable primary-to-secondary leakage suggests that an active degradation phenomenon is occurring. As noted in Appendix A, some scenarios that result in secondary side activity (e.g., a leaking tube plug) may not portray a rapidly propagating phenomena. The following recommendations are suggested if leak rates fall within the Increased Monitoring criteria:

a. Identify leaking steam generator and requantify leakage if possible.

b. Elevate necessary repair of out-of-service monitoring equipment to highest (non-emergency) station priority.

c. Establish more frequent radiochemical grab sample monitoring of secondary cycle. Use the results to recalibrate radiation monitors.

d. Increase operator awareness of radiation monitor readings and lower monitor set points to provide prompt indication of increased leakage. Section 4 presents a discussion of individual radiation monitors and their response to primary-to-secondary leak scenarios. Station procedures should direct Operators to the preferred radiation monitors to meet Action Level 1 monitoring requirements.

e. Routinely trend leak rates from radiochemical data and report trends to plant management.

Action Level 1:

Definition: Action Level 1 is defined as primary-to-secondary leakage ≥30 gpd and ≤150 gpd with a rate of increase of ≤60 gpd/hr. This condition requires increased attention and monitoring to ensure the leak does not propagate rapidly to tube rupture without operator action. During this condition, it is important that confidence of station personnel in process radiation monitor data is high so Action Level 2 actions will be implemented if monitor data so indicate. In other words, the station primary-to-secondary leakage monitoring program must be capable of responding to rapidly propagating steam generator tube defects without reliance on time-consuming chemistry grab samples.

Recommended Actions:

a. Increase grab sample monitoring to identify leaking steam generator and to requantify primary-to-secondary leak rates. Monitoring of radiation monitors should be increased to once every 15 minutes. Leak rates should be obtained directly from radiation monitors and converted to gpd from CPM-to-gpd conversion tables (or some equivalent, plant-specific mechanism). Once leak rate is stable for 1 hour (≤10% increase during a one-hour period), monitoring of radiation monitor can be reduced to once every 2 hours. Once leak rates are stable for 24 hours, monitoring frequencies can return to those required by plant procedures for the Increased Monitoring condition.

b. Evaluate secondary contamination potential and contain as required. It should be noted that plants which were operated for lengthy periods of time with primary-to-secondary leakage in Action Level 1 range found

secondary system contamination so significant that outage related activities were highly impacted.

c. Initiate review of applicable procedures to be utilized by Operations, Chemistry, Radiation Controls, etc. in case leak rate conditions change. Items for review include but are not limited to:

- Transition criteria from steam generator leak to steam generator tube rupture,
- Plant shutdown/cooldown with a steam generator leak, and
- Requirements for posting radiological hazard signs (e.g., radiation areas, contaminated areas, etc.) where not normally required (e.g., turbine building).

d. Once stable, reset off gas alert/alarm setpoint to 30 gpd above existing baseline reading to permit detection of rapidly increasing leak rate. Other radiation monitor setpoints (e.g., blowdown, N-16) should also be reset if these are used by the station for leak rate trending.

Action Level 2:

Definition: Action Level 2 is entered when primary-to-secondary leakage has increased by ≥60 gpd in ≤1 hour <u>OR</u> is >150 gpd in any steam generator. To avoid an unnecessary plant shutdown, Action Level 2 leakage should be <u>qualitatively</u> confirmed prior to declaration. Leakage is <u>confirmed</u> when two independent radiation monitors (typical monitor pairs like off gas/SGBD monitors, off-gas/N-16 monitors, or N-16/SGBD monitors) trend in the same direction. Confirmation time should be kept to a minimum. Precise duplication of leak rates, as indicated by the monitors, is not important. Since OTSGs do not have blowdown, primary-to-secondary leak monitoring programs for these steam generators may require grab samples or portable survey/radiation monitoring for confirmation. If grab samples are used, shutdown should be commenced prior to laboratory radiochemical results. If results do not confirm Action Level 2 criteria, shutdown can be suspended until the leak rates can be ascertained. Chemistry personnel should evaluate grab sample response times to determine their most effective confirmation method(s).

Recommended Actions:

a. If leakage exceeds 150 gpd in any one steam generator, then commence shutdown (i.e., be in Mode 3 within 6 hours); <u>OR</u> if the accelerated leak rate (i.e., ≥60 gpd/hr) has been confirmed by another qualitative method, then commence prompt and controlled plant shutdown as quickly as safe plant operation permits (i.e., initiate emergency boration to be in Mode 3 in about 1 hour - See Technical Basis Section 2.3.2).

Ensure the other recommendations established below are also performed.

b. Attempt to identify leaking steam generator and quantify primary-to-secondary leakage. Monitoring of radiation monitors by plant operators should be increased to once every 15 minutes (or use computer/monitor alarm settings as discussed below). Leak rates should be obtained directly from radiation monitors and converted to gpd from CPM-to-gpd conversion tables (or some equivalent, plant-specific mechanism). Station personnel may wish to develop a process computer program which performs CPM-to-gpd conversations based on entered correlation factors. A process computer subroutine can also be used to calculate the instantaneous rate of change from radiation monitors.

c. Contain systems in secondary plant to minimize spread of contamination such as:
   - Turbine building sump effluent paths,
   - Hotwell spill to Condensate Storage Tanks, and
   - Condenser off gas system realigned through HEPA/Charcoal filter system if available

d. Review plant resources and request additional resources if needed, such as:
   - Operations staffing
   - Chemistry staffing
   - Radiological Control staffing
   - Water processing capability
   - Makeup water capability
   - Secondary contamination and containment

e. Once shutdown, isolate leaking steam generator to minimize spread of contamination to secondary plant. Initiate plant cooldown and depressurization to maintain control of leaking steam generator level. It is recommended that station personnel refer to NSSS vendor recommendations for operational details regarding steam generator isolation during cooldown.

f. Utilize other application sections of site procedures as necessary to complete plant shutdown/cooldown.

2.3 TECHNICAL BASIS FOR ACTION LEVELS

Normal Operation, Increased Monitoring and Action Level 1 have been assigned leak rate criteria that initiate the actions recommended. It should be noted that these criteria have been assigned to promote heightened attention to ensure leaks do not accelerate to tube rupture without plant actions. These criteria are

consistent with grab sample and RMS sensitivity, subject to the restrictions noted in Sections 3 and 4. Utility personnel may wish to modify these criteria to ensure they are consistent with plant-specific conditions.

The recommended actions to be taken if Action Level 2 criteria are exceeded include immediate plant shutdown. Given the significance of this action and given the fact that plant-specific implementation of the guidelines' philosophy is encouraged, the technical bases for selection of these criteria are defined in this section.

Action Level 2 can be entered if either of two parameters are exceeded: (1) If a total leak rate of >150 gpd in any steam generator is reached OR (2) If primary-to-secondary leakage has increased by ≥60 gpd in ≤1 hour. The following subsections address these two individual conditions.

2.3.1 Leakage in Any One Steam Generator of >150 gpd

The primary-to-secondary maximum leak rate of 150 gpd was derived from the Steam Generator Degradation Specific Management (SGDSM) submittal to the Nuclear Regulatory Commission. The maximum leak rate of 150 gpd per steam generator has been established for normal operation. This leakage rate provides added assurance against tube rupture at normal and faulted conditions and, together with limiting the number of degraded tubes that can remain in service, helps to ensure that the dose contribution from tube leakage will be limited to less than 10CFR100 dose limits for postulated faulted events. This limit is also used to provide additional assurance that cracks that might grow at a much greater rate than expected are detected by leakage.

General Design Criteria (GDC) 14 requires the reactor coolant pressure boundary to be designed, fabricated, erected and tested so as to have an extremely low probability of abnormal leakage, of rapidly propagating to failure and of gross rupture. GDC 15 requires the reactor coolant system and associated auxiliary, control and protection systems to be designed with sufficient margin to assure the design margins of the reactor coolant pressure boundary are maintained during any condition of normal operation, including anticipated operating occurrences.

It should be emphasized that the 150 gpd maximum leak rate does not necessarily indicate that a leak is rapidly propagating. It may simply indicate the presence of one or more slowly propagating tube leak mechanisms. It is suggested, therefore, that the recommended maximum leak rate per steam generator be reviewed against other site-specific information, such as secondary side contamination levels, proximity to next refueling outage, etc. to ensure the resulting value is appropriate.

2.3.2 Leak Rate Increase of ≥60 gpd in ≤1 Hour

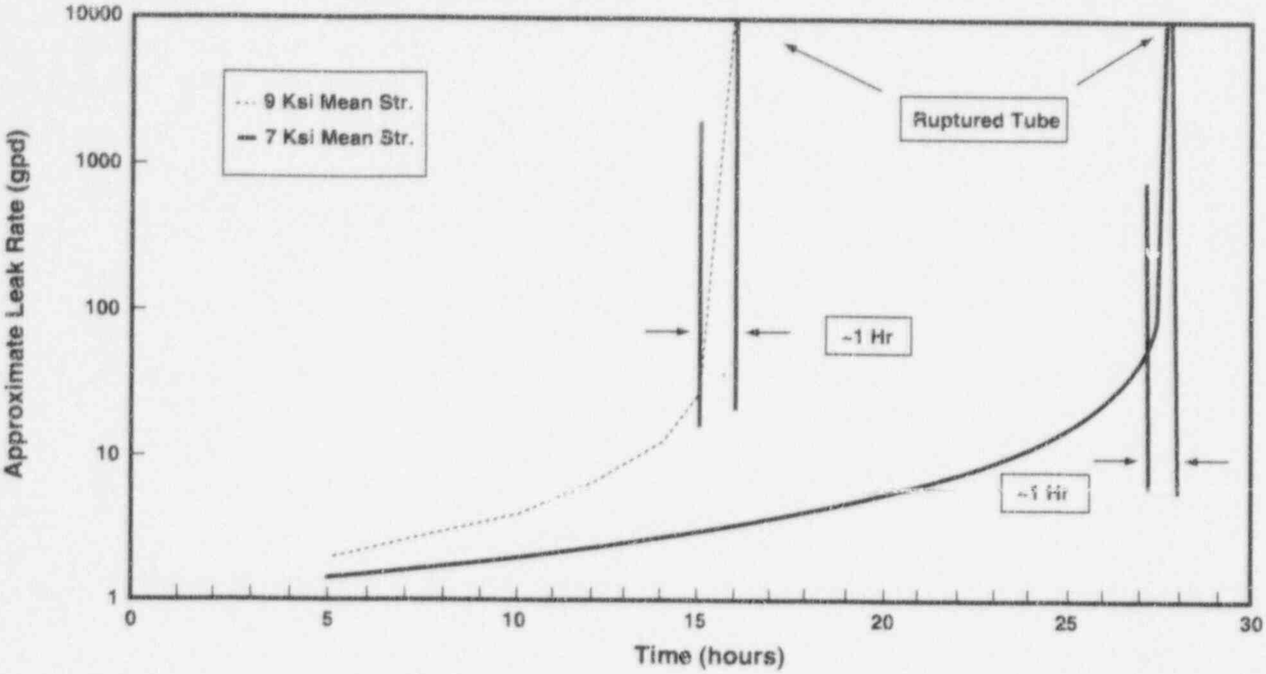
A review of industry data available from NRC Information Notice 91-43 was performed to develop a steam generator leak rate criteria that would reduce the probability that small but rapidly increasing steam generator leak rates would develop into tube ruptures. Data from tube ruptures at Indian Point 3, Three Mile Island 1, Maine Yankee, and Mihama 2 were compared with the characteristic curve provided for the North Anna event in NRC IE Bulletin 88-02. It was noted that all of these subsequent events proceeded at a pace much faster than the North Anna event, providing less time for aggressive corrective measures. In spite of these escalating leak rates, the operators at TMI and Maine Yankee were commended for their action in reducing power/commencing rapid shutdown before their procedural and Technical Specification action limits were reached. The data indicated that the Maine Yankee operators took the most conservative actions based on the rate of rise of their leak rate. They began a slow shutdown when the leak rate was about 60 gpd and went into a rapid shutdown when it was about 250 gpd. The leak rate was escalating at about 60 gpd/hr when these actions were taken.

Figure 2-1 shows the trends of two industry tube rupture events due to fatigue cracking. Despite uncertainties in the precision of the data, note that each event shows an exponentially increasing leak rate and the rupture occurs within an hour after the rate of change of leak rate reaches about 60 gpd/hr. Initiating a prompt and controlled plant shutdown as quickly as safe plant operation permits (i.e., initiate emergency boration to be in Mode 3 in about 1 hour) when this leak rate growth is reached will reduce the potential for a tube rupture or the consequences should one occur.

The leak rate criteria recommended in this section should be applied automatically (i.e., prior to management notification) when confirmed by a second qualitative method (e.g., steam generator blowdown radiation monitors) that the leak rate has been exceeded. Rapid operator response to this trend is key to minimizing the consequences of a tube rupture; the confirmation time should be kept to a minimum.

The Action Level 2 recommendations were reviewed against the recommendations of US NSSS vendors. They are also consistent with or conservative to the current NSSS vendor recommendations. The recommended actions are also more conservative than required by station Technical Specifications, as they consider appropriate responses to rapidly propagating leaks. Thus, the recommendations should be aggressive in reducing the probability of a tube rupture event without significantly increasing the risk of unnecessary plant transients caused by rapid shutdown actions for events that would not lead to a tube rupture.

Figure 2-1: Trends of Industry Tube Rupture Events Resulting from Fatigue Cracking



2.4 OTHER PRIMARY-TO-SECONDARY PROGRAMMATIC COMPONENTS

2.4.1 Contingency Plan For Control And Processing of Large Volumes of Contaminated Water

Plants should have a prescribed plan for the control and processing of large volumes of contaminated water in the secondary side of the plant. Provisions should be made to confine the contaminated water in the condenser hotwell. Capabilities to transfer excess water to another storage area once hotwell level is exceeded should be established. Storage areas where contaminated water can be drained should be considered in a prescribed sequence. Contingency plans for processing large volumes of contaminated water should be established.

2.4.2 Plant Simulator Training

Operators should be trained on monitoring tube leakage and what actions should be taken in response to an increasing tube leakage trend.

Simulator training scenarios should be representative of industry experience and shall include one model wherein all decisions are based on radiation monitoring responses and sampling results, if necessary, to demonstrate usage and compliance with these guidelines. Simulator scenarios should be varied to include different radiation monitor responses (from different radiation monitors) which initiate the recommended actions contained in these guidelines. Reference 9 of Section 4 provides simulator scenario overviews that could be of assistance in this effort.

2.4.3 Other Recovery Activities

There are many station activities that result from primary-to-secondary leakage. These include radiological consequences resulting from BOP contamination, rapid outage scheduling resulting from unplanned shutdown, radwaste processing of large water volumes, etc. Recommendations concerning these activities are out of the scope of this guideline and will not be covered. However, the importance of contingency plans for these activities should not be overlooked by station management.

3

LEAK RATE CALCULATIONS

3.1 INTRODUCTION

Recommended operational responses to primary-to-secondary leakage discussed in Section 2 require an accurate assessment of the leak rates. This section identifies how to calculate leak rates based on isotopic analyses of various secondary system samples. The information contained in this section quantifies some of the mathematical "unknowns" required for leak rate calculation. These can be used if plant-specific values have not yet been determined.

The calculations provided by this section are based on specific assumptions and all leak rates are converted to room temperatures. Care should be exercised by each utility to ensure the plant-specific conditions are bounded by these assumptions or make appropriate modifications to the calculations as identified.

3.2 Leak Rate Calculations Via Condenser Off Gas Analysis

3.2.1 Introduction

Dissolved radiogases in the RCS pass into the secondary side of a steam generator when a primary-to-secondary leak exists. These radiogases are quickly transported out of the steam generators with the main steam and are removed from the condensing steam by the condenser air removal system. Quantification of the primary-to-secondary leak can be made by comparing the radiogas activity removed through the condenser off gas system (neglecting the solubility of the radiogases in condensate) to the radiogas in the reactor coolant. This method of leak rate quantification provides a total primary-to-secondary leak rate and does not identify the leaking steam generator(s).

The condenser off gas analysis for leak rate determination has several major advantages over the other methods that make it the preferred method under most (but not all) conditions. Some advantages of this method are as follows:

- It is universally applicable to both RSGs and OTSGs;
- It utilizes noble gas isotopes which makes it unnecessary to factor partition effects or other chemical/physical reactions; and

- This method provides an instantaneous leak rate determination because equilibrium considerations are unnecessary, since it is assumed the noble gases are 100% removed by the condenser air removal system.

3.2.2 *The Basic Relationship*

The basic relationship can be developed for leak rate measurements based on the condenser off gas analysis as follows:

$$LR = \frac{A_g F_g C}{A_{RCS}} \qquad \text{(eq. 3-1)}$$

Where:

LR	=	Primary to Secondary leak rate (gpd)
A_g	=	Activity of noble gas radionuclide in the condenser off gas sample (μCi/cc)
A_{RCS}	=	Activity of noble gas isotope in the reactor coolant (μCi/g).
F_g	=	Flow rate of the condenser off gas (SCFM).
C	=	1.08×10^4, the conversion factor from SCFM to gpd

This calculation can be used for an instantaneous leak rate determination in accordance with following assumptions:

1. No significant condenser off gas sample transport decay effects;

2. No significant mother/daughter decay relationship effects;

3. RCS noble gas concentrations remain constant, i.e. no power transients, RCS degassing, etc.;

4. All of the noble gas radionuclides are instantaneously transported into the steam flow upon entering the steam generator via the leak;

5. All of the noble gas radionuclides are removed via the condenser off gas system so that the entire noble gas isotope inventory enters the secondary system at the steam generator and exits at the condenser off gas;

6. The condenser off gas flow is accurately measured and accurately sampled; and

7. There are no significant changes in steam or off gas flows.

3.2.3 *Radionuclide Selections*

The noble gases are the isotopes of choice due to their inert nature. This allows a simple determination of the leak rate. The isotopes of choice are as follows:

Isotope	Half-Life
Xe-133	5.25 days
Xe-135	9.1 hours
Kr-85m	4.5 hours
Kr-88	2.84 hours
Ar-41	1.8 hours
Kr-87	1.3 hours
Xe-135m	15.6 min

Due to its long half life and relative abundance Xe-133 (or Xe-135) provides the most reliable leak rate measurement of the possible isotopes under most circumstances. The other isotopes can be used but care must be taken to minimize the effect of the shorter half lives.

3.2.4 *Limitations*

1. The condenser off gas method is essentially a gross (i.e., not isotope specific) determination. The accuracy and precision of the determination is dependent on the accuracy of the condenser off gas flow rate measurements.

2. The condenser off gas method measures the total primary-to-secondary leakage and does not identify the leaking steam generator.

3. In addition to the factors presented in Section 4, leak rate sensitivity is also affected by such factors as the total condenser air inleakage (since this dilutes the concentration of the radioactive species), sample size, RCS noble gas concentrations, etc.

