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**SODIUM-WATER REACTION ANALYSIS
OF THE BABCOCK & WILCOX
PROTOTYPE STEAM GENERATOR IN THE
SODIUM COMPONENTS TEST INSTALLATION**

**J. H. Coleman
A. G. Hosler**

**United States Atomic Energy Commission
Contract No. At(11-1)-2021
Subcontract No. 534025 GB**

DECEMBER 1970

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Approved: _____

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ABSTRACT

As part of the steam generator development program being conducted by The Babcock & Wilcox Company (B&W) for the USAEC, sodium-water reaction studies were performed for the B&W prototype steam generator that will be tested in the Sodium Components Test Installation (SCTI).

A leak detection system is proposed based on installation of the steam generator in the SCTI. In addition to the proposed system, the results of an analysis of the effectiveness of the system are presented along with the model and computer program used.

To evaluate the capability of the steam generator to withstand the pressure effects of a large leak, a pressure analysis is presented which also includes an analysis of the existing sodium-water relief system at the SCTI. Also included is a detailed description of the mathematical model and computer program used for pressure analysis.

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I. PREFACE

The work described in this report was conducted by APDA under subcontract No. 534025 GB/610-0170-45 to The Babcock & Wilcox Company (B&W). This work forms a part of the steam generator development program being conducted by The Babcock & Wilcox Company for the United States Atomic Energy Commission under Contract No. AT(11-1)-2021. The work described in the report is directly related to Tasks 3-6 and 4-3 of the Components Section and Instrumentation and Control Section, respectively, of the LMFBR Program Plan (WASH-1104).

The scope of the work covered in this report was

- Small Leak Analysis

An analysis was made of the effects of a small leak on the B&W prototype steam generator patterned after an analysis made of a "typical" steam generator under the sodium-water reaction program at APDA being sponsored by the AEC.

- Pressure Analysis

An analysis of the B&W prototype steam generator design was performed to determine the pressure as a function of time as a result of sodium-water reactions at various locations. The piping model BUG-2, was used for this analysis which is similar to the analysis reported in APDA-175.

II. INTRODUCTION

Designers of sodium-heated steam generators must consider the possible consequences of a sodium-water reaction resulting from a water-to-sodium leak. Methods must be provided for the rapid detection of leaks so that the steam generator can be shut down before major damage and leak propagation have occurred. Also, the steam generator must be designed to safely withstand the effects of the largest credible leak. This report covers the results of a leak detection and large leak pressure analysis of The Babcock & Wilcox (B&W) prototype steam generator, shown in Figure 1, for a sodium-water reaction.

The leak detection analysis is primarily concerned with the detection of small leaks because the state-of-the-art of leak detection systems for large leaks is well advanced. Since the sodium system in which the steam generator is located has a large influence on the design and effectiveness of the leak detection system, the analysis was based on the intended installation of the prototype steam generator in the Sodium Components Test Installation (SCTI) at the Liquid Metal Engineering Center. The leak detection system proposed for this installation is described in Section III, and the analysis of the effectiveness of the proposed system is presented in Section IV.

To evaluate the capability of the prototype steam generator to withstand the pressure effects of large leaks, the reaction pressures must be known as a function of time, location in the steam generator, and leak rate. The pressure analysis, described in Section V, also includes an analysis of the existing sodium-water reaction relief system at the SCTI. The structural analysis to determine the response of the shell to the pressures described by the analysis was performed by The Babcock & Wilcox Company and will be reported in their design report for the prototype steam generator. A detailed description of the mathematical model used for the pressure analysis (BUG-2) is given in Section VI. Since the subject of each section is somewhat independent of the other sections, the conclusions and recommendations are included with each section rather than being consolidated at the end of the report.

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FIG. 1 BABCOCK & WILCOX PROTOTYPE STEAM GENERATOR

III. DESCRIPTION OF PROPOSED LEAK DETECTION SYSTEM

A. INTRODUCTION

This report describes the proposed leak detection system for the B&W prototype steam generator, shown in Figure 1, as installed in the Sodium Components Test Installation (SCTI) at the Liquid Metal Engineering Center (LMEC). The proposed system is designed for optimum detection of small leaks which have the potential of causing wastage damage to surrounding tubes, thus propagating the leak. The ultimate objective of the system is to provide rapid detection and shutdown to prevent significant damage to adjacent tubes and structures by a small leak, minimizing the economic consequences of such a leak. An analysis of the effectiveness of this system as applied to the prototype steam generator installed in the SCTI was also performed.