3.2.5 *Precautions*

The precision and accuracy of the condenser off gas method is predominantly affected by the off gas flow rate measurement. Unless accurate mass flow measurements are made, the inaccuracies of the off gas flow rate measurement can mask most other sources of error. Comparison to more accurate and precise methods, such as tritium, may be useful to characterize a specific leak scenario. Usually a reasonably adequate correlation can be determined. If the leak rates do not correlate adequately, station personnel may consider the precautions offered and the additional corrections which follow:

1. The radionuclide transport time to the grab sample should be evaluated. It may be necessary to correct for short-lived radionuclides, such as Ar-41 and Xe-135m. A correction methodology for this is presented in Appendix B.

2. Parent/daughter relationship effect of iodine decay to xenon can result in error in the leak rate determination. This is especially significant for the RCS sample since this will result in under-estimating the leak which is non-

conservative. Analyzing the RCS samples as soon as possible after sampling, helps to minimize this effect of decay in the sample. Another effect is the addition of xenon in the off gas from iodine decay in the steam generator bulk water. Under some circumstances, this can result in a 10-20% over-estimation of the leak for Xe-135 and a lesser extent for Xe-133. However, this is a conservative error and may not be significant under most circumstances. This is also discussed in Appendix B.

3. Steady state conditions between the secondary noble gas concentrations and the primary noble gas concentrations are necessary for an accurate leak rate determination. Changes in the RCS noble gas activity can result from power transients, changes in fuel integrity, RCS degassing operations, etc. These effects can be minimized by sampling the RCS and off gas at approximately the same time. A maximum differential of 15 minutes is recommended.

4. Differences in off gas and RCS sample gas volume parameters can negatively affect the accuracy. Care can be taken to analyze the samples at the approximately same temperature and pressure to minimize the effect. If this is not possible, then these parameters can be measured and corrected using the gas laws.

5. A substantial difference in the temperature and pressure conditions of the off gas activity sample and the measurement of the off gas flow rate can also introduce error. Care should be taken to ensure the off gas activity sample and the off gas flow rate measurement are taken at approximately the same conditions.

6. Air inleakage (off gas flow) can affect the sensitivity of the method if the value is large. This can be minimized by a good air inleakage program. If a rotameter is used to measure the flow rate, it is recommended to take an average of the high-low fluctuations in readings. Some utilities sparge the condenser with nitrogen to aid in dissolved oxygen removal. If a condition exists where greater sensitivity is needed, the nitrogen sparge can be temporarily suspended during the off gas sampling to avoid this dilution. However, it should be noted that this may substantially increase the delay time.

7. Accurate, calibrated mass flow measuring equipment will minimize errors in leak rate calculations.

3.3 Leak Rate Calculations Via Blowdown Analysis

3.3.1 Introduction

Radionuclides from the reactor coolant system enter the steam generator bulk water when a primary-to-secondary leak exists. Due to their low solubility,

radiogases are quickly transported out of the steam generator bulk water into the steam. Dissolved solids and very low concentrations of radiogases remain in the steam generator bulk water. These radionuclides can be quantified in the steam generator blowdown and used to estimate primary-to-secondary leak rate and determine which steam generator is leaking. However, due to hideout, steam-water partitioning, blowdown rate, secondary system lineups, sampling uncertainties, etc., this method has the most uncertainty and should be used with caution. It is suitable for gross leak rate estimates, trending, or identifying which steam generator is leaking. See Figure 3-1 for a comparison of the accuracy of the steam generator blowdown vs. the off gas method for a primary-to-secondary leak estimated to be 450 gpd which occurred at San Onofre on March 1, 1988. Also, note in the figure how calculated leak rates for the blowdown varied depending on isotope half-life.

3.3.2 The Basic Relationship

The basic relationship can be developed for leak rate estimates based on steam generator blowdown analysis as follows:

$$LR = \left[\frac{A_{SG}}{A_{RCS}} \left(B + \lambda V_{SG} \right) \right] 1440 \qquad \text{(eq. 3-2)}$$

Where:

LR	=	Leak rate (gpd)
A_{SG}	=	Activity of isotope in steam generator blowdown (μCi/g)
A_{RCS}	=	Activity of isotope in RCS (μCi/g)
B	=	Steam generator blowdown flow corrected to room temperature (gpm)
λ	=	0.693 divided by the half life of the isotope (minutes)
V_{SG}	=	Volume of the water in steam generator corrected to room temperature (gal)
1440	=	Conversion factor to convert from gpm to gpd

This relationship can be used to estimate the primary-to-secondary leak rate in accordance with the following assumptions:

1. No significant sample transport time.

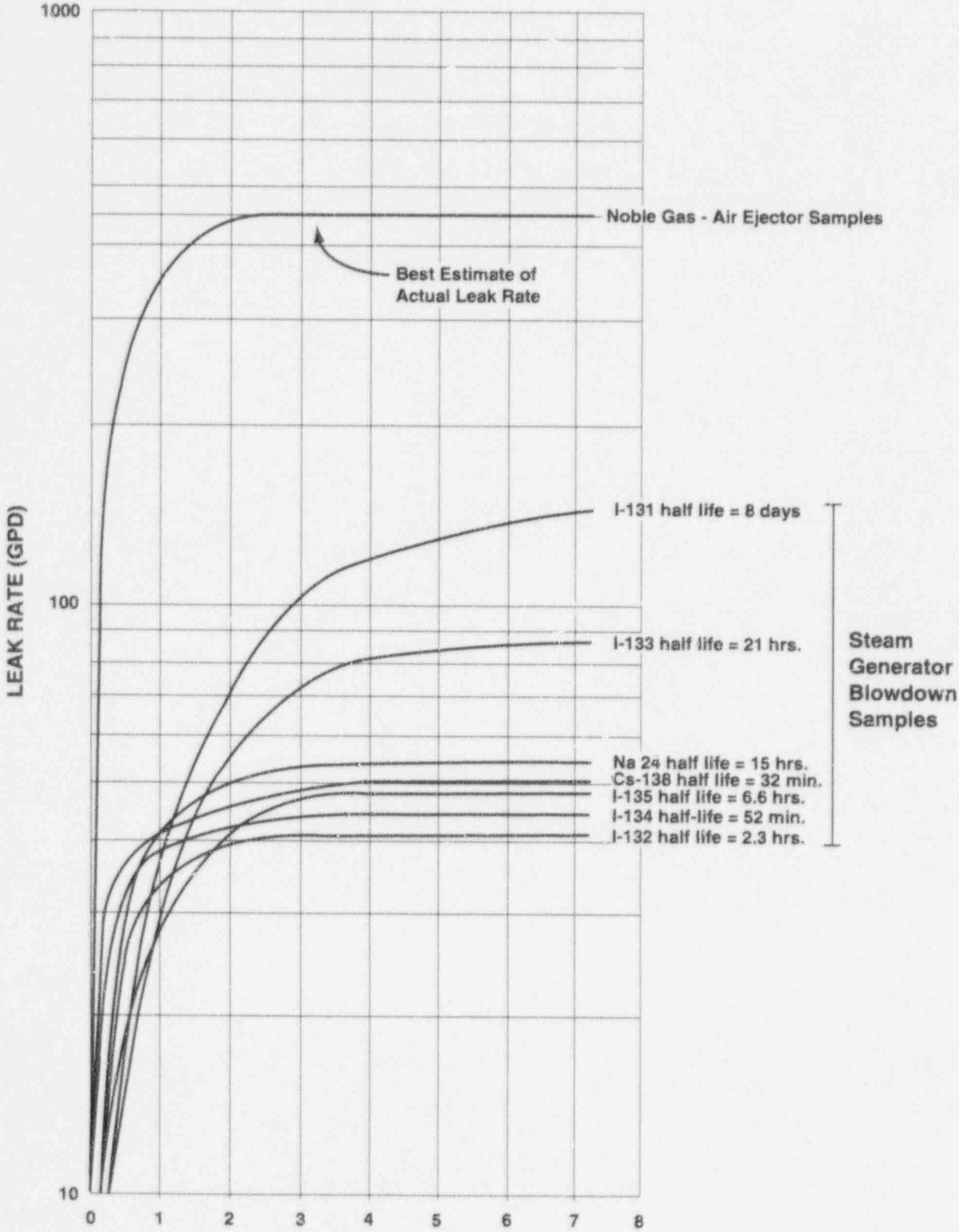
2. Effects of carryover and partitioning are neglected.

3. The system is at steady state conditions, i.e. power level, blowdown rate, purification rate, etc.

4. The density of the steam generator liquid is 1 g/cc.

5. The radionuclide of interest is at equilibrium in the secondary system.

Figure 3-1: Variation of Leak Rate Calculations with Radionuclide



6. No significant hideout or decay of the radionuclide of interest.

7. The steam generator blowdown sample is representative of completely mixed bulk water.

8. The isotope concentration in the RCS is constant.

3.3.3 Radionuclide Selections

In general, any radionuclide that can be accurately identified in the steam generator blowdown and the RCS can be used to estimate the primary-to-secondary leak rate. However, for simplicity and relative accuracy, radionuclides are chosen according to the following criteria:

1. Should have a moderately short half-life to allow separation from old leaks and to reduce time to equilibrium.

2. Should be water soluble and have a very small steam-water partitioning factor (not readily transported out of the steam generator in the steam).

3. Should be relatively abundant in the RCS to provide sensitivity and be easily measurable by γ spectroscopy.

The isotopes generally chosen for quantification are as follows:

Isotope	Half-Life
I-131	8 days
I-132	2.3 hours
I-133	21 hours
I-134	53 minutes
I-135	6.6 hours
Na-24	15 hours
Cs-138	32 minutes

3.3.4 Limitations

1. The steam generator blowdown method provides only an estimate of the leak rate (accuracy is limited). It is suitable for trending purposes and may be used for identification of which steam generator is leaking.

2. In addition to the factors listed in Section 4, sensitivity is affected by the steam generator blowdown rate.

3.3.5 Precautions

1. Many factors can affect the error associated with the steam generator blowdown method such as steam carry-over of the radionuclide, partitioning effects, hideout/return, chemical reactions, leak location (in sludge pile), etc. For example, iodine readily reacts with sludge metals such as copper and sodium is subject to hideout. However, it may be possible in some circumstances to obtain a leak rate which correlates with the more reliable methods, taking these factors into consideration and making the applicable corrections.

2. The steam generator blowdown sample itself may not truly reflect blowdown, due to deposition of solids within the sample line. Each plant should evaluate the specific design for transport time and determination of a representative sample of the steam generator bulk water.

3. A steady state condition of the secondary system is essential to avoid gross errors in the estimate of the leak rate. A change in steam generator blowdown rate, for example, can introduce error into the result until a new steady state is achieved.

4. Inaccuracies in the measurement of the necessary flow rates (blowdown, main steam, feedwater, etc.) introduce error.

5. Inaccuracies in the steam generator liquid volume also introduces error. This error is minimized by maximizing steam generator blowdown rate.

3.3.6 Additional Calculation Methods

Corrections to the basic relationship in 3.3.2 are necessary to account for deviations from the assumptions listed. Appendices C and D provide additional information and derivations for the mathematical methods used in the steam generator blowdown leak rate determinations. From these derivations, methods are offered to correct or account for some of the conditions where the assumptions in 3.3.2 are not met. This information may be helpful in developing plant-specific methodology for estimating the primary-to-secondary leak rate via the steam generator blowdown analysis.

3.4 Leak Rate Calculations Via Tritium

3.4.1 Introduction

Tritium can be detected in PWR secondary systems as a result of diffusion of tritiated dissolved hydrogen through steam generator tubing. Tritium can also enters the secondary system during primary-to-secondary leak events. Due to the low concentrations produced by diffusion, all of the tritium can be assumed to be

in the form of tritiated water. This presents several advantages in determining a leak rate with tritium over other methods as listed below:

- Do not have to consider ion exchange effects when considering equilibrium,
- Do not have to consider hideout and hideout return effects,
- Do not have to account for liquid/steam partitioning,
- Do not have to account for concentration effects in the blowdown,
- Sampling errors are minimized,
- Is universally applicable to OTSGs and RSGs,
- The radiochemistry analysis is specific for tritium, precise, and accurate, and
- The half-life of tritium is long (12.3 years), therefore decay considerations are unnecessary. This makes it especially advantageous for monitoring small leaks.

Because of these factors, the tritium method is recommended to validate the condenser off gas and steam generator blowdown methods when circumstances permit. This assumes that the RCS tritium is at the necessary concentration, the situation is not urgent as during a rapidly propagating leak, and the tritium is not at equilibrium in the secondary system, which requires accurate makeup rates.

The major disadvantages of the tritium method is an effect of the long half-life. This makes system leakage the only practical removal mechanism, requiring a lengthy time period, relative to most other isotopes used for leak rate determinations, to reach equilibrium. This reduces the sensitivity of the analysis to a new leak in the initial stages.

The following sections deal with calculating the leak rate prior to equilibrium (3.4.2.1 and 3.4.2.2) and after equilibrium is achieved (3.4.2.3) in the secondary system. The leak rate prior to equilibrium can be determined, under some circumstances, in a reliable manner with knowledge only of the secondary system volume. If the required conditions do not exist, it is necessary to accurately know the makeup rate. Because of the half-life of tritium, the time to equilibrium may be 2-3 weeks with a maximum makeup rate of 50 gpm. Plant designs with higher makeup rates (blowdown is directed to waste) of approximately 100 gpm or greater may achieve equilibrium in as little as 3 days. After equilibrium, the tritium concentration in the secondary system becomes a function of the makeup rate, which must be accurately known in order to calculate a reliable leak rate.

3.4.2 The Tritium Calculations

3.4.2.1 Tritium Calculation Prior to Equilibrium:

$$\text{Leak rate (gpd)} = \frac{\left(A_{s2} - \left(A_{s1} e^{-\left(\frac{Mu}{V_s}+\lambda\right)t}\right)\right) Mu}{A_p\left(1 - e^{-\left(\frac{Mu}{V_s}+\lambda\right)t}\right)} \qquad \text{(eq. 3-3)}$$

Where:

A_{s2}	=	Activity in the secondary coolant at T_2 (μCi/g)
A_{s1}	=	Activity in the secondary coolant at T_1 (μCi/g)
T_1	=	Time of First Sample
T_2	=	Time of Second Sample
V_s	=	Secondary system mass expressed as equivalent room-temperature volume (gal.)
t	=	(T_2 - T_1) = the difference of the sample times (days)
A_p	=	Activity of tritium in the primary coolant (μCi/g)
Mu	=	Makeup rate to secondary system (gpd)
λ	=	Decay constant for tritium

And the following assumptions are valid:

- The RCS tritium is at a concentration high enough to permit secondary leak measurement and is constant.
- The mass of the secondary system is accurately known.
- The secondary makeup rate is relatively constant.

3.4.2.2 Tritium Calculation Simplified for Specific Conditions (Prior to Equilibrium)

$$Leakrate(gpd) = \frac{V_s(A_{s2} - A_{s1})}{A_p(T_2 - T_1)} \qquad \text{(eq. 3-4)}$$

Where the following assumptions are valid:

- The RCS tritium is at a concentration high enough to permit secondary leak measurement and is constant.
- The mass of the secondary system is accurately known.
- The leak is of the magnitude that the increase from A_{s1} to A_{s2} is large during a relatively short time period, approximately 24 hours.
- The leak is constant from T_1 to T_2.
- The secondary makeup rate is relatively constant and small compared to system volume during the time period.

3.4.3 *Tritium Calculation After Equilibrium*

$$\text{Leak rate (gpd)} = \frac{A_s Mu}{A_p} \quad \text{(eq. 3-5)}$$

Where:

A_s = H-3 Activity in the secondary coolant (μCi/g)
A_p = H-3 Activity in the primary coolant (μCi/g)
Mu = Makeup rate to secondary system (gpd)

And the following assumptions are valid:

- The RCS tritium is at the necessary concentration.
- The secondary makeup rate is relatively constant.

3.4.4 *Limitations*

1. Tritium provides a total system leak rate and cannot be used to determine which steam generator is leaking. However, after the leaking steam generator is isolated, tritium samples from the steam generator can be used to provide an accurate leak rate of the leaking steam generator using the equation from 3.4.2.2 and substituting the steam generator volume for the secondary system volume.

2. Sensitivity of the method depends on the following interrelated factors:

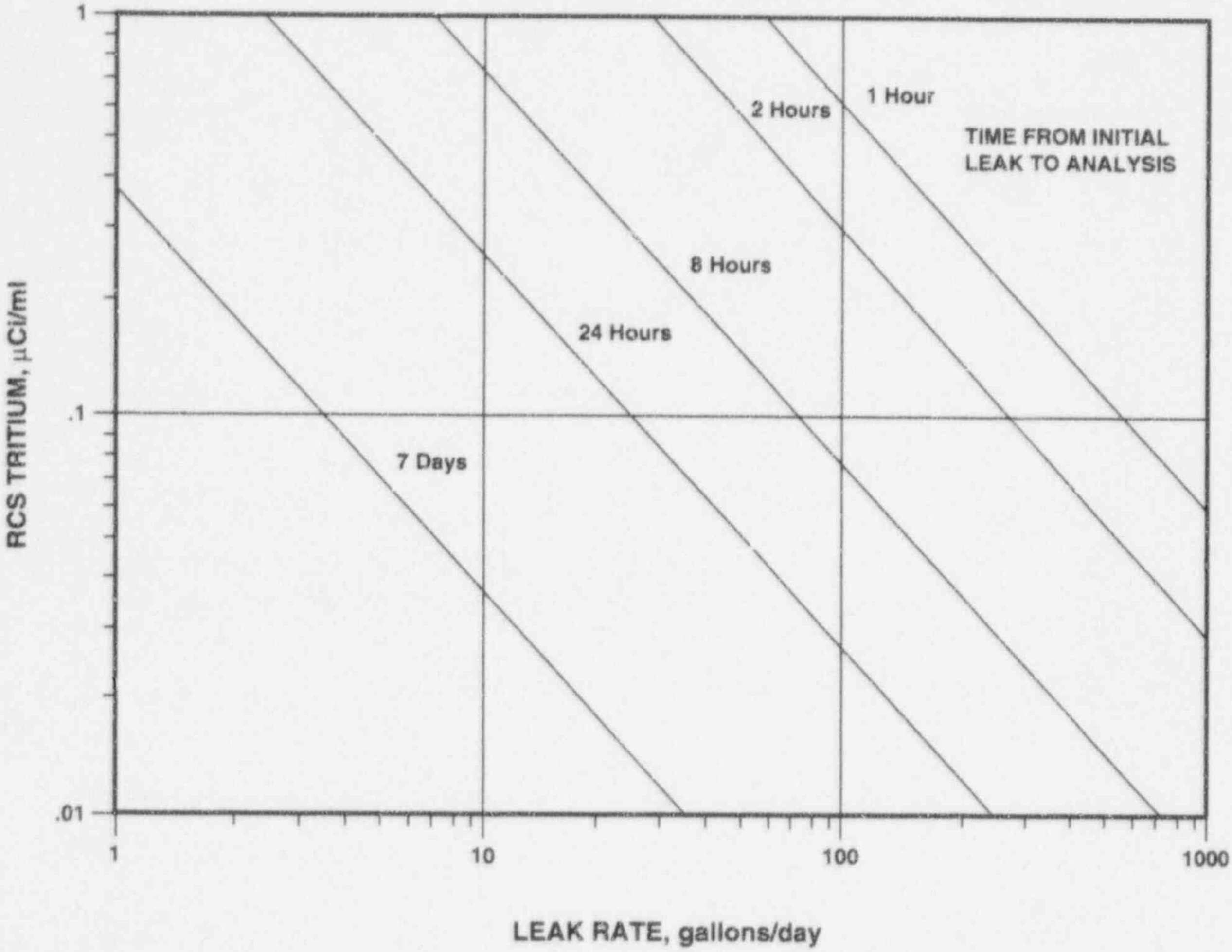
   - Tritium concentration in the RCS. This is not directly related to fuel condition like the other isotopes, but does depend on growth of tritium concentration in the RCS due to other factors. This is usually only an issue during periods of significant dilution evolutions of the RCS and for plants in early core life when there is little tritium in the RCS. The tritium method will provide the best sensitivity when the RCS tritium is 0.01 μCi/g or greater. See Figure 3-2 for an example of the relationship of tritium leak rate sensitivity for OTSGs.