A discussion of detection systems for large leaks is not included since the state-of-the-art of instrumentation for this purpose is advanced and is well known in the industry. A typical system that could be used for large leak detection with the B&W design is as follows:

Actuation of Alarm - Cover gas pressure switch set 3 psi above normal cover gas pressure

Actuation of Automatic Isolation and Dump of Steam Generator - Cover gas pressure switch set 15 psi above normal cover gas pressure; rupture of rupture disk detected by wires which are forced from a socket.

The effective use of either the small or large leak detection system requires a method of rapidly terminating the reaction resulting from a leak. The method normally used for this purpose is the rapid isolation of the unit from the water and steam system and blowdown of the unit to the atmosphere. For the analysis reported, it is presumed that such a system is available. Since it is understood that orifices may be installed in the tubes at the water tubesheet, it is recommended that water dump lines be provided on both the water and steam sides of the unit.

A brief description of LMEC'S plans for upgrading the SCTI with respect to sodium monitoring and a leak detection system was received by APDA after the analyses were completed and, therefore, was not factored into the analyses. However, a review of the plans indicated that the LMEC program is consistent with the system proposed by APDA with the exception of the choice of instruments for in-sodium hydrogen detection.

B. DESCRIPTION OF LEAK DETECTION SYSTEM

The leak detection analysis considered five basic instruments based on their sensitivity for the detection of sodium-water reaction products: an in-sodium hydrogen detector, an oxygen meter, a Rhometer, a continuous plugging meter, and a cover gas monitoring system incorporating a thermal conductivity cell. The location of the leak detection system is shown schematically in Figure 2, and the system proposed in Figure 3. A sodium sampling station is also included as a part of the detection system although it has no direct role in leak detection. The principal function of the sample station is a back-up calibration of the instrumentation through periodic chemical analysis of the sodium.

1. In-Sodium Hydrogen

Figure 4 is a schematic of the in-sodium hydrogen detection system and represents that portion of the system indicated by box No. 1 on Figure 3.

The catalytic hydrogen detector is an APDA development. The principle of operation and the results of in-loop testing have been reported in several APDA documents^{1,2}. Basically the meter operates at 900 F. The sodium flow rate is not critical and should be optimized for minimum transport time to the detector. The oxidant gas flow rate has an inverse effect on the sensitivity and response time of the meter. A flow rate of 100 cc/min was acceptable for testing and calibration purposes; however, each installation will require a design effort specific to that system. To ensure the accuracy of the detector, in-line calibration is necessary and is accomplished by placing a hydrogen injector in-line upstream of the detector. By injecting hydrogen into the sodium, a reproducible stepchange occurs in the hydrogen concentration.

In-line testing of the detector using the sodium technology loop at APDA showed a positive response of the instrument to a change of 0.018 ppm H₂ at the 0.5 ppm level². The sensitivity, in a leak detection application and for a meter of this specific design, has been set at approximately three times this value, or 0.06 ppm H₂. If required for application to larger systems, the sensitivity can be increased to approximately 0.03 ppm H₂ by any one of the following procedures:

- a. Increase the surface area by a factor of two
- b. Decrease the gas flow rate to 50 cc/min
- c. Increase the operating temperature by approximately 60 F

Any combination of two of the above steps would further increase the sensitivity to 0.015 ppm H₂; all three items would yield a sensitivity of 0.008 ppm H₂.

FIG. 2 THE SCTI SECONDARY SODIUM SYSTEM — LOCATION OF PROPOSED LEAK DETECTION SYSTEM

Legend:

- 1. Hydrogen Detector
- 2. Oxygen Meter
- 3. Rhometer
- 4. Plugging Meter
- 5. Sodium Sample Line

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FIG. 3 PROPOSED LEAK DETECTION SYSTEM

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FIG. 4 IN-SODIUM HYDROGEN DETECTOR

2. Oxygen Meter

The electrochemical oxygen meter developed by United Nuclear Corp. (UNC) has been selected as the second leak detection instrument to operate in parallel with and be complimentary to the hydrogen detector (box No. 2, Figure 3). A description of the meter and summary remarks on field testing the meter have been reported by UNC and APDA.^{3,4}