   - Time elapsed from initiation of the leak for buildup of tritium concentration in the secondary system towards the equilibrium value.

   - Secondary system leak rate (system makeup rate). Note that this can be very high and erratic for PWRs that use condensate to rinse condensate polishers.

   - Multiple-unit water transfers, where water is freely transferred between units at multiple-unit sites, can introduce errors.

Figure 3-2: Leak Rate Sensitivity for Tritium



3.4.5 Precautions

1. Care must be taken in the applicable calculations to ensure the makeup rate to the secondary system was relatively constant during the time period between samples or corrected for the additional dilution. For example, the makeup rate was taken at the times of the two samples and the calculation was performed using this number as the makeup rate (was approximately the same). However, for over half of the time interval the steam generator blowdown was substantially increased for a plant which wastes the blowdown, the result would be in error unless the higher average makeup rate was used for the sample time period.

2. The entire applicable secondary volume must be accounted for in the calculation. This must include the mass in the steam generators, piping, components, and recirculation masses such as condensate storage tanks.

3. Care should be exercised in the radiochemistry counting of the tritium samples due to the possible interferences with counting a low energy beta. If possible, samples should be drawn from a demineralizer effluent or distilled in the laboratory.

3.5 Leak Rate Evaluation Via Other Methods

3.5.1 Introduction

There are other qualitative and quantitative methods to detect and determine primary-to-secondary leaks and leak rates. Qualitative methods can be used for a rapid determination of the presence of a leak and identification of the leaking steam generator.

3.5.2 Main Steam Sample Method

3.5.2.1. Discussion

The main steam sample method is very similar to the condenser off gas method described in Section 3.2 because it involves collection and analysis of radioactive noble gases. Some plants have the capability of sampling the main steam. These plants (both OTSGs and RSGs) can use the main steam condensed sample and the isotope selection from Section 3.2 to accurately calculate a leak rate. The leak rate is calculated as follows:

$$LR = \frac{A_{STM} F_{STM} 2.88}{A_{RCS}} \qquad \text{(eq. 3-6)}$$

Where:

LR = Leak rate (gpd)

A_{STM} = Activity of the isotope in the main steam sample (μCi/g)

F_{STM} = Flow rate of the main steam at the specific power level when the sample was taken (lbm/hr)

A_{RCS} = Activity of the radionuclide in the RCS sample (μCi/g)

2.88 = Conversion factor from lbm/hr to gpd

3.5.2.2 Limitations

1. The accuracy and precision of the condensed main steam sample method is affected by the difficulties of obtaining a representative steam sample. Also, this method does not employ a concentrated stream as the condenser off gas and is therefore not as sensitive. The results may be more qualitative than quantitative. This method should be correlated with more accurate methods such as tritium.

2. The collected steam sample should be carefully drawn and sample container secured to avoid loss of the gases to be counted.

3. Precautions 1, 2 and 3 in Section 3.2.5 from the condenser off gas method may also apply and should be evaluated.

3.5.2.3 *Alternate Method*

A qualitative determination of which steam generator is leaking can be accomplished by the use of a portable multiple-channel analyzer (MCA) to measure N-16 at the steam line of each steam generator. Another variation is to use any suitable portable radiation monitor to determine which steam line has the most activity.

3.5.3 *Steam Generator Blowdown Cation Columns (or Resin-Impregnated Filters)*

3.5.3.1 *Sampling Method*

Steam generator blowdown cation columns or samples collected on resin-impregnated filter papers in corrosion product samplers provide a convenient measurement of primary to secondary leakage. They can be used as a rapid determination of which steam generator is leaking by using a portable radiation detection instrument to determine which steam generator cation column contains the most activity. If the area background activity will not allow this determination, then the columns may be removed to a low background area and monitored there, if this can be accomplished quickly enough to be of value.

3.5.3.2 *Calculation*

A quantitative estimate of the leak rate may be determined using cation columns. This is especially suitable for tracking small leaks on the order of approximately 1-2 gpd or less. This is accomplished by measuring the flow through the cation column for the time necessary to obtain suitable isotope concentrations for γ spectroscopy. The resin must be quantitatively transferred to a suitable container for identification of cation radioisotopes by γ spectroscopy. The leak rate can then be estimated by the following formula:

$$LR = \frac{\frac{A_R}{V}(B)\,1440}{A_{RCS}} \qquad \text{(eq. 3-7)}$$

Where:

LR = Leak rate (gpd)
A_R = Total curie content of the isotope in the resin (μCi)
V = Volume of sample passed through the cation column (ml)
B = Steam generator blowdown flow (gpm)
1440 = Conversion factor from gpm to gpd

This calculation is subject to the same assumptions, limitations, and precautions in 3.3.2. However, it should not be necessary to make the corrections suggested for other isotope conditions in the referenced appendices. Additional error or variance can be introduced by the uncertainties of measuring resin volumes and the method chosen for determining the volume of sample. For example, if the median flow rate is used, this will obviously introduce error. If the sample period is lengthy, variations in flows, such as blowdown, will also introduce errors. But, it is judged not to be beneficial to correct for these errors. This method is used to track very small leaks where even large variances or errors are not a significant concern, especially since it can be correlated with the tritium analysis.

3.5.3.3 *Selection of Radionuclides*

Because the time periods to obtain suitable concentrations on the resin for γ spectroscopy can be lengthy (up to 30 days), Cs-137 is the preferred radionuclide. The 30 year half-life of Cs-137 makes decay correction unnecessary and eliminates this error. If the time period is short enough, other radionuclides may be utilized (such as Na-24), but it may be necessary to correct for decay.

3.5.3.4 *Alternate Method*

Another estimate can be obtained by passing a known volume of steam generator sample (20-40 liters) through a column with a suitable volume ($\approx$50 ml) of mixed bed HOH resin. After quantitatively transferring the resin for γ spectroscopy, the activity for a specific isotope can be calculated as follows:

$$A_{SG} = \frac{A_R}{V} \qquad \text{(eq. 3-8)}$$

Where:

A_{SG} = Activity of the steam generator sample (μCi/ml)
A_R = Total curie content of the resin (μCi)
V = Volume of the sample passed through the resin (ml)

The leak rate can then be calculated using the calculations and radionuclide selections in Section 3.3.2 utilizing the same assumptions, limitations, and precautions.

3.5.4 Steam Generator Blowdown Cleanup Systems

Due to the requirement for activity monitoring of any material "free released" from the controlled area, plants with steam generator blowdown resin cleanup system and/or filters can obtain an early indication of a small primary-to-secondary leak if these materials become contaminated. However, this is a qualitative indication only and a quantitative leak rate determination should be accomplished with other methods.

3.5.5 Condensate Polisher Resin Analyses

Some slightly volatile species that enter the secondary system via primary-to-secondary leakage (e.g., radioiodines) will exit the steam generator via the steam and partially condense with condensate. These isotopes will be collected on the ion exchange resins in the condensate polishers. Sampling and analyses of these resins can be used to detect/confirm (but not quantify) the existence of suspected primary-to-secondary leakage. This method will not be further discussed due to its uncertainties (from non-representative sampling, unknown decay times, etc.).

3.6 Trending Leak Rates Via Radiation Monitors (Excluding N-16 Monitors)

Plant designs include radiation monitors on the condenser off gas, main steam and steam generator blowdown (for RSGs). A radiation monitor is far more suited for trending leak rates than grab sample analyses, especially if the monitor is trended on a data acquisition system. Some of the advantages are as follows:

- Not manpower-intensive like consecutive grab sampling.
- No time delay from sample to results, (reading is instantaneous).
- There are no gaps in the data points, i.e., the reading is continuous.
- Not subject to the variations associated with the parameters of grab sampling.

The major drawback is that radiation monitors read out in dose, counts, etc., not leak rate. This can be overcome by a correlation process with the monitor reading and the sensitivity values for isotopes detected by the monitor obtained from the manufacturer's calibration curve or an in-house generated curve. This can be converted into an estimation of the leak rate based on the monitor reading and used until this estimated leak rate can be correlated with an actual leak.

The best correlation would be at least three points that span the workable range of the monitor that corresponds to a leak of large magnitude. However, in reality this would most likely not occur. The plant must correlate the monitor with small leaks that are more likely to occur.

This would be accomplished by determining the leak rate as accurately as possible with several methods, including tritium. Then, a correlation of that leak rate would be determined with the reading of the particular monitor for trending purposes. For example, a leak rate was determined to be 5 gpd by the tritium method and the condenser off gas monitor was reading 1000. This correlates to a monitor response of 200 cpm/gpd. If the count rate increased to 1500 cpm, then the leak rate could be assumed to have increased by 2.5 gpd to a value of 7.5 gpd. A single point calibration may not be linear over the range of the instrument, but it could be used to determine an action level for grab sample analysis to obtain an accurate leak rate or used in tracking the increase in a rapidly propagating leak.

4

MONITORING METHODS

4.1 MONITORING PROGRAM AND METHODS

4.1.1 Elements of an Effective Monitoring Program

As noted in Section 1, an effective primary-to-secondary leakage monitoring program should be capable of handling the following three specific scenarios:

- Low level and/or slowly increasing primary-to-secondary leakage;
- Rapidly increasing primary-to-secondary leakage (as described in Reference 1); and
- Steam generator tube rupture (no leak before break).

In order to meet these objectives, an effective leakage monitoring program cannot rely simply on grab sampling. Rather, the program should be designed such that an operator can respond to rapidly escalating leak rates on the order of one to six hours. This can only be accomplished if real time data are used to provide the basis for operator actions. Therefore, the leakage monitoring program must use the installed Radiation Monitoring System (RMS) to detect the level and the rate of change of radioactivity in the secondary plant. The RMS provides continuous on-line monitoring capability to plant operators for detection of primary-to-secondary leaks. Effective use of RMS setpoints provides early notification of changes in leak rates.

Routine plant sampling is also a necessary component to the leakage monitoring program. The plant sampling program should be used to verify the performance of the RMS, verify alarms and confirm leak rate estimates, and provide early detection of levels or changes in radioactivity in the secondary system that are either below the sensitivity of the RMS or not able to be sensed by the particular type of detector.

As discussed in Appendix A, operational experience indicates that the location and type of leak influence the radioactivity seen in the secondary system. No single monitored pathway or radionuclide should be relied upon to detect/monitor primary-to-secondary leakage. Both the RMS and sampling programs should employ the concept of "radionuclide diversity." Radionuclide diversity simply means that multiple pathways should be monitored/sampled for the specific type

of radionuclide anticipated to be in the pathway. This includes comparing leak rates calculated by using different radionuclides from each pathway. The importance of comparing primary-to-secondary leak rate calculations to ensure the validity of the method used is the subject of USNRC Information Notice 94-43. Not comparing leak rates calculated with different methods and attempting to resolve discrepancies, have led to non-conservative leak rate estimates being used to make operational decisions.

Most plant RMSs include instrumentation for monitoring:

- **Condenser Off Gas** - used to identify the presence of radioactive gases removed from steam condensate,
- **Steam Generator Blowdown** - used to identify non-volatile radioactive species in the steam generator bulk water (excluding OTSGs), and
- **Main Steam** - used to detect volatile gases, and in some cases N-16, carried from the steam generator via the main steam.

To identify the presence of a primary-to-secondary leak and to permit its quantification, routine grab samples are collected from:

- **Reactor Coolant** - used to quantify the source term,
- **Steam Generator Blowdown** - used to detect non-volatile radioactive species in liquid,
- **Condenser Off Gas** - used to detect noble gas and other volatile species removed from steam condensate,
- **Condensed Main Steam** - used to detect noble gas and other volatile species carried over with main steam,
- **Condensate** - used to detect tritium, iodine and other soluble species, and
- **Blowdown Filters and Ion Exchanger Columns** (or ion exchange materials used for chemistry sampling that receive continuous flow) - used to detect particulates and ionic species from liquid streams.

The monitoring program should have clearly defined entry conditions. Monitoring should be required whenever the primary system is pressurized and at an elevated temperature. Except for monitoring secondary system boron, all leak detection and quantification methods evaluate RCS activation or fission products as they escape into the secondary system. To ensure that the activity can be detected, the minimum plant requirements should be:

- The steam generator(s) should be steaming to the turbine or condenser or, at a minimum, it must be under adequate pressure to deliver an acceptable sample, and

- Measurable concentrations of secondary system radionuclides from the primary system should be present.

For initial startup conditions, this may require routine sampling for tritium or other chemical species in the secondary system until activity levels increase in the primary system allowing for detection by the RMS (refer to Section 2.2.1 for a discussion on the relationship of primary source terms to RMS detection sensitivity). During initial startup, leak detection may be performed by monitoring for tritium increases in a steam generator that is "bottled" (i.e., no significant steam removal mechanisms) with the primary system pressurized. In many cases, the RCS contains a sufficient concentration of tritium to perform this monitoring.

Finally, the leak rate monitoring program should contain actions to be taken at various leak rates or rates of change (refer to the recommendations in Section 2). Leak detection capabilities must be consistent with leak rate action levels.

4.2 EVALUATION OF MONITORING METHODS

When selecting which monitoring method to use or evaluating the best way to use the method, two key elements that should be considered are detection capability and measurement uncertainty.

4.2.1 Factors Affecting Leak Detection and Measurements

Detection capabilities and measurement uncertainties are dynamic rather than fixed parameters. The specific values can change depending on plant operating status and history. Detection capability and measurement uncertainties are a function of the following parameters:

- **Source Term** - This is the RCS activity that leaks into the secondary side. Larger source terms enhance the leak detection capability and lower the uncertainty due to improved counting statistics. Plant operating status and history can have significant impact on the source term. The production of activation products (e.g., N-16, Ar-41, Na-24, etc.) depend on reactor power level, and with the exception of N-16, the RCS concentration of the material being activated. Production of fission products (e.g., Xe-133, Xe-135, Kr-88, I-131, etc.) depends on core operating history and fuel integrity. Tritium production is influenced by boron concentration and by water management practices (e.g., RCS evaporator distillate recycle/discharge). Finally, operations such as degassing RCS or diluting at the end of cycle, can also influence the RCS source term.

- **Primary-to-Secondary Leak Rate** - The leak rate determines the rate at which activity is released in the secondary system. The higher the leak rate for a given source term, the higher the activity in the secondary side and the less uncertainty due to improved counting statistics.

- **Sample Transport Time** - The sample transport time includes time for mixing as well as transport to the radiation monitor. The location of the leak can impact transport time as well as mixing within the steam generator. An active leak in a free span region will provide significantly different data than a leak with less communication with the steam generator water (e.g., a leaking tube plug or deep tubesheet crevice leak). Transport time becomes very important for radionuclides with short half-lives.

- **Properties of the Radionuclide Measured** - The properties of the isotope being measured by the detection system that affect sensitivity include solubility in water (partition coefficients), chemical interactions (plate out), hideout, half-life (decay), parent/daughter ingrowth (species from transformation), and decay scheme (type of radiation emitted).

- **Detector Efficiency** - The response of the detector used to measure a particular radionuclide as a function of the type and energy of the radiation measured. In the case of gross channel analyzers, such as those commonly found in plant RMS monitors, the systematic errors associated with the monitor readings caused by the specific radionuclide energy response can be significant unless a correction is made for the specific isotopic mix.

- **Detection Sensitivity** - The ability of the detection system to distinguish between signal and noise response. All monitors and laboratory instrumentation have a lower limit of detection (LLD) capability based on the system design parameters and the type of detector. Sensitivity can be enhanced by ensuring the sample is not diluted by other liquid/gas streams.

All of these parameters interrelate and should be considered over the operating conditions expected.

4.2.2 Detection Capability

The detection capabilities of the RMS and sampling program should be consistent with the operational response recommendations presented in Section 2. The detection capability of the primary-to-secondary leak rate measurements should be sufficient to identify leak rates which have the potential to cause a radiological problem on the secondary side and are rapidly increasing (e.g., due to very rapid tube degradation).

Under certain plant operating conditions (e.g., startup, shutdown, etc.) the detection capability of the RMS may not be sufficient to provide indication of leak rates or changes in leak rates at the established action levels described in Section 2. Under these conditions, it may be necessary to implement frequent grab sampling in order to attain the required sensitivities.

Detection capabilities should be assessed for the instrumentation and sampling techniques used to quantify leak detection. The technique uses the calculational methodology developed in Section 3. The minimum leak detection capability can be calculated by substituting the following into the appropriate equation described in Section 3:

- For Sample or Radiation Monitor Concentration - substitute the minimum detection capability of the radiation monitor or grab sampling technique as the measured concentration. For radiation monitors that operate in a gross counting mode and respond differently depending on the specific isotopic mix of the process stream monitored, the calculation becomes more complicated. In these cases, the monitor response must be related to the isotopic mixture of the RCS source term using energy response data obtained during the primary calibration of the detector. In addition, the lower limit of detection for the monitor is influenced by monitor background. In locations where monitor background is elevated, the detection sensitivity of the monitor should be re-evaluated.

- For RCS Concentration - substitute values that are based on an assumed (from UFSAR and/or historical data) typical concentration or if available, an actual measured source term concentration;

- For Other Operational Parameters (system flow rates, etc.) - substitute typical (based on design or historical data) or actual measured parameters.

4.2.3 Measurement Uncertainty

Measurement uncertainty consists of systematic (or bias) and random errors. These errors influence the accuracy and precision of the measurement. An analysis of the methods used to quantify leak rate should be performed. The program action levels described in Section 2 do not represent precise safety limits for operation, but rather represent approximate values which should institute predetermined plant actions, based on history of tube rupture events.