The basic operating temperature of the oxygen meter is 600 F with a maximum of 650 F, limited by the stability of the electrolyte which is in contact with the sodium. Recent advances in the electrolyte area have pushed the operating temperature range upward to approximately 750 F making the meter more versatile. The output of the meter is insensitive to the sodium flow rate and can be optimized for short transport times. The early meter cells were very sensitive to changes in the ambient temperature at the cell; however, this problem has reportedly been corrected, and the sensitivity of the oxygen meter is estimated at 20% change of the base concentration.³

The oxygen meter has been calibrated by injecting solid Na_2O into the sodium or by raising the cold trap temperature. These methods do not readily lend themselves to the proposed leak detection system. An indirect method of calibration, now under development at ANL, utilizes the insertion of a getter-metal tab into the sodium. Removal of the tab and subsequent analysis for oxygen provides a measure of the oxygen concentration of the sodium. The number obtained can then be applied as a check on the meter reading during the time the tab was in the sodium. Installation of this calibration system is recommended, assuming the developmental effort has been successfully completed by the time the leak detection system design is finalized.

3. Rhometer

The third leak detection device is the Rhometer which is non-specific and will respond to the overall change in purity—hydrogen, oxygen, or both. In addition, because the Rhometer senses changes in the resistivity of the sodium, any discontinuity of the sodium, i. e., from bubbles or particulates suspended in the stream, will be detected. Such bubbles or particulates may be generated as a result of the sodium-water reaction.

The operating temperature can be anywhere from 450 F to 900 F (with modification). With proper compensation, the temperature may be allowed to vary around the set point with no adverse effect.^{5,6} The Rhometer is slightly sensitive to the sodium flow rate and exhibits the minimum noise-to-signal ratio at approximately 3 gpm.

The Rhometer may be installed directly at position No. 3 of Figure 3; alternatively, it may be placed in series with the oxygen meter or the hydrogen detector (preferably in the low-temperature region of this circuit) provided the system transport time is not seriously increased. Auxiliary equipment for the Rhometer may be either a standard platinum temperature compensator or an APDA-designed resistance temperature detector (RTD) connected to a temperature compensating circuit. Pending further development of the RTD, the platinum temperature compensator is recommended.

The sensitivity of the Rhometer has been measured at $0.0043 \Delta\%$ resistivity per $\Delta\text{ppm O}_2$ and $0.055 \Delta\%$ resistivity per $\Delta\text{ppm H}_2$.^{5, 6} The minimum detectable change is estimated at 0.03% resistivity which corresponds to 3 ppm H_2O (0.333 ppm H_2 and 2.664 ppm O_2).

The Rhometer can be calibrated indirectly by correlation to the hydrogen detector and oxygen meter.

4. Plugging Meter

The fourth in-sodium leak detection instrument is the plugging meter located in position No. 4 of Figure 3. Integral with the plugging meter is an economizer and a cooling section.

The plugging meter will be of the continuous type, operating in the partially plugged mode. Intermittant operation, because of a relatively long turn-around time, is unacceptable in terms of leak detection. The sodium flow rate is dependent on the design of the specific instrument and is expected to be approximately 1 gpm.

Although APDA has no direct experience operating a continuous-type plugging meter; based upon intermittent operation, the minimum detectable change is estimated at 20 F.^{7, 8}

5. Cover Gas Hydrogen Monitor

The cover gas hydrogen monitor, incorporating a thermal conductivity cell, is the fifth leak detector and is located as shown in Figure 2. Two detectors will be utilized, one for the cover gas region outside the shroud surrounding the downcomer tubes and one for the cover gas in the downcomer region. Only the former detector was considered in the analysis since too many uncertainties existed in the prediction of the performance of the detector in the downcomer region. The suggested installation is shown schematically in Figure 5. The gas removed from the cover gas area of the steam generator will contain hydrogen and sodium vapor. If drawn directly into cold tubing, the sodium will condense, gettering the hydrogen. The output of the thermal conductivity cell will be erroneously low, and the

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FIG. 5 COVER GAS HYDROGEN MONITORING SYSTEM

potential signal will also be significantly reduced. To avoid this problem, it will be cooled gradually to approximately 500 F; held at 500 F until condensation is complete, except for the minor amount of vapor in equilibrium at that temperature; and then brought to room temperature where the remaining sodium is precipitated before the gas enters the thermal conductivity cell.⁹ The effluent from this system will be returned to the cover gas space to avoid constant make-up. The delay time in similar systems is typically 1 to 2 minutes.