If a measurement is accurate, then it has a low degree of systematic error. A measurement is accurate if it is very nearly the actual value of the parameter being measured. The accuracy of a measurement is important when the measurement value (or calculated leak rate) is compared with program action levels. As discussed in earlier sections, sample hide out and decay, or some other removal

mechanism (e.g., chemical reaction, ion exchange, etc.), can induce a systematic error into the measured result and ultimately into the calculated leak rate.

A simple method to test the accuracy of the results, is to compare leak rates calculated using actual grab sample data for different isotopes and sample media. If there are large but reproducible discrepancies in the calculated leak rates, one of the measured results most likely contains a systematic error. Therefore, it is important to compare leak rates calculated by different methods in order to cross validate the accuracy of the sample. If the systematic error can be determined, a correction can be applied to the inaccurate measurement.

If a measurement is precise, then it has a low degree of random error. Precision quantifies how reproducible a measurement is. Precision should not be confused with accuracy. A precise measurement can be inaccurate if the measurement contains a systematic error. Under these circumstances, precise but inaccurate measurements, can provide reliable trend information. In fact, the more precise the measurement - the more sensitive the parameter may be for identifying trend changes. A good example would be monitoring I-131 levels in steam generator blowdown even with a significant amount of hideout. Although using the measured iodine concentration used to calculate leak rates under estimates leak rates, small changes in the relative leak rate are easily detected because of the high precision associated with the laboratory analysis method.

4.2.4 Classification of Monitoring Methods

Monitoring methods should be classified as either qualitative or quantitative depending on how the method is used. The classification of each method depends on the uncertainty associated with the monitored parameter or estimated leak rate. Both methods are useful in monitoring and assessing changes in primary-to-secondary leak rates. However, it is important that personnel performing the leak rate calculation have guidance on when to utilize each method as well as the limitation associated with each method.

Quantitative methods generally have low uncertainties (both accurate and precise) and provide a reliable estimate of the actual parameter measured. Quantitative methods are used to determine leak rate monitoring program action levels. Currently accepted quantitative methods include leak rates calculated using noble gas activity in condenser off-gas samples and for low level leakage, tritium in secondary system samples (provided that corrections can be made to account for any other sources of secondary side system tritium contamination). With respect to the RMS, reasonable estimates of primary-to-secondary leakage can be made using condenser off-gas monitor readings (provided that the monitor response has been corrected to either the RCS source term isotopic mixture or correlated to actual grab sample data). Other methods may fall into this category provided that sufficient operational experience is available to confirm the validity of the method by comparing results with that obtained from other independent quantitative

methods. Methods that are subject to a fixed systematic error can also be used to determine leak rate provided that the measurement result is corrected for the inherent systematic error.

Qualitative methods can be either imprecise but accurate or inaccurate but precise. Although actions levels may not be directly ascertained from these measurements, they still can provide useful trend information and can be used to identify the affected steam generator. An example of a measurement that is inaccurate but precise would be using I-131 and Na-24 measurements in steam generator blowdown to trend leak rate changes even though there is hideout and decay occurring. An example of an accurate but imprecise measurement would be calculating leak rates using a radionuclide that has large measurement uncertainty due to a low concentration (poor counting statistics). Most calculational methods fall into this category.

4.3 RADIATION MONITORING PROGRAMS

4.3.1 Regulatory Requirements

The selection of specific instrumentation used to monitor the secondary system and its performance characteristics may be governed by specific regulatory requirements. The following summarizes the applicable regulatory guidance that should be considered when selecting instrumentation. Although the guidance may not be related to a specific leakage monitoring program, the design requirements should be reviewed if existing instrumentation is to be replaced or if additional instrumentation is to be installed to ensure that there are no conflicts.

General Design Criterion 30, "Quality of Reactor Coolant Pressure Boundary (RCPB)," of Appendix A to 10 CFR Part 50, "General Design Criteria for Nuclear Power Plants, " requires that means be provided for detecting and, to the extent practical, identifying the location of the source of reactor coolant leakage. Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems", provides acceptable methods for meeting GDC 30. Although this regulatory guide is typically associated with monitoring containment atmosphere for RCPB leaks, the guide also addresses inter-system leakage. Steam generator tube leakage falls into this category. Essentially, the guide requires detection methods which include radiochemical monitoring of water in any connected system where the systems flow through the containment boundary, and monitoring of airborne radioactivity where such systems are vented outside the containment boundary. This requirement provides the basis for monitoring for radioactivity in steam generator blowdown and condenser air removal systems.

General Design Criterion 64, "Monitoring Radioactivity Releases," of Appendix A to 10 CFR Part 50 includes a requirement that means be provided for monitoring effluent discharge paths and the plant environs for radioactivity that may be released from postulated accidents." Regulatory Guide 1.97 provides an acceptable

position to meet GDC 64. The regulatory guide provides specific accuracy and range requirements for main steam line monitors and condenser air removal monitors (if monitoring effluent activity).

4.3.2 *Leak Detection and Monitoring Instrumentation*

Radiation monitors available in most plants are located in steam generator blowdown, condenser off-gas, and main steam lines. In addition to these, some facilities have also installed N-16 monitors that supplement the main steam line monitors required by Regulatory Guide 1.97. Finally some facilities utilize portable instrumentation and area monitors to supplement the existing installed instrumentation. The types of portable instrumentation available includes N-16 or other portable radiation monitors and survey instruments. Each type of monitor is discussed in greater detail in the following sections.

Steam Generator Blowdown Radiation Monitors

The blowdown monitors typically used are liquid monitors in an off-line sampling configuration. A sodium iodide detector is the most common type used. The monitor is operated in a gross counting mode. The monitors detect soluble gamma emitters in steam generator blowdown. Since they are operated in a gross counting mode, monitor response depends on the radionuclide mix of the sampled stream. Typical lower limits of detection range from approximately 1E-7 to 1E-6 μCi/cc for effluent and process monitoring applications, respectively.

The monitors are typically relied on to provide qualitative information on primary-to-secondary leakage. Due to their sensitivity, they are responsive to small changes in activity. When no radioactivity is present or at concentrations less than the sensitivity of the monitor, setpoints are typically set at some multiple of background that prevents spurious alarms but still provides early warning of increasing radioactivity. Once detectable activity is present, leak rates calculated based on a quantitative grab sample method can be correlated directly to monitor readings. In this instance, the assumption would be made that if the leak rate doubles, the monitor reading would be expected to double. This assumption is subject to significant errors as discussed below. Caution should be taken with respect to acting solely on the blowdown monitor readings without confirmation from another monitor or grab sample. Operational actions, such as a power decrease, can initiate hideout return and cause steam generator activity to increase without a corresponding increase in leak rate.

Limitations associated with using these monitors for performing quantitative leak rate assessment include:

- Hideout - If radionuclides are deposited in steam generator crevices prior to reaching the monitor, the blowdown leak rate calculation will underestimate the actual leak rate.

- Dependency on Radionuclide Mix - Due to operation in the gross count mode, the monitor response is dependent on the specific radionuclide mix sampled. If the radionuclide mix changes, errors in monitor readings can result. For example, during a reactor down power, if a significant amount of hideout return occurs, the radionuclide mix of the sampled stream will be altered. In addition, erroneously high readings will be indicated with no change in leak rate. Therefore, alarms on these monitors need to be verified using an independent pathway (typically main steam N-16 monitors or the condenser off-gas monitor).

- Response Times - Another problem that has occurred with these monitors is slow response Times due to relatively low sample flows through long sample lines. In fact, if a steam generator tube rupture were to occur, there is a possibility that containment isolation could be actuated by a safety system prior to the blowdown sample reaching the monitor. If containment isolation isolates the monitor sample lines from containment, the monitor may never respond to the steam generator tube rupture (SGTR) event. Monitor time response should be examined. Time response can someTimes be decreased by increasing sample flow without making design modifications.

- Background Radiation Levels - If high background contamination levels exist in the secondary system (due to a prior leak or a large ongoing leak), the sensitivity of the monitor to detect changes in activity will be reduced due to higher background readings.

Condenser Air Removal Radiation Monitors

The typical condenser air removal radiation monitors monitor non-condensable gases discharged from the condenser. The monitors are sensitive to noble gas activity. There are several sampling configurations available: off-line, in-line (or in-duct), and adjacent to line. The detectors commonly used are Geiger-Muller (GM) detectors or organic (beta) scintillation detectors, operated in a gross counting mode. The organic scintillation detectors respond to beta emission from the noble gas activity discharged from the condenser. Since they are operated in a gross counting mode, monitor response depends on the radionuclide mix of the sampled stream. The GM detectors are sensitive to both the beta and gamma emissions (if used in an in-line or off-line configuration) and gamma emissions (if used in an adjacent to line configuration) from noble gases in the condenser off-gas. The GM tubes energy response depends on the

window thickness and material used. In some applications, the monitors may perform a dual role. The monitors may function as both a process monitor and effluent radiation monitor. Typical lower limits of detection range from approximately 1E-7 to 1E-5 μCi/cc for in-line/off-line monitors and adjacent to line monitors, respectively.

Like other monitors, there are limitations associated with using condenser air removal monitors for evaluating primary-to-secondary leakage. These include:

- The energy response characteristics of the associated detectors operating in a gross counting mode should be considered. In order to provide accurate readings, monitor response should be corrected for the specific isotopic mix of the sample stream. The radionuclide energy response can either be calculated or, if activity is present, directly correlated to monitor readings by comparing grab sample data to monitor readings obtained during sampling.

- Accurate measurement of process flow is another limitation. In order to calculate leak rates, the process flow past the monitor must be known. Because the process stream consists of a moisture saturated vapor that can contain water droplets, the effect of this sample steam needs to be considered on the instrumentation used to measure process flow. In addition, for utilities that do not have any process flow instrumentation, the leak rate estimates made would be only as accurate as the assumed process flow. Therefore, estimates of process flow should be confirmed by measurement or ensured to be conservative.

Limitations notwithstanding, the condenser air removal monitors provide the most accurate estimate of primary-to-secondary leakage for all leak scenarios. Readings from these monitors can be used to give a rapid assessment of leak rate to operators.

Although these monitors provide reliable leak rate information, when looking for rapid increases in leak rates, the sample transport time from the condenser to the monitor should be evaluated. Typically, those condenser systems that operate with vacuum pumps have low flow rates (on the order of a few cubic feet per minute) and large diameter exhaust lines (to accommodate flow rates when initially pulling a vacuum). If the monitor is not located near the condenser, transport time could be significant. Although the monitor would respond to leak rate increases, the response might not be observed until some time after the event occurs. A typical run of 90 to 100 feet of eight inch diameter piping could give response times that are on the order of 15 to 20 minutes.

If no activity is present in the process stream or if it is below the sensitivity of the monitor, setpoints for these monitors should be set as low as possible without causing spurious alarms in order to provide early indication of primary-to-secondary leakage. If the energy response characteristics of the monitor are known (usually this information is available from primary calibration data), the setpoint can be set to correspond to a leak rate action level by using actual RCS activity. If the monitor is used in effluent applications, the setpoints used to relate monitor readings to off-site dose may not provide early alarm indication of changing leak rates. Refer to Appendix B for corrections that should be considered for leak rate calculations associated with condenser off gas.

Main Steam Line Radiation Monitors

There are two types of main steam line monitors available. The main steam line monitors that are designed specifically to detect N-16 activity are discussed separately. The main steam line monitors installed at most facilities are required by Regulatory Guide 1.97. Due to the high pressure and temperatures of the process stream, these monitors typically are installed in an adjacent to line configuration. The detectors used are either ion chambers, GM tubes, or in some applications, sodium iodide detectors. The monitors respond to the gamma rays emitted from the radioactive gases and vapors being carried through the steam lines. The accuracy and range requirements for these monitors are specified by Regulatory Guide 1.97. GM and Ion Chamber monitors typically read out in gamma dose rates. Calculations are necessary to estimate the actual activity in the main steam lines. Typical ranges are 1E-4 R/hr to 1E+2 R/hr (corresponding to fission product concentrations between 1E-3 to 1E+3 μCi/cc after applying calculated conversion factors).

The major limitation of these monitors is that they are not sensitive to small leak rate changes. Because these monitors measure activity through a steel line that is about an inch thick, the sensitivity to isotopes with low energy g (such as Xe-133 with an 80 keV photon) is minimal. These monitors would only respond if there was a significant RCS source term. As a result, these monitors cannot be used for low level leak rate detection and are limited to post-accident assessment of significant releases. However, these monitors will exhibit a response to N-16, but typically only at levels corresponding to leak rates in the gallons per minute range. Because of the N-16 response, these monitors can provide a clear indication of a SGTR IF the rupture occurs while the unit is at power. However, once the reactor trips the readings will typically return to normal levels.

Because of the low sensitivity of these monitors under normal failed fuel conditions and low leak rates, they typically do not provide any useful trend information.

Alarm setpoints are typically set at three Times background. In most facilities that have these monitors, the setpoint is controlled by the plant Technical Specifications.

N-16 Monitors

These monitors are typically mounted on the main steam lines in an adjacent to line configuration. A large volume sodium iodide detector is typically used. The monitor is usually operated in either a multi-channel analyzer mode with an energy window set to detect the N-16 6.13 MeV photopeak or in a gross counting mode with a lower level discriminator set to detect only high energy gamma radiation. The effectiveness of leak rate monitoring via N-16 detectors can vary depending on the leak scenario. For example, it has been calculated that the N-16 concentration resulting from an 11 gpd leak can range from 2.4E-5 to 4.0E-14 μCi/cc, depending on whether the leak is from an active leak or a plugged tube. However, these monitors can be very effective for most leak scenarios that will lead to rupture. Because N-16 has a 7 sec. half-life, sample transport time to the monitor becomes significant. In most calculations, the sample holdup time in the steam generator becomes the limiting factor. Small errors in the estimate of the hold up Times in the generator can result in significant errors when calculating leak rates based on N-16 monitor response. Therefore, N-16 monitor response to leak rate is normally determined empirically by correlating indicated monitor response to known leak rates calculated from chemistry sampling. This correlation is only specific to the particular leak and may not be transferable to leaks occurring at different locations in the generator.

Some of the advantages of N-16 monitors are:

- N-16 is produced by the activation of oxygen in water in the reactor, the source term remains stable and is dependent only on reactor power.

- Due to the high flow velocity in the steam lines, the transport time from the generator to the radiation monitor is usually very short. Thus, the monitors respond almost instantaneously to increases in leak rates. However, the half-life of N-16 is short and there can be considerable error associated with estimating leak rates, unless the monitor readings are correlated to leak rates calculated via chemistry sampling.

- Depending on monitor design, N-16 monitors can be used below 20% load by using local electronic meters to readout in CPM. This capability allows leak rates to be monitored into Mode 2 of operations.

- An N-16 monitor can also provide diagnostic information. For example, if grab sampling at the condenser exhaust indicates a significant leak rate but there is no N-16 activity detected, the leak may be caused by a leaking tube plug or sleeve or by a crack in a deep tubesheet crevice.

Because N-16 has a seven second half-life and there are no other isotopes with a photopeak energy near that of N-16, response checking and calibration requires the use of a special source. The reference source used is a Cm-244/C-13 source that generates an excited state of O-16 by an a,n reaction with the C-13. As the excited state of O-16 decays, a 6.13 MeV gamma is emitted.

Another difficulty involves using a sodium iodide detector with a fixed window. N-16 monitors have built-in sources which compensate for temperature changes and detector drift, which minimizes this problem.

Detector "cross talk" can cause problems related to using N-16 monitors. Cross talk is simply the response of one steam line monitor detecting high-energy g radiation emitted from an adjacent steam line. For steam lines that are in close proximity to one another, a significant response (on the order of 10 to 25 % for two foot diameter steam lines that are separate seven feet apart from centerline) can be observed on a steam line monitor that may be monitoring an unaffected generator. This can present difficulties to operators when attempting to assess an affected generator or if tracking leaks that occur in more than one generator.

Once monitor readings are correlated with leak rates calculated using chemistry grab sample data, the monitor readings can provide a direct measurement of leak rate. An increase in monitor readings would suggest that the leak rate increased by the same factor. However, it is possible for the leak rate to increase without any response on the N-16 monitor. For example, if a new leak develops that has a significantly different transport time than the leak causing the initial response. Therefore, N-16 leak rate estimates must be periodically compared to leak rates calculated using chemistry grab sample data to ensure the correlation remains valid.

With no detectable activity, setpoints should be set as low as possible to alert operators to potential changes in leak rate while minimizing spurious alarms. If detectable activity is present in the steam line, the monitor reading can be correlated to the calculated leak rate based on chemistry grab sample analysis. The alarm setpoint on the monitor can then be set to correspond to a leak rate action level.

Portable Instrumentation

Some utilities that do not have installed N-16 monitors, utilize a portable system to detect N-16 in the steam lines. The system consists of a portable MCA/amplifier/power supply coupled to a sodium iodide detector. The instrumentation can be used as a diagnostic tool to identify the affected generator and possibly obtain information concerning the cause of the leak. Refer to the previous section for more detailed information regarding N-16 monitoring.

A few utilities use area monitors attached to the side of piping, ion exchangers, or flash tanks to provide a qualitative indicator of changing leak rates. In addition, some facilities have incorporated into their station operating procedures/instructions to perform surveys on ion exchange columns on in-line analyzers in the laboratory to provide a rapid method for confirming increasing radioactive contamination or assessing the affected steam generator.

The information obtained from portable survey instrumentation and/or area monitors can provide a qualitative indication of changing leak rates. For example, in the event a rapid assessment is necessary to determine an affected generator, as in the case with a SGTR, a rapid survey of ion exchange columns on in-line chemistry analyzers can be used to identify the generator with the high leak rate. However, caution must be exercised when using this technique during SGTR events. If containment isolation, and subsequent isolation of the sample lines, occurs prior to the sample being transported to the survey point, the information obtained may be erroneous. In addition, as with blowdown monitoring instrumentation, erroneous alarms may be caused by hideout return caused by a reactor power decreases or other transients. Readings should be verified by observing readings on another monitored pathway. Finally, if significant activity is present in the secondary system from either an earlier tube leak or an ongoing leak, the information obtained may be masked because of the reduced sensitivity of the monitoring instrumentation caused by high background.

4.3.3 Maintenance/Surveillance Requirements

As noted in Section 2, operational responses to rapidly propagating primary-to-secondary leaks must be based on continuous radiation monitor response, precluding the delays associated with grab samples. Therefore, plant programs must be designed to ensure that the monitors are operable at all Times, or at least to ensure that monitors have high service reliability. Some items that should be included in the program are:

- Operability checks should be made periodically. Operability checks consist of reviewing RMS readings and trends to ensure channel operability. These checks should be performed at least monthly if no radioactivity is detected in the secondary system. If indications of primary-to-secondary leakage exist, the frequency of operability checks may be increased depending on the action level entered.

- The radiation monitors should be calibrated at least once every 18 months.

- If one of the radiation monitors used to monitor for primary-to-secondary leakage becomes inoperable, station management should assign its highest, non-emergency priority to its repair. If the affected monitor is part of the Technical Specifications or Off-site Dose Calculation Manual (ODCM), follow the appropriate actions for that monitor. If the monitor is not addressed in either the Technical Specifications or ODCM, other actions might be applicable.

  In the interim, alternate primary-to-secondary leakage monitoring should implemented. Alternate monitoring requirements can be satisfied if another primary-to-secondary leak rate monitor is available and operable. For example, if a steam generator blowdown monitor becomes inoperable, the monitoring requirement can be fulfilled by the condenser off-gas monitor. If no alternate monitor is available, station personnel should attempt to use portable radiation monitors to fulfill the void. It is not deemed acceptable to monitor primary-to-secondary leak rates via grab samples, though grab sampling should be initiated on at least one of the monitored pathways to fulfill effluent requirements.

4.4 SAMPLING PROGRAM

For primary-to-secondary leak detection and quantification, samples of the primary and secondary coolants must be routinely collected and analyzed radiochemically. Section 3 discusses methods used to calculate primary-to-secondary leak rates based on the radionuclide concentrations. This section also presents the limitations associated with each sampling/analysis method

Routine sampling of RCS and secondary systems is typically scheduled on a weekly, multi-day or someTimes a daily basis. If primary-to-secondary leakage is detected, sampling frequencies may increase depending on program requirements (refer to Section 2). During periods when RCS source term is low enough to prevent effective monitoring by the RMS or if RMS equipment is out of service, the sampling frequency may be increased to verify leak rates.

4.5 REFERENCES

1. USNRC Information Notice No. 91-43: "Recent Incidents Involving Rapid Increases in Primary-to-Secondary Leak Rate," (July 1991).

2. USNRC Information Notice No. 94-43: " Determination of Primary-to-Secondary Steam Generator Leak Rate," (June 1994).

3. Code of Federal Regulations, Title 10 Part 50.

4. USNRC Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," (May 1973).

5. USNRC Regulatory Guide 1.97, "Instrumentation for Light-Water-Cooled Nuclear Power Plants to assess Plant and Environs Conditions during and following an Accident," (December 1980).

6. USNRC Information Notice No. 88-99: "Detection and monitoring of Sudden and/or Rapidly Increasing Primary-to-Secondary Leakage," (December 1988).

7. USNRC Information Notice No. 88-02: "Rapidly Propagating Fatigue Cracks in Steam Generator Tubes," (February 1988).

8. INPO Significant Operating Experience Report (SOER) 93-1, "Diagnosis and Mitigation of Reactor Coolant System Leakage Including Steam Generator Tube Rupture." September 1993.

9. National Acadamy for Nuclear Training, "Training Assistance Materials To Supplement SOER 93-1." January 1994.

Appendix A

DATA INTERPRETATION

Introduction

This appendix provides guidance to plant personnel attempting to categorize a primary-to-secondary leak. The data contained in this appendix was collected from the experiences of PWRs with primary-to-secondary leakage throughout the United States. It must be recognized, however, that each primary-to-secondary leak is an individual event that may not share any or all of the characteristics listed in this appendix.

Background

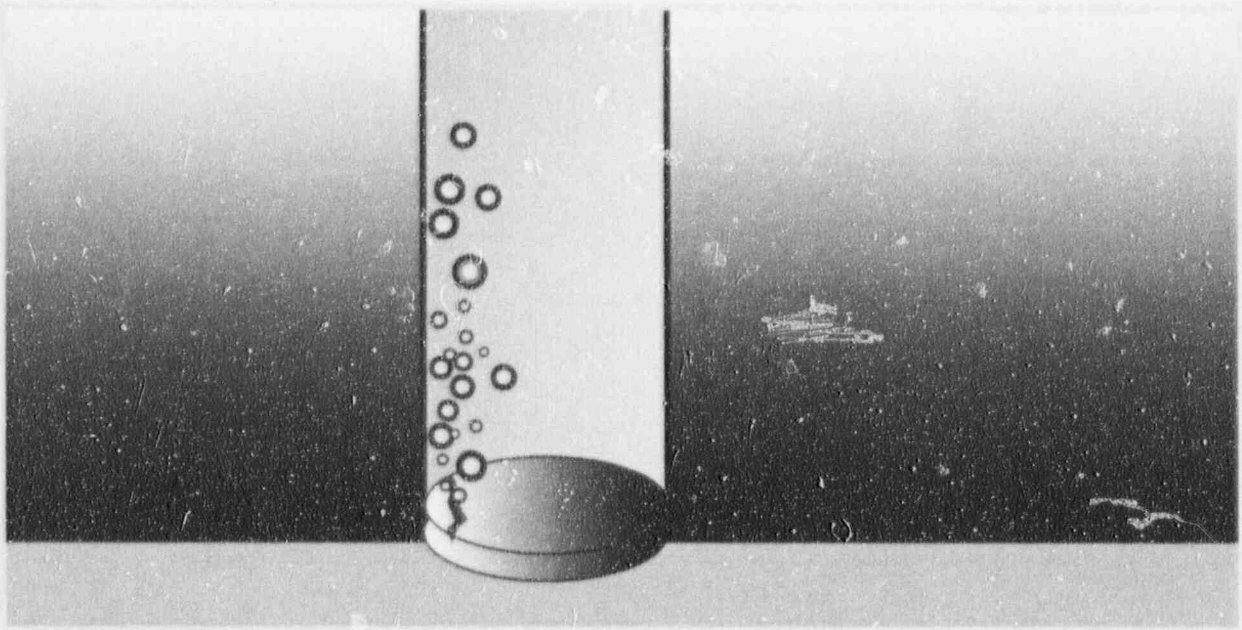
After the discovery of the initiation of primary-to-secondary leakage, plant personnel must immediately identify the faulted steam generator and the magnitude of the leak in order to ascertain if continued plant operation can be justified consistent with plant Technical Specifications and administrative limits. Once it has been determined that plant operation may continue, plant management should require a prediction of the leak's future behavior in order to adequately plan for the eventual repair of the tube. In order to make such a prediction, the cause of the primary-to secondary leakage must be hypothesized. This will allow comparisons with other primary-to-secondary leakage events with the same cause, and give a basis for predicting future leakage behavior.

Use of the guidance given in the various scenarios should be tempered with the knowledge of what type of attack the respective steam generators are subject to. Plants without a history of denting, for example, and that are adding boric acid to the secondary system should not assume that a primary-to-secondary leak is due to denting simply because their symptoms fit the denting scenario. Knowledge of previous steam generator leak history, as well as recent eddy current test results,

pulled tube examinations, chemistry history, FOSAR results and physical characteristics (tube material type, AVB material, propensity for tube vibration, etc.) should all be considered with the radiochemistry data when hypothesizing the cause for a primary-to-secondary leakage event.

CHARACTERISTICS OF PRIMARY-TO-SECONDARY LEAKAGE

SCENARIO 1: LEAKING TUBE PLUG



Leak Symptoms:

1. Low, relatively constant leak rates are expected, unless the tube plug totally fails.

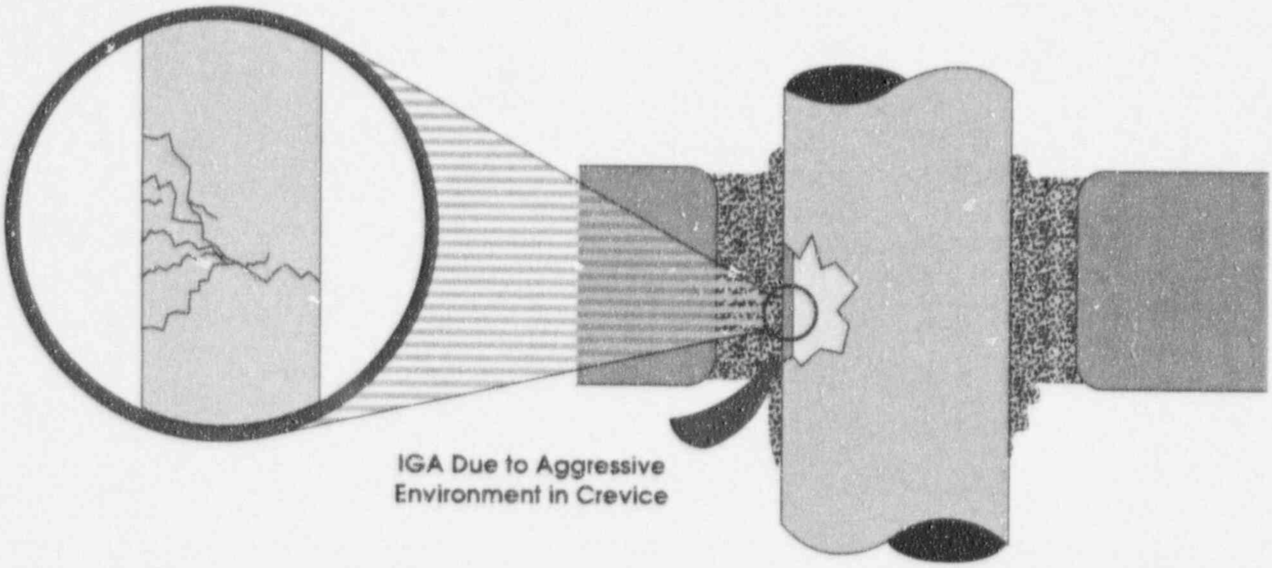
2. Leakage may not be detected on N-16 monitors, due to delays in migration through the plug crack and the faulted tube, as well as the transit time through the steam generator.

3. Leakage may not be immediately detected on blowdown radiation monitors, since low-volatility species may not be seen in the bulk water. The blowdown monitors may detect the leak later, as radioiodines and particulate daughter products build up in the steam generator bulk water.

4. Short-lived isotopes will probably not be detected, or will be detected in relatively small quantities.

5. Tube plug failure may be accompanied by alarms on steam generator acoustic monitors, as well as a rapidly increasing leak rate.

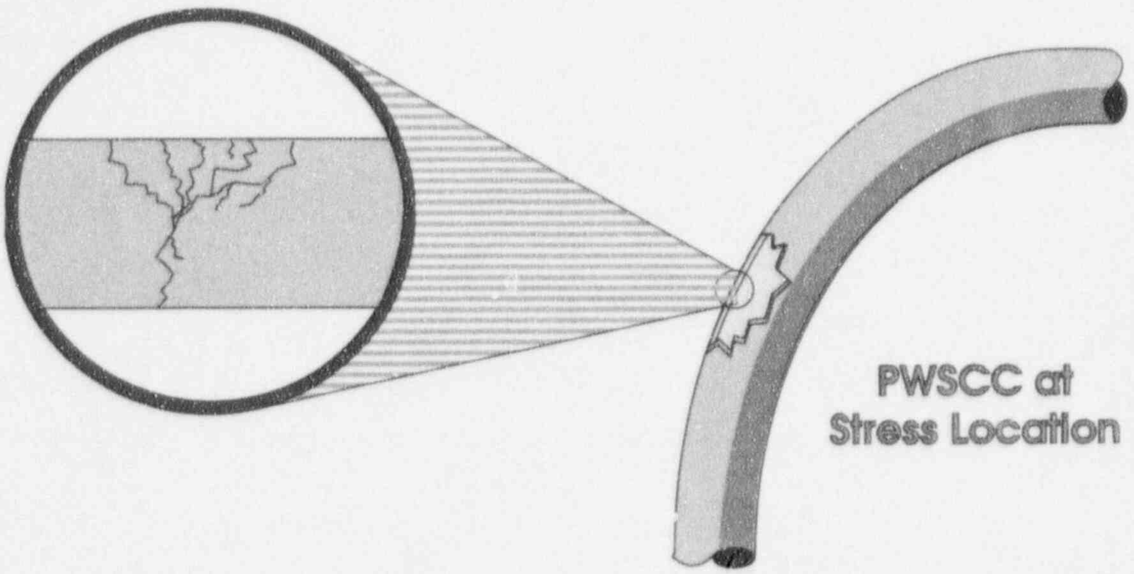
SCENARIO 2: IGA/SCC AT PACKED TUBE SUPPORT PLATE INTERSECTION



Leakage Symptoms:

1. Low leak rates are expected at the initiation of primary-to-secondary leakage.
2. Power transients may change the leak rate, particularly if the transient is severe enough to open the crack.
3. Non-volatile species may not be detected during operation, but may show up in hideout return.
4. Due to delays in migrating through the crack and the corrosion product deposit, N-16 monitors may underestimate or not even detect the leak.
5. Blowdown monitors may not immediately detect the leakage event, since non-volatile species will be held up in the crevice deposit. The sudden appearance of short-lived and non-volatile species may indicate that the leakage has opened a clear path through the crevice deposits.

SCENARIO 3: PWSCC AT STRESS LOCATION (any free span cracking mechanism)

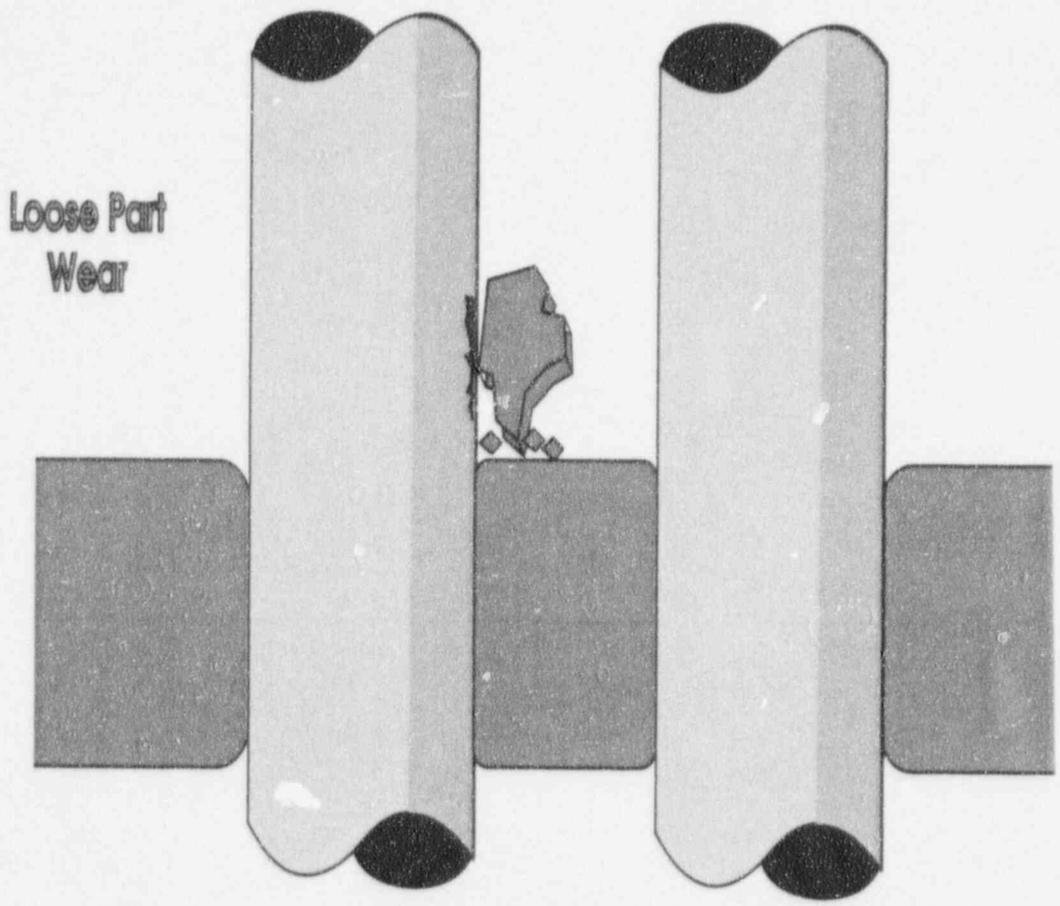


Leak Symptoms:

1. Low leak rates with plateaus are expected. Plant transients may increase or decrease the measured leak rate.

2. Leakage should be detected by the air ejector monitor, blowdown monitor and main steam monitors (if the leak rate is of sufficient magnitude). All isotopes, regardless of volatility and half-life, should be detected. Secondary radioisotopes should simply be a dilution of the RCS less a hideout factor for low volatility species.

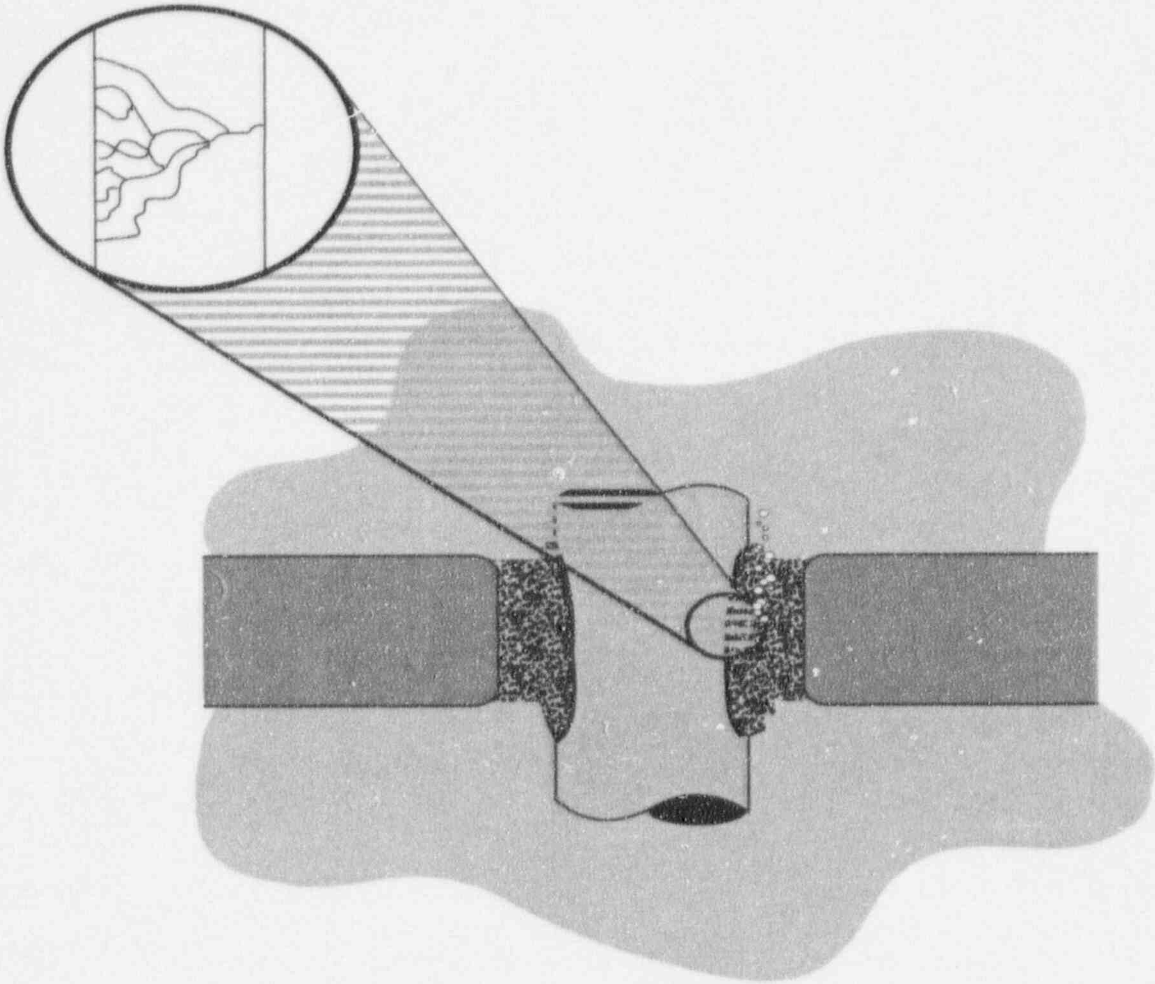
SCENARIO 4: LOOSE PART WEAR



Leak Symptoms:

1. Relatively high leak rates can be expected.
2. Leak rates may be accompanied by alarms on steam generator acoustic monitors.
3. The leak rate may be subject to dramatic increase, and even tube rupture. Adjacent tubes may also become involved.
4. Leakage should be detected by the air ejector, blowdown, and main stem radiation monitors. All isotopes, regardless of volatility and half-life, should be detected. Secondary radioisotopes should simply be a dilution of the RCS less a hideout factor for low volatile species.

SCENARIO 5: SCC AT DENTED TUBE SUPPORT PLATE INTERSECTION

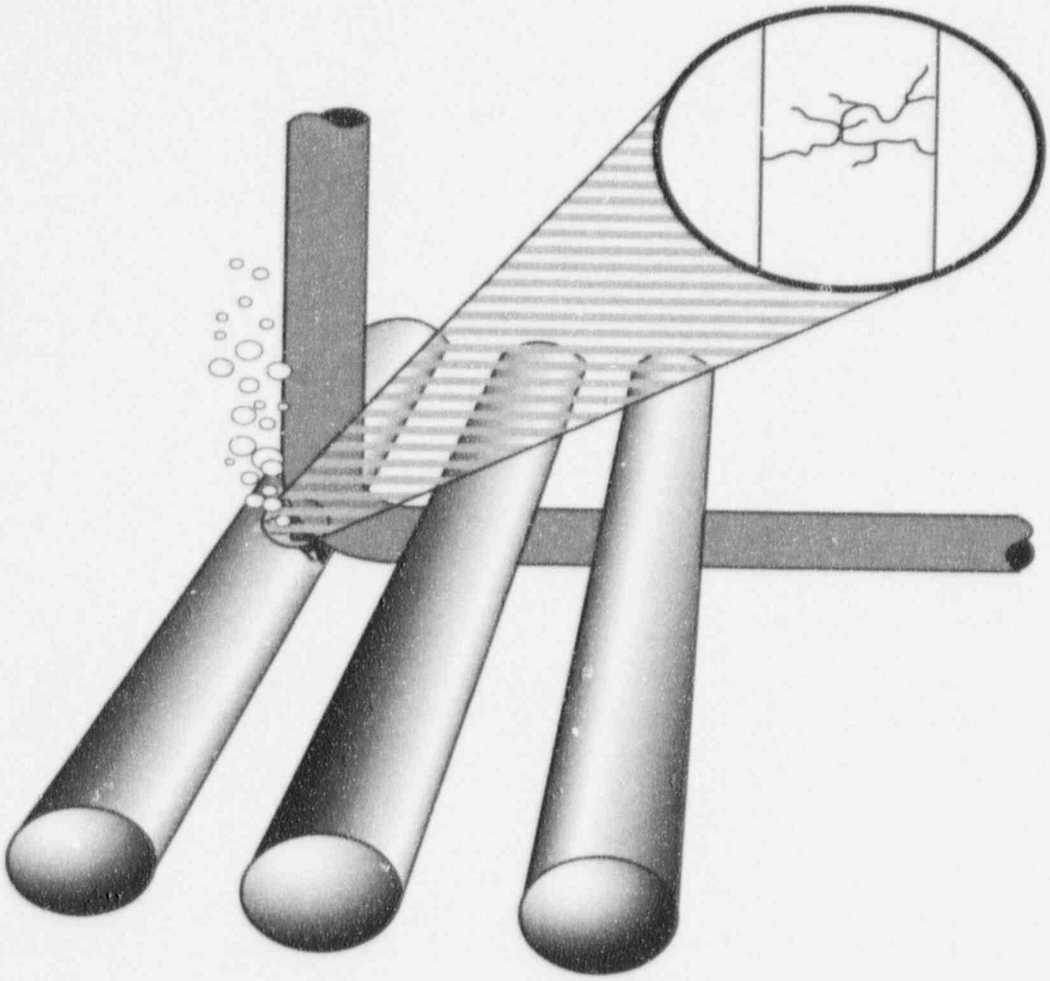


Leak Symptoms:

1. Low leak rates that plateau and grow as more pressure is applied on the steam generator tube are characteristic of the denting process.

2. Other symptoms are similar to those found in Scenario 2.

SCENARIO 6: VIBRATION-INDUCED CRACKING



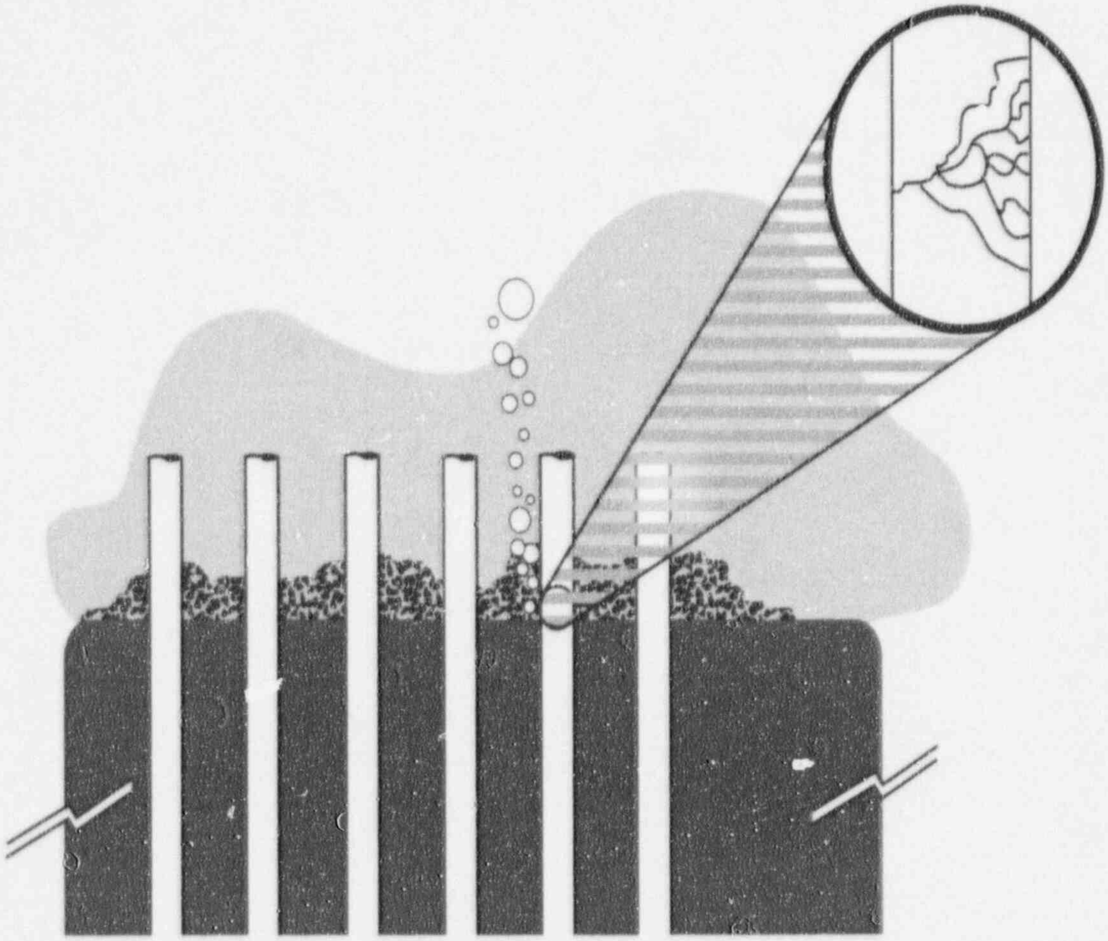
Leak Symptoms:

1. Leakage may or may not start small, but can rapidly increase to tube rupture.

2. Fatigue-type cracks due to vibration may increase very rapidly, giving the impression that they were large at the start.

3. Leakage is readily detected by the air ejector, blowdown and main steam radiation monitors. All isotopes, regardless of volatility and half-life, should be detected. Secondary radioisotopes should simply be a dilution of the RCS less a hideout factor for volatility species.

SCENARIO 7: SLUDGE PILE PITTING/CRACKING



Leak Symptoms:

1. Low l[illegible] are expected at the initiation of primary-to-secondary leakage.

2. Other symptoms are similar to those found in Scenario 2, except that leakage due to pitting is not expected to change following a plant transient.

General Rules of Thumb for Data

1. With the exception of N-16 and Ar-41, activation products are of little or no use in trying to determine a primary-to-secondary leak rate.

2. Copper in steam generator sludge and/or crevice deposits, grab sample lines or radiation monitor sample lines will react with any iodine species present, removing significant radioiodine. This must be taken into consideration when selecting an isotope for primary-to-secondary leak rate calculation.

3. Non-radioactive constituents are generally poor for use in primary-to-secondary leak rate calculations. Boric acid has a high volatility at operating conditions; it is also added to many secondary systems to prevent denting and corrosion in the steam generators. The sensitivity of lithium for use in measuring primary-to-secondary leakage is poor; even ignoring hideout, a 1 gpm primary-to-secondary leak with 2 ppm lithium in the RCS will result in a concentration of only 40 ppb in the affected steam generator at 50 gpm blowdown flow.

4. Steam generator blowdown radiation monitors are generally not as sensitive for primary-to-secondary leakage as the air ejector radiation monitor for the following reasons:

   a. Only the soluble radioactive constituents will remain in the bulk water and be available for detection in the steam generator blowdown. This eliminates all of the noble gases (although xenon is slightly soluble in water), argon-41 and a portion if the iodines.

   b. The sample matrix for the blowdown radiation monitor is water, while the matrix for the air ejector radiation monitor is gas. As a result, the air ejector radiation monitor is subject to much less self-shielding and is therefore more sensitive to the presence of radio-active material.

5. Except for very unique, low-level primary-to-secondary leakage, use of tritium for quantifying leak rates is generally too slow (analytically) and too uncertain (inaccurate water balance, etc.) a technique.

Appendix B

CONDENSER OFF GAS CORRECTIONS

1. Condenser Off Gas Transport Decay Effects

The transport time of radiogas from the steam generator to the condenser off gas sample collection point may be significant, relative to the half life of certain radiogases. This transport time is plant specific and has been known to be as long as 20 minutes. When using a radiogas of a relatively short half life (e.g., Ar-41) the decay associated with the transport time may be significant. An estimate of the specific plant radiogas transport time can be made using the following equation:

$$T = \frac{\ln\left(\frac{A(g)_{xe-133}}{A(g)_{Ar-41}}\right) - \ln\left(\frac{A(rcs)_{xe-133}}{A(rcs)_{Ar-41}}\right)}{\lambda_{Ar-41} - \lambda_{xe-133}} \qquad \text{(eq. B-1)}$$

Where:

T	=	Transport time (in same time units as the half-life)
$A(g)_{(x)}$	=	Activity of identified radionuclide in off gas (µCi/cc)
$A(rcs)_{(x)}$	=	Activity of identified radionuclide in RCS (µCi/cc)
$\lambda_{(x)}$	=	Decay constant of identified radionuclide ($0.693 / t_{1/2}$)

It may be appropriate to make a decay correction if a 20 minute transit time exists and an radionuclide such as Ar-41 (half-life of 110 minutes) is being used to quantify primary-to-secondary leakage. Each plant should evaluate the significance of this transport time relative to the radionuclide of choice used in the primary-to-secondary leak rate calculation. If it is necessary to correct for transport time, perform the following:

Substitute *Ag(c)* for *Ag* in the leak rate calculation in 3.2.2 according to:

$$Ag(c) = \frac{Ag}{e^{-\lambda T}} \qquad \text{(eq. B-2)}$$

Where:

$Ag(c)$ = Activity of the noble gas radionuclide corrected for decay time (μCi/cc)
Ag = Activity of the noble gas radionuclide as measured in the sample (μCi/cc)
T = Transport time (in the same time units as the half-life)
λ = 0.693 divided by the half-life of the noble gas radionuclide

2. Parent/Daughter Relationship Effects

A number of radiogas radionuclides which are typically used for primary-to-secondary leak rate quantification have parent/daughter relationships which can effect the calculation of the leak. For example, I-135 present in the steam generator bulk water decays to Xe-135 which is then removed from the steam generators with the main steam. This can result in approximately a 10-20% error in the conservative direction. There is a similar relationship with I-133 and Xe-133 but the error is much smaller. However, since these errors are in the conservative direction, it is not usually considered necessary to correct the result.

If deemed necessary, this error can be evaluated by comparing the leak rate value with other radionuclides, such as Ar-41 and Kr-85m, for which the parent/daughter relationship effect does not occur.

A parent/daughter effect also exists in measuring dissolved Xenon in a reactor coolant sample. Iodine in the reactor coolant will decay into Xenon after a reactor coolant sample is obtained. If a reactor coolant sample is not analyzed promptly, this effect is minimized and need not be considered. However, since this error is in the non-conservative direction, care should be taken to minimize this error.

Each plant should evaluate the significant of these parent/daughter relationships and incorporate them in the condenser off gas primary to secondary leak rate calculation if it is considered significant.

Appendix C

LEAK RATE CALCULATION METHODOLOGY FOR THE BLOWDOWN ANALYSIS

This section discusses the derivation and calculational methodology of primary-to-secondary leak rate determination by analysis of steam generator blowdown. This analysis utilizes an "activity" balance around a single steam generator which is used to quantity the leak rate in that particular steam generator under all conditions including transient conditions.

The use of this analysis provides an instantaneous leak rate at the time samples were taken. This analysis does not provide a total leak rate of all steam generators but the individual leak rate for which the "activity" balance is being performed around.

A solution to the differential equation describing the instantaneous leak rate provides a calculation that can be used under all conditions to determine the primary-to-secondary leak rate. Unfortunately, because of the many uncertainties associated with the sampling and analyses required to provide a solution to the transient leak rate the use of this solution is generally not practical. Some assumptions and simplifications can be made, as discussed below, to determine a non-steady state leak rate.

1.0 The Relationship Transient Leak Rate

A relationship describing a primary-to-secondary leak in a single steam generator can be developed by developing an "activity" balance around a leaking steam generator. This relationship can be described as follows: the change in the activity concentration in a steam generator is the difference between the activity being added (leak rate and feedwater) and what is being removed (blowdown, decay and main steam). Hideout is intentionally ignored for this application. Presented below is the differential equation describing this "activity" balance:

$$V_{SG}\frac{dA_{SG}}{dt} = \left[\left(F_{FW}A_{FW}\right)+\left(LRA_{RCS}\right)\right]-\left[\left(F_{S}A_{S}\right)+\left(F_{BD}A_{SG}\right)+\left(V_{SG}\lambda A_{SG}\right)\right] \qquad \text{(eq. C-1)}$$

Where:

A_{SG} = Activity concentration in the steam generator bulk water
A_{FW} = Activity concentration in the feedwater
A_{RCS} = Activity concentration in the reactor coolant
A_S = Activity concentration in the main steam
V_{SG} = Apparent steam generator volume
F_{FW} = Feedwater flow to the individual steam generator
LR = Primary-to-secondary leak rate
F_S = Main steam flow from the individual steam generator
F_{BD} = Blowdown flow rate
λ = Decay constant

2.0 The Simplified Transient

The solution to the transient relationship is complicated and relies on obtaining precise results of a number of activity samples and flow rates at two discrete times. (See Appendix D for more information of non-equilibrium conditions.) Due to the inherent errors and assumptions in the data used for the analysis, the benefits achieved in using this solution will be offset by a significant error associated with the solution. However, a number of assumptions can be made to simplify the transient solution. If it is assumed that these is no carryover of activity and that at time equals zero (t_0), there is no primary-to-secondary leak the simplified transient relationship becomes:

$$A_{SG} = \frac{A_{RCS} LR \left[1 - e^{-(\lambda + B)t}\right]}{V_{SG} \lambda F_{BD}} \qquad \text{(eq. C-2)}$$

Where:

B = Blowdown rate divided by apparent steam generator volume
t = Time from the initial indication of the leak to when the sample was obtained

In many cases, the "no carryover" of activity assumption may be appropriate. The error associated with the assumption that the steam carryover activity fraction equals the feedwater activity fraction may be small compared with the other errors associated with the solution, unless there is a condensate polisher in the system. In this case, the feedwater activity fraction must be evaluated (refer to Section 3.2 of this appendix). Each plant should evaluate the significance of these assumption before using the simplified transient solution presented above.

3.0 The Steady State Solution

The transient relationship can be simplified as follows during steady state conditions.

$$(F_{FW}A_{FW})+(LRA_{RCS})=(F_SA_S)+(F_{BD}A_{SG})+(\lambda[V_{SG}A_{SG}]) \quad \text{(eq. C-3)}$$

The leak rate can be determined by solving for *LR* in the above equation. Difficulties may exist in obtaining good samples and analyses for the feedwater and main steam activity concentrations, but as previously discussed, it may be appropriate to ignore both terms by assuming the steam carryover activity fraction equals the feedwater activity fraction. However, if it is determined that this assumption is not appropriate and the feedwater and main steam activity concentrations can not be accurately determined on a routine basis, the individual steam generator activities can generally be used in place of these terms as described below.

3.1 *Main Steam Activity Concentration*

Soluble isotopes present in the bulk water of the steam generators are carried off with the main steam due to partitioning and due to moisture carryover. Iodine partially partitions between the main steam and the steam generator bulk water to such an extent that approximately equal masses are distributed between the two sources. Sodium will in general, not partition into the steam but remain in the bulk water. Steam generator moisture carryover will, in most cases, be a much more significant factor in removing soluble activity from the steam generators and into the main steam. The moisture carryover from a steam generator is in general near 0.2% although variations exist between individual steam generators. The actual moisture carry should be known. A moisture carryover of 0.2% means 0.2% of the main steam contains soluble activity at the same concentration in the steam generator bulk water. The main steam portion of the steady state leak rate equation can therefore be represented as follows:

$$F_SA_S = F_S\ MC\ A_{SG} \quad \text{(eq. C-4)}$$

Where:
MC = Moisture carryover fraction from the individual steam generator

3.2 *Feedwater Activity Concentration*

The soluble activity which is carried over from the steam generators is ultimately condensed and returned to each steam generator in the feedwater. However, the contaminated main steam leaving the leaking steam generator is condensed and diluted with the main steam condensate from the other (non-leaking) steam generators. If the actual activity concentration in the feedwater cannot be accurately measured, it can be calculated by taking an average of the activity being removed from each steam generator. The feedwater portion of the steady state leak rate equation can therefore be represented as follows:

$$F_{FW}A_{FW} = F_{FW}\left[\frac{MC_A A_{SCA} F_{SA} + MC_B A_{SGB} F_{SGB} + \ldots}{F_{SA} + F_{FB} + \ldots}\right] \quad \text{(eq. C-5)}$$

Where:

F_{FW} = Flow rate of feedwater to the individual steam generator

MC_i = Moisture carryover fraction from steam generator i

F_{Si} = Flow rate of main steam from steam generator

A_{SCi} = Activity concentration from steam generator i

A simplification can be made if one assumes:

$$F_{SA} = F_{SB} = \ldots \quad \text{(eq. C-6)}$$

and

$$F_{SA} = F_{FWA}; F_{SB} = F_{FWB} \ldots\ldots \quad \text{(eq. C-7)}$$

then:

$$F_{FW} \cdot A_{FW} = \frac{F_{FW}}{n} \cdot \left[MC_A \cdot A_{SGA} + MC_B \cdot A_{SGB} + \ldots\right](1 - f) \quad \text{(eq. C-8)}$$

Where:

n = Number of steam generators

For plants with a condensate polisher, a portion of the soluble activity will be present in the condenser condensate and will be removed by the polishers. The partitioning of the soluble activity in the MSRs will determine what fraction of the activity will be present in the condensate. For example, it would be typical for less than 10% of the soluble iodine activity in the main steam to reach the condenser hotwells for some plant designs. Most of the soluble activity would drain forward to the heater drain tank.

Adding a condensate polishing factor to the above equation for the feedwater portion of the steady state solution results in the following:

$$F_{FW} \cdot A_{FW} = \frac{F_{FW}}{n} \cdot \left[MC_A \cdot A_{SGA} + MC_B \cdot A_{SGB} + \ldots\right](1 - f) \quad \text{(eq. C-9)}$$

Where:

f = Partition fraction of soluble isotopic activity in the main steam which reaches the condenser hotwells

Each plant with condensate polishers will need to quantify the value of the partition factor "f" for the isotope of choice.

4.0 Simplified Leak Rates in Equilibrium and Non-Equilibrium

The following calculation methodologies use sodium -24 as the example, but any other of the isotope selection can be substitutes. These methodologies are for isotopes prior to and after equilibrium. The advantage of the short-lived isotopes is that with a high ion exchange removal the time to equilibrium can be as short as one hour.

4.1 *Sodium-24 Calculation Prior to Equilibrium*

$$Leakrate\,(gpd) = \frac{A_{sB1} V_s Q_s}{A_p\left(1 - e^{-Q_s t_L}\right)} \qquad \text{(eq. C-10)}$$

Where:

A_{sB1} = The sodium-24 activity of the steam generator before the blowdown demineralizer
V_s = Volume of the steam generator
t_L = Duration of the leak
A_p = Sodium-24 activity in the primary coolant
Q_s = The removal constant for sodium-24. as calculated by the following:

$$Q_s = \lambda + \left[\frac{F_{d1}}{V_s}\left(\frac{A_{sB1} - A_{sA1}}{A_{sB1}}\right)\right] + \left[\frac{F_{d2}}{V_s}\left(\frac{A_{sB2} - A_{sA2}}{A_{sB2}}\right)\right]$$

Where:

λ = Sodium-24 decay constant ($0.693/t_{1/2}$)
V_s = Volume of secondary system
F_{d1} = Flow through blowdown demineralizer
A_{sB1} = Sodium-24 activity before blowdown demineralizer
A_{sA1} = Sodium-24 activity after blowdown demineralizer
F_{d2} = Flow through the condensate polisher
A_{sB2} = Sodium-24 activity before the condensate polisher
A_{sA2} = Sodium-24 activity after the condensate polisher

NOTE: If the DFs for the blowdown demineralizer (X_1) and the condensate polisher (X_2) are known or an approximation of the leak rate is to be calculated using an estimation of the DFs, then Q_s can be calculated by:

$$Q_s = \lambda + X_1 + X_2 \qquad \text{(eq. C-12)}$$

Under certain conditions, a powdered resin polisher DF can be very small and its value may be very small and its value may be neglected in the calculation. For a deep bed condensate polisher or blowdown demineralizer, a DF of 90% can be assumed for estimation purposes.

4.2 Sodium-24 Calculation at Equilibrium

$$Leak\ rate(gpd) = \frac{A_{sB1}V_s\lambda + F_{d1}(A_{sB1} - A_{sA1}) + \left(\frac{A_{sB1}F_{d2}(A_{sB1}F_{d2}(A_{sB2} - A_{sA2}))}{A_{sB2}}\right)}{A_p} \qquad \text{(eq. C-13)}$$

Where:

A_{sB1}	=	Sodium-24 activity before blowdown demineralizer
V_s	=	Volume of steam generator
λ	=	Sodium-24 decay constant ($0.693/t_{1/2}$)
F_{d1}	=	Flow through blowdown demineralizer
A_{sA1}	=	Sodium-24 activity after blowdown demineralizer
F_{d2}	=	Flow through the condensate polisher
A_{sB2}	=	Sodium-24 activity before the condenser polisher
A_{sA2}	=	Sodium-24 activity after the condenser polisher
A_p	=	Sodium-24 activity in the primary coolant

NOTE: If the DFs for the blowdown demineralizer (X_1) and the condensate polisher (X_2) are known or an approximation of the leak rate is to be calculated using an estimation of the DFs, then the leak rate can be calculated by:

$$Leakrate(gpd) = \frac{A_sV_s(\lambda + X_1 + X_2)}{A_p} \qquad \text{(eq. C-14)}$$

Where:

A_s = A_{sB1}

NOTE: Under certain conditions, a powdered resin condensate polisher DF can be very small and its value may be neglected in the calculation. For a deep bed condensate polisher or blowdown demineralizer, a DF of 90% can be assumed for estimation purposes.

Appendix D

CALCULATION OF PRIMARY-TO-SECONDARY LEAK RATE FROM BLOWDOWN ANALYSIS DURING NON-EQUILIBRIUM CONDITIONS

This section discusses the derivation and calculation methodology during non-equilibrium conditions of the isotope of choice. This analysis assumes that the leak rate does not change during the period from the start of the leak until the quantification of the leak rate, i.e., an instantaneous leak of constant rate. It also assumes that the time of initiation of the leak is accurately known. Additionally, the assumption is made that the activity of the radionuclide in the reactor coolant system is already in an equilibrium condition. This calculation methodology was developed for the specific case where the plant will begin a rapid shutdown and a leak rate is to be determined from a single sample.

1.0 Analysis:

When a primary to secondary leak occurs, the concentration of each radionuclide in the secondary system will increase until the removal rate equals the rate of introduction, i.e., equilibrium has been achieved.

Removal of the radionuclide from the affected steam generator is by radioactive decay, removal by blowdown, sampling, carryover in the steam cycle and other factors. The major factors considered in this analysis will be removal by radioactive decay and removal by blowdown. The removal rate by radioactive decay per unit time is given by the decay constant, λ:

$$\lambda = 0.693 / t_{1/2} \quad \text{(eq. D-1)}$$

The removal rate by blowdown per unit time is given by the blowdown constant, β

β = blowdown flow rate/mass of the system,
mass per time /mass, or
volume per time/volume

The blowdown half-life ($p\frac{1}{2}$) is given by:

$$p1/2 = 0.693/\beta \qquad \text{(eq. D-2)}$$

The effective removal rate (τ) per unit time is the sum of all the removal rates

$$\tau = \lambda + \beta \qquad \text{(eq. D-3)}$$

The effective half-life (eff(1/2)) is given by:

$$eff(1/2) = 0.693/\tau \qquad \text{(eq. D-4)}$$

Introduction of the radionuclide into the affected steam generator is by transfer from the primary side and for some radionuclides the decay of a parent nuclide. This analysis will consider only the transfer of the radionuclide from the primary side. It must be remembered that even as the radionuclide is being introduced into the steam generator it is being removed by both radioactive decay and by blowdown. The equation which describes the growth of radionuclide subject only to decay is:

$$\text{Rate} = \text{Activity}/\left(1-e^{-\lambda t}\right) \qquad \text{(eq. D-5)}$$

The factor $\left(1-e^{-\lambda t}\right)$ is known as the Saturation Factor or Equilibrium Fraction. As t becomes large with respect to λ, the Saturation Factor nears 1, i.e., an equilibrium condition has been achieved. The Saturation Factor can be used to determine the equilibrium activity of the radionuclide if the time is known.

For the case of a steam generator tube leak, the decay constant must be replaced with the effective removal rate (τ) due to the removal by both radioactive decay and by blowdown. Thus the Saturation Factor can be modified to become $\left(1-e^{-\tau t}\right)$.

The basic equation for describing a primary to secondary leak at equilibrium is given by:

$$LR = A_{SEC}\frac{\left(Bldn+(\lambda V)\right)}{A_{RCS}} \qquad \text{(eq. D-6)}$$

Where:

LR	=	Leak rate
A_{SEC}	=	Secondary activity
$Bldn$	=	Blowdown rate
λ	=	Decay constant
V	=	Steam generator volume
A_{RCS}	=	Primary Activity

In order to determine the leak rate at non equilibrium conditions the secondary activity must be corrected to its equilibrium value by dividing the activity in the secondary side at time t after the leak has commenced by the modified saturation factor $\left(1-e^{-\tau t}\right)$.

Thus the modified leak rate calculation now becomes:

$$LR = \frac{A_{SEC}\left(Bldn + (\lambda V)\right)}{A_{RCS}\left(1-e^{-\tau t}\right)} \quad \text{(eq. D-7)}$$

As the activity in the secondary side approaches equilibrium the modified Saturation Factor approaches 1 and does not affect the calculation. See Figure D-1 for a graphical representation of a calculation for Cs-138.

2.0 Example

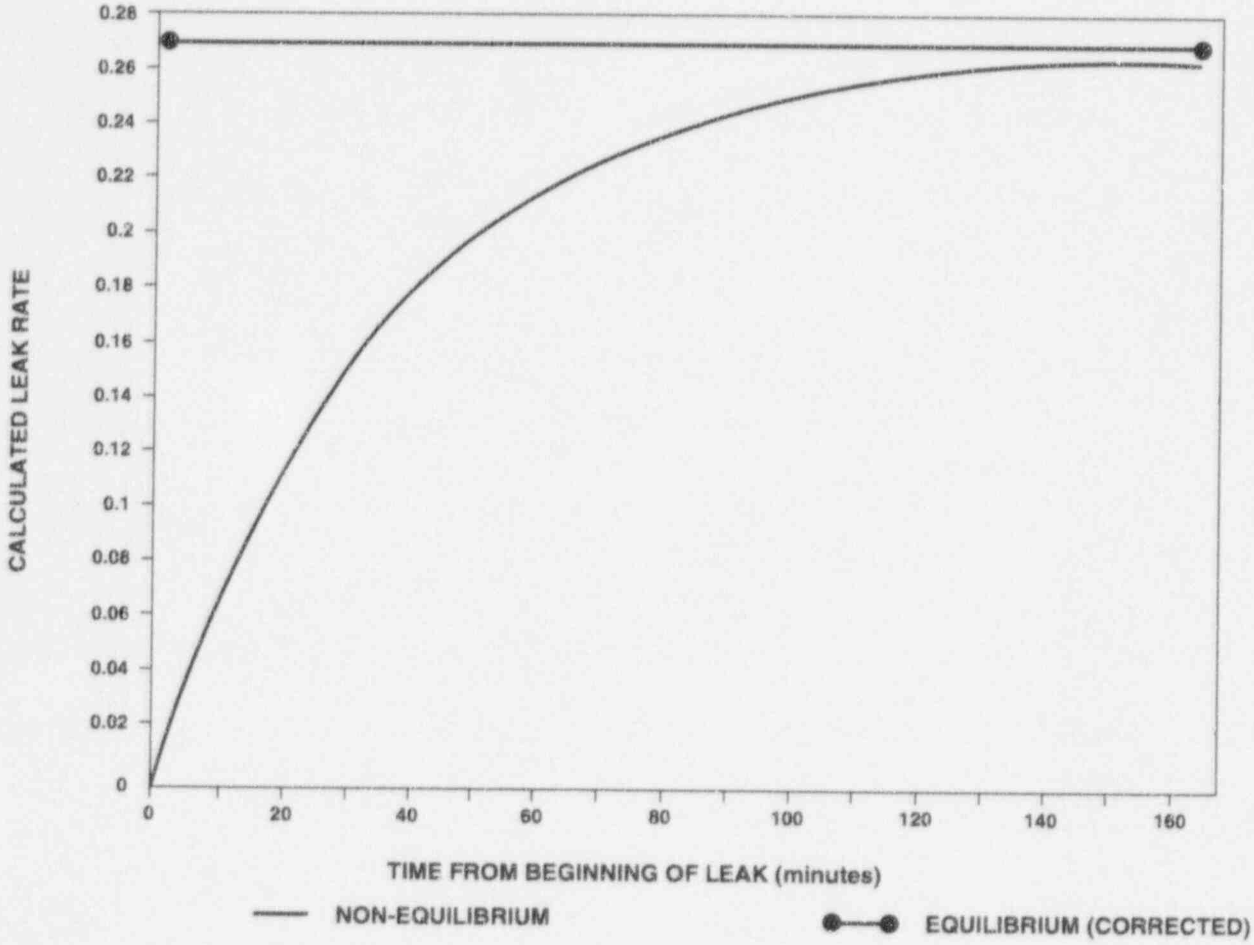
Table D-1 is a computer printout that details the approach to equilibrium for Cs-138 activity in the steam generator during the approach to equilibrium following a steam generator tube leak. It is assumed that the following are constant during the approach to equilibrium:

- Primary side Cs-138 activity
- Leak rate
- Reactor power level
- Blowdown flow rate
- Steam generator mass

These calculations are based on the use of the effective removal rate (τ) in calculating the Saturation Factor.

It should be noted that the calculated equilibrium leak rate for an incremental time of 5.18 minutes is initially 0.2491 gallons per minute and approaches 0.2327 gallons per minute when it is given that the actual leak rate is 0.2700 gallons per minute. This is due to the large increment between discrete calculations for removal by decay and blowdown. When the increment between calculations is decreased to 0.518 minutes the calculated equilibrium leak rate is initially 0.2681 gallons per minute and approaches 0.2675 gallons per minute versus the actual leak rate of 0.2700 gallons per minute. As the increment between calculations approaches 0 the calculated leak rate will approach the actual value.

Figure D-1: Equilibrium Corrected Leak Rate Based on Cs-138
(Hideout Not Considered)



Notes for Table D-1

The following information applies to the printout shown in Table D-1:

Time (min)

This is the incremental time between "addition" to the steam generator. All of the activity is added at the beginning of the increment. As the incremental time approaches zero, the addition becomes constant, thus approaching a dynamic system.

Activity Added (μCi)

Calculated by multiplying the leak rate (gallons/minute) by the activity concentration (μCi/g) and a conversion factor (3785.4 g/gal) and the time between "additions".

Total Activity (μCi)

Calculated by adding the previous "Balance Activity" from the previous time increment to the "Added Activity" for the present time increment.

Balance Activity (μCi)

This is the activity remaining at the end of the time increment after correction for decay and removal by blowdown.

Activity Conc. (μCi/g)

Calculated by dividing the "Balance Activity" (μCi) by the steam generator volume (gallons) and multiplying by a conversion factor (1 gal/3785.4 g)

Instan. Leak Rate (gal/min)

Calculated using the classical "equilibrium" leak rate equation.

Equilibrium Leak Rate (gal/min)

Modified leak rate calculation

Table D-1

VOL S/G	11.500			
LEAK RATE	0.27 GPM	LEAKRATE	388.8 GPD	
PRIM ACT	8.438E-03 uCi/g			
BLOWDOWN	60 GPM	BETA	5.217E-03 /m	
HALFLIFE	32.2 m	LAMBDA	2.153E-02 /m	
EFF H-L	25.918 m	REMOVAL	2.674E-02 /m	
INCREMENT	5.1836 m			

TIME (m)	ACTIVITY ADDED	TOTAL ACITIVITY	BALANCE ACTIVITY	ACTIVITY CONC.	INSTAN. LEAKRATE	EQUILIBRIUM LEAKRATE	
5.184E+00	4.470E+01	4.470E+01	3.851E+01	8.846E-07	3.224E-02	2.491E-01	12.94%
1.037E+01	4.470E+01	8.321E+01	7.168E+01	1.646E-06	6.001E-02	2.478E-01	24.21%
1.555E+01	4.470E+01	1.164E+02	1.002E+02	2.303E-06	8.393E-02	2.467E-01	34.02%
2.073E+01	4.470E+01	1.449E+02	1.249E+02	2.868E-06	1.045E-01	2.456E-01	42.56%
2.592E+01	4.470E+01	1.696E+02	1.461E+02	3.355E-06	1.223E-01	2.446E-01	50.00%
3.110E+01	4.470E+01	1.908E+02	1.643E+02	3.775E-06	1.376E-01	2.436E-01	56.47%
3.629E+01	4.470E+01	2.090E+02	1.800E+02	4.136E-06	1.507E-01	2.427E-01	62.11%
4.147E+01	4.470E+01	2.247E+02	1.936E+02	4.447E-06	1.621E-01	2.419E-01	67.01%
4.665E+01	4.470E+01	2.383E+02	2.053E+02	4.715E-06	1.719E-01	2.411E-01	71.28%
5.184E+01	4.470E+01	2.500E+02	2.153E+02	4.946E-06	1.803E-01	2.404E-01	75.00%
5.702E+01	4.470E+01	2.600E+02	2.240E+02	5.145E-06	1.875E-01	2.397E-01	78.24%
6.220E+01	4.470E+01	2.687E+02	2.314E+02	5.316E-06	1.938E-01	2.391E-01	81.05%
6.739E+01	4.470E+01	2.761E+02	2.379E+02	5.464E-06	1.991E-01	2.385E-01	83.51%
7.257E+01	4.470E+01	2.826E+02	2.434E+02	5.591E-06	2.038E-01	2.379E-01	85.64%
7.775E+01	4.470E+01	2.881E+02	2.482E+02	5.700E-06	2.078E-01	2.375E-01	87.50%
8.294E+01	4.470E+01	2.929E+02	2.523E+02	5.795E-06	2.112E-01	2.370E-01	89.12%
8.812E+01	4.470E+01	2.970E+02	2.558E+02	5.875E-06	2.142E-01	2.366E-01	90.53%
9.330E+01	4.470E+01	3.005E+02	2.588E+02	5.946E-06	2.167E-01	2.362E-01	91.75%
9.849E+01	4.470E+01	3.035E+02	2.615E+02	6.006E-06	2.189E-01	2.359E-01	92.82%
1.037E+02	4.470E+01	3.062E+02	2.637E+02	6.058E-06	2.208E-01	2.355E-01	93.75%
1.089E+02	4.470E+01	3.084E+02	2.657E+02	6.103E-06	2.224E-01	2.352E-01	94.56%
1.140E+02	4.470E+01	3.104E+02	2.673E+02	6.141E-06	2.238E-01	2.350E-01	95.26%
1.192E+02	4.470E+01	3.121E+02	2.688E+02	6.175E-06	2.251E-01	2.347E-01	95.88%
1.244E+02	4.470E+01	3.135E+02	2.700E+02	6.203E-06	2.261E-01	2.345E-01	96.41%
1.296E+02	4.470E+01	3.147E+02	2.711E+02	6.228E-06	2.270E-01	2.343E-01	96.87%
1.348E+02	4.470E+01	3.158E+02	2.720E+02	6.249E-06	2.278E-01	2.341E-01	97.28%
1.400E+02	4.470E+01	3.167E+02	2.728E+02	6.267E-06	2.284E-01	2.340E-01	97.63%
1.451E+02	4.470E+01	3.175E+02	2.735E+02	6.283E-06	2.290E-01	2.338E-01	97.94%
1.503E+02	4.470E+01	3.182E+02	2.741E+02	6.297E-06	2.295E-01	2.337E-01	98.21%
1.555E+02	4.470E+01	3.188E+02	2.746E+02	6.308E-06	2.299E-01	2.336E-01	98.44%
1.607E+02	4.470E+01	3.193E+02	2.750E+02	6.318E-06	2.303E-01	2.335E-01	98.64%
1.659E+02	4.470E+01	3.198E+02	2.754E+02	6.327E-06	2.306E-01	2.334E-01	98.82%
1.711E+02	4.470E+01	3.201E+02	2.758E+02	6.334E-06	2.309E-01	2.333E-01	98.97%
1.762E+02	4.470E+01	3.205E+02	2.760E+02	6.341E-06	2.311E-01	2.332E-01	99.10%
1.814E+02	4.470E+01	3.207E+02	2.763E+02	6.346E-06	2.313E-01	2.331E-01	99.22%
1.866E+02	4.470E+01	3.210E+02	2.765E+02	6.351E-06	2.315E-01	2.331E-01	99.32%
1.918E+02	4.470E+01	3.212E+02	2.767E+02	6.355E-06	2.316E-01	2.330E-01	99.41%
1.970E+02	4.470E+01	3.214E+02	2.768E+02	6.359E-06	2.318E-01	2.330E-01	99.48%
2.022E+02	4.470E+01	3.215E+02	2.769E+02	6.362E-06	2.319E-01	2.329E-01	99.55%
2.073E+02	4.470E+01	3.216E+02	2.771E+02	6.364E-06	2.320E-01	2.329E-01	99.61%
2.125E+02	4.470E+01	3.218E+02	2.772E+02	6.367E-06	2.321E-01	2.329E-01	99.66%
2.177E+02	4.470E+01	3.219E+02	2.772E+02	6.369E-06	2.321E-01	2.329E-01	99.70%
2.229E+02	4.470E+01	3.219E+02	2.773E+02	6.370E-06	2.322E-01	2.328E-01	99.74%
2.281E+02	4.470E+01	3.220E+02	2.774E+02	6.372E-06	2.322E-01	2.328E-01	99.78%
2.333E+02	4.470E+01	3.221E+02	2.774E+02	6.373E-06	2.323E-01	2.328E-01	99.80%
2.384E+02	4.470E+01	3.221E+02	2.775E+02	6.374E-06	2.323E-01	2.327E-01	99.83%
2.436E+02	4.470E+01	3.222E+02	2.775E+02	6.375E-06	2.324E-01	2.327E-01	99.85%
2.488E+02	4.470E+01	3.222E+02	2.776E+02	6.376E-06	2.324E-01	2.327E-01	99.87%
2.540E+02	4.470E+01	3.223E+02	2.776E+02	6.377E-06	2.324E-01	2.327E-01	99.89%
2.592E+02	4.470E+01	3.223E+02	2.776E+02	6.377E-06	2.324E-01	2.327E-01	99.90%

VOL S/G	11,500				
LEAK RATE	0.27	GPM	LEAKRATE	388.8	GPD
PRIM ACT	8.438E-03	uCi/g			
BLOWDOWN	60	GPM	BETA	5.217E-03	/m
HALFLIFE	32.2	m	LAMBLA	2.153E-02	/m
EFF H-L	25.918	m	REMOVAL	2.674E-02	/m
INCREMENT	0.51836	m			

TIME (m)	ACTIVITY ADDED	TOTAL ACITIVITY	BALANCE ACTIVITY	ACTIVITY CONC.	INSTAN. LEAKRATE	EQUILIBRIUM LEAKRATE	
5.184E-01	4.470E+00	4.470E+00	4.408E+00	1.013E-07	3.691E-03	2.681E-01	1.38%
1.037E+00	4.470E+00	8.879E+00	8.756E+00	2.011E-07	7.331E-03	2.681E-01	2.73%
1.555E+00	4.470E+00	1.323E+01	1.304E+01	2.996E-07	1.092E-02	2.681E-01	4.07%
2.073E+00	4.470E+00	1.751E+01	1.727E+01	3.967E-07	1.446E-02	2.681E-01	5.39%
2.592E+00	4.470E+00	2.174E+01	2.144E+01	4.925E-07	1.795E-02	2.681E-01	6.70%
3.110E+00	4.470E+00	2.591E+01	2.555E+01	5.869E-07	2.139E-02	2.680E-01	7.98%
3.629E+00	4.470E+00	3.002E+01	2.960E+01	6.801E-07	2.479E-02	2.680E-01	9.25%
4.147E+00	4.470E+00	3.408E+01	3.360E+01	7.719E-07	2.813E-02	2.680E-01	10.50%
4.665E+00	4.470E+00	3.807E+01	3.755E+01	8.625E-07	3.144E-02	2.680E-01	11.73%
5.184E+00	4.470E+00	4.202E+01	4.143E+01	9.518E-07	3.469E-02	2.680E-01	12.94%
5.702E+00	4.470E+00	4.590E+01	4.527E+01	1.040E-06	3.790E-02	2.680E-01	14.14%
6.220E+00	4.470E+00	4.974E+01	4.905E+01	1.127E-06	4.107E-02	2.680E-01	15.33%
6.739E+00	4.470E+00	5.352E+01	5.278E+01	1.212E-06	4.419E-02	2.680E-01	16.49%
7.257E+00	4.470E+00	5.725E+01	5.645E+01	1.297E-06	4.727E-02	2.679E-01	17.64%
7.775E+00	4.470E+00	6.092E+01	6.008E+01	1.380E-06	5.030E-02	2.679E-01	18.77%
8.294E+00	4.470E+00	6.455E+01	6.366E+01	1.462E-06	5.330E-02	2.679E-01	19.89%
8.812E+00	4.470E+00	6.813E+01	6.718E+01	1.543E-06	5.625E-02	2.679E-01	21.00%
9.330E+00	4.470E+00	7.165E+01	7.066E+01	1.623E-06	5.916E-02	2.679E-01	22.08%
9.849E+00	4.470E+00	7.513E+01	7.409E+01	1.702E-06	6.203E-02	2.679E-01	23.16%
1.037E+01	4.470E+00	7.856E+01	7.747E+01	1.780E-06	6.486E-02	2.679E-01	24.21%
1.089E+01	4.470E+00	8.194E+01	8.080E+01	1.856E-06	6.765E-02	2.679E-01	25.26%
1.140E+01	4.470E+00	8.527E+01	8.409E+01	1.932E-06	7.041E-02	2.678E-01	26.29%
1.192E+01	4.470E+00	8.856E+01	8.733E+01	2.006E-06	7.312E-02	2.678E-01	27.30%
1.244E+01	4.470E+00	9.180E+01	9.053E+01	2.080E-06	7.580E-02	2.678E-01	28.30%
1.296E+01	4.470E+00	9.500E+01	9.368E+01	2.152E-06	7.844E-02	2.678E-01	29.29%
1.348E+01	4.470E+00	9.816E+01	9.679E+01	2.224E-06	8.104E-02	2.678E-01	30.26%
1.400E+01	4.470E+00	1.013E+02	9.986E+01	2.294E-06	8.361E-02	2.678E-01	31.22%
1.451E+01	4.470E+00	1.043E+02	1.029E+02	2.363E-06	8.614E-02	2.678E-01	32.17%
1.503E+01	4.470E+00	1.074E+02	1.059E+02	2.432E-06	8.864E-02	2.678E-01	33.10%
1.555E+01	4.470E+00	1.103E+02	1.088E+02	2.499E-06	9.110E-02	2.678E-01	34.02%
1.607E+01	4.470E+00	1.133E+02	1.117E+02	2.566E-06	9.353E-02	2.677E-01	34.93%
1.659E+01	4.470E+00	1.162E+02	1.146E+02	2.632E-06	9.593E-02	2.677E-01	35.83%
1.711E+01	4.470E+00	1.190E+02	1.174E+02	2.697E-06	9.829E-02	2.677E-01	36.71%
1.762E+01	4.470E+00	1.219E+02	1.202E+02	2.760E-06	1.006E-01	2.677E-01	37.58%
1.814E+01	4.470E+00	1.246E+02	1.229E+02	2.823E-06	1.029E-01	2.677E-01	38.44%
1.866E+01	4.470E+00	1.274E+02	1.256E+02	2.886E-06	1.052E-01	2.677E-01	39.29%
1.918E+01	4.470E+00	1.301E+02	1.283E+02	2.947E-06	1.074E-01	2.677E-01	40.13%
1.970E+01	4.470E+00	1.328E+02	1.309E+02	3.007E-06	1.096E-01	2.677E-01	40.95%
2.022E+01	4.470E+00	1.354E+02	1.335E+02	3.067E-06	1.118E-01	2.677E-01	41.76%
2.073E+01	4.470E+00	1.380E+02	1.361E+02	3.126E-06	1.139E-01	2.676E-01	42.56%
2.125E+01	4.470E+00	1.405E+02	1.386E+02	3.184E-06	1.160E-01	2.676E-01	43.36%
2.177E+01	4.470E+00	1.431E+02	1.411E+02	3.241E-06	1.181E-01	2.676E-01	44.14%
2.229E+01	4.470E+00	1.455E+02	1.435E+02	3.297E-06	1.202E-01	2.676E-01	44.90%
2.281E+01	4.470E+00	1.480E+02	1.459E+02	3.353E-06	1.222E-01	2.676E-01	45.66%
2.333E+01	4.470E+00	1.504E+02	1.483E+02	3.407E-06	1.242E-01	2.676E-01	46.41%
2.384E+01	4.470E+00	1.528E+02	1.507E+02	3.461E-06	1.262E-01	2.676E-01	47.15%
2.436E+01	4.470E+00	1.552E+02	1.530E+02	3.515E-06	1.281E-01	2.676E-01	47.88%
2.488E+01	4.470E+00	1.575E+02	1.553E+02	3.567E-06	1.300E-01	2.676E-01	48.59%
2.540E+01	4.470E+00	1.598E+02	1.575E+02	3.619E-06	1.319E-01	2.676E-01	49.30%
2.592E+01	4.470E+00	1.620E+02	1.598E+02	3.670E-06	1.338E-01	2.675E-01	50.00%

Table D-1 (cont'd.)

VOL S/G	11.500				
LEAK RATE	0.27	GPM	LEAKRATE	388.8	GPD
PRIM ACT	8.438E-03	uCi/g			
BLOWDOWN	60	GPM	BETA	5.217E-03	/m
HALFLIFE	32.2	m	LAMBDA	2.153E-02	/m
EFF H-L	25.918	m	REMOVAL	2.674E-02	/m
INCREMENT	0.051836	m			

TIME (m)	ACTIVITY ADDED	TOTAL ACITIVITY	BALANCE ACTIVITY	ACTIVITY CONC.	INSTAN. LEAKRATE	EQUILIBRIUM LEAKRATE	
5.184E-02	4.470E-01	4.470E-01	4.464E-01	1.025E-08	3.738E-04	2.698E-01	0.14%
1.037E-01	4.470E-01	8.935E-01	8.922E-01	2.050E-08	7.470E-04	2.698E-01	0.28%
1.555E-01	4.470E-01	1.339E+00	1.337E+00	3.072E-08	1.120E-03	2.698E-01	0.42%
2.073E-01	4.470E-01	1.784E+00	1.782E+00	4.093E-08	1.492E-03	2.698E-01	0.55%
2.592E-01	4.470E-01	2.229E+00	2.226E+00	5.113E-08	1.864E-03	2.698E-01	0.69%
3.110E-01	4.470E-01	2.673E+00	2.669E+00	6.132E-08	2.235E-03	2.698E-01	0.83%
3.629E-01	4.470E-01	3.116E+00	3.112E+00	7.149E-08	2.606E-03	2.698E-01	0.97%
4.147E-01	4.470E-01	3.559E+00	3.554E+00	8.164E-08	2.976E-03	2.698E-01	1.10%
4.665E-01	4.470E-01	4.001E+00	3.996E+00	9.178E-08	3.345E-03	2.698E-01	1.24%
5.184E-01	4.470E-01	4.443E+00	4.436E+00	1.019E-07	3.715E-03	2.698E-01	1.38%
5.702E-01	4.470E-01	4.883E+00	4.877E+00	1.120E-07	4.083E-03	2.698E-01	1.51%
6.220E-01	4.470E-01	5.324E+00	5.316E+00	1.221E-07	4.451E-03	2.698E-01	1.65%
6.739E-01	4.470E-01	5.763E+00	5.755E+00	1.322E-07	4.819E-03	2.698E-01	1.79%
7.257E-01	4.470E-01	6.202E+00	6.194E+00	1.423E-07	5.186E-03	2.698E-01	1.92%
7.775E-01	4.470E-01	6.641E+00	6.632E+00	1.523E-07	5.553E-03	2.698E-01	2.06%
8.294E-01	4.470E-01	7.079E+00	7.069E+00	1.624E-07	5.919E-03	2.698E-01	2.19%
8.812E-01	4.470E-01	7.516E+00	7.506E+00	1.724E-07	6.284E-03	2.698E-01	2.33%
9.330E-01	4.470E-01	7.953E+00	7.942E+00	1.824E-07	6.649E-03	2.698E-01	2.46%
9.849E-01	4.470E-01	8.389E+00	8.377E+00	1.924E-07	7.014E-03	2.698E-01	2.60%
1.037E+00	4.470E-01	8.824E+00	8.812E+00	2.024E-07	7.378E-03	2.698E-01	2.73%
1.089E+00	4.470E-01	9.259E+00	9.246E+00	2.124E-07	7.741E-03	2.698E-01	2.87%
1.140E+00	4.470E-01	9.693E+00	9.680E+00	2.224E-07	8.105E-03	2.698E-01	3.00%
1.192E+00	4.470E-01	1.013E+01	1.011E+01	2.323E-07	8.467E-03	2.698E-01	3.14%
1.244E+00	4.470E-01	1.056E+01	1.055E+01	2.422E-07	8.829E-03	2.698E-01	3.27%
1.296E+00	4.470E-01	1.099E+01	1.098E+01	2.522E-07	9.191E-03	2.698E-01	3.41%
1.348E+00	4.470E-01	1.142E+01	1.141E+01	2.621E-07	9.552E-03	2.698E-01	3.54%
1.400E+00	4.470E-01	1.186E+01	1.184E+01	2.720E-07	9.912E-03	2.698E-01	3.67%
1.451E+00	4.470E-01	1.229E+01	1.227E+01	2.818E-07	1.027E-02	2.698E-01	3.81%
1.503E+00	4.470E-01	1.272E+01	1.270E+01	2.917E-07	1.063E-02	2.698E-01	3.94%
1.555E+00	4.470E-01	1.315E+01	1.313E+01	3.015E-07	1.099E-02	2.698E-01	4.07%
1.607E+00	4.470E-01	1.357E+01	1.356E+01	3.114E-07	1.135E-02	2.698E-01	4.21%
1.659E+00	4.470E-01	1.400E+01	1.398E+01	3.212E-07	1.171E-02	2.698E-01	4.34%
1.711E+00	4.470E-01	1.443E+01	1.441E+01	3.310E-07	1.206E-02	2.698E-01	4.47%
1.762E+00	4.470E-01	1.486E+01	1.484E+01	3.408E-07	1.242E-02	2.698E-01	4.60%
1.814E+00	4.470E-01	1.528E+01	1.526E+01	3.506E-07	1.278E-02	2.698E-01	4.74%
1.866E+00	4.470E-01	1.571E+01	1.569E+01	3.604E-07	1.313E-02	2.698E-01	4.87%
1.918E+00	4.470E-01	1.613E+01	1.611E+01	3.701E-07	1.349E-02	2.698E-01	5.00%
1.970E+00	4.470E-01	1.656E+01	1.654E+01	3.799E-07	1.385E-02	2.698E-01	5.13%
2.022E+00	4.470E-01	1.698E+01	1.696E+01	3.896E-07	1.420E-02	2.698E-01	5.26%
2.073E+00	4.470E-01	1.741E+01	1.738E+01	3.993E-07	1.455E-02	2.698E-01	5.39%
2.125E+00	4.470E-01	1.783E+01	1.780E+01	4.090E-07	1.491E-02	2.698E-01	5.53%
2.177E+00	4.470E-01	1.825E+01	1.823E+01	4.187E-07	1.526E-02	2.698E-01	5.66%
2.229E+00	4.470E-01	1.867E+01	1.865E+01	4.284E-07	1.561E-02	2.698E-01	5.79%
2.281E+00	4.470E-01	1.909E+01	1.907E+01	4.380E-07	1.597E-02	2.698E-01	5.92%
2.333E+00	4.470E-01	1.952E+01	1.949E+01	4.477E-07	1.632E-02	2.698E-01	6.05%
2.384E+00	4.470E-01	1.994E+01	1.991E+01	4.573E-07	1.667E-02	2.698E-01	6.18%
2.436E+00	4.470E-01	2.035E+01	2.033E+01	4.669E-07	1.702E-02	2.698E-01	6.31%
2.488E+00	4.470E-01	2.077E+01	2.074E+01	4.765E-07	1.737E-02	2.698E-01	6.44%
2.540E+00	4.470E-01	2.119E+01	2.116E+01	4.861E-07	1.772E-02	2.698E-01	6.57%
2.592E+00	4.470E-01	2.161E+01	2.158E+01	4.957E-07	1.807E-02	2.698E-01	6.70%

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