The instrument will be calibrated by three methods: (a) by standard gas flow introduced just ahead of the thermal conductivity cell, (b) by standard gas flow introduced at the condenser section, and (c) by periodic rerouting for sampling by a gas chromatograph.

The minimum detectable limit is approximately 5 vpm H₂ below about 50 vpm and 10% change above 50 vpm H₂.

6. Alternate Instrumentation

In addition to the above instruments there are several variations of the hydrogen and oxygen meters.

A vacuum hydrogen detector is under development at ANL and in France.^{10,11} In these versions, the hydrogen diffuses through the nickel in a manner similar to the catalytic detector, but the hydrogen is measured directly by either an ion pump or a mass spectrometer. Another variation of a hydrogen detector is being developed by UNC based essentially on an electrochemical cell which measures the hydrogen potential.¹²

A variation of the UNC oxygen meter has been developed at Westinghouse.^{13,14} The Westinghouse meter is smaller and reported to be more durable and stable than the UNC meter.

A lack of test data on these alternate meters precluded their use at this time as the other devices have seen much more service. As development continues in these areas, the state-of-the-art should be reviewed again before finalizing the instrument specifications.

C. BASIS OF SELECTION

1. General Requirements

Presently, five instruments are being evaluated for their potential as leak detection devices as described above. This section describes the basis of selection for these instruments. The general requirements considered in their selection are as follows:

- The detection system must have instruments of sufficient sensitivity to detect very small leaks (10^{-3} lb/sec) rapidly enough to prevent significant damage
- The detection system must contain instruments of sufficiently short response times to permit the very rapid detection of larger small leaks (10^{-2} to 10^{-3} lb/sec)
- The detectors should be insensitive to variations in operating conditions or expected changes in background levels of the parameters being measured
- The detectors should be developed and tested to the point that operator confidence in the system is such that alarms and/or interlocks can be directly utilized
- The detection system should provide multiple detectors to enhance the reliability of detection through cross-correlation of signals
- The detectors shall have suitable redundancy to provide against the adverse effects of instrument failure
- The detectors shall have provisions for periodic checkout and calibration
- The detectors shall be suitable for operation in a commercial plant environment
- The detectors shall be arranged for maintenance without interference with the operation of the remaining instruments in the system
- The detectors should have a long and relatively maintenance-free service life and should not be subject to degradation of detector signal or fouling.

2. Specific Requirements

Other considerations for instrument selection are the conditions imposed by the particular design of the B&W prototype steam generator and uncertainties in the distribution of reaction products from a leak. The prototype steam generator includes a large volume of stagnant sodium in the downcomer region where a leak can occur. The absence of circulation in this area would prevent a timely detection of a leak in this area by the in-sodium instruments. In such a case, detection must rely on bubble transport to the cover gas region which is monitored by a thermal conductivity cell.

Leaks in the cover gas will produce hydrogen which can also be detected utilizing the thermal conductivity cell.

The products of a sodium-water reaction are hydrogen gas, dissolved NaH, dissolved Na_2O , and possibly particulates of NaH, Na_2O , or NaOH. Little information is currently known of their distribution in the system. For this reason, selection of detection instruments dependent upon measurement of these products has been made to cover more than one constituent.

The basis for selection of the in-sodium oxygen and hydrogen detectors described above is their excellent sensitivity to very small leaks, reasonable response time, and the significant development and testing experience available. These detectors are the most promising of existing instruments for detection of dissolved hydrogen-and oxygen-containing compounds in the sodium. Also, it is expected that the base level of oxygen and hydrogen in the secondary sodium will remain relatively constant during plant operation, providing a minimum of shift in the base line of these instruments. Since a slow increase in hydrogen in the sodium may occur during steam generator startup due to the diffusion of corrosion-generated hydrogen through the steam generator tubing, inclusion of the oxygen meter will provide a means of verifying that the increase is due to this cause and not a leak. Periodic calibration and checkout of the hydrogen detector can be accomplished using the hydrogen injector included in the system. Sodium sampling and the refractory metal tab method can be used for calibration of the oxygen meter. Isolation valves are provided in the sodium line on either side of the instrument to allow for maintenance while not interfering with operation of the rest of the system.

The Rhometer is included as a rapid means of detecting larger leaks (10^{-2} lb/sec) due to its very rapid response time. Also, if a significant amount of gaseous or particulate products are produced, the Rhometer responds to these products. The Rhometer is not as sensitive as the other two meters (for dissolved H_2 and O_2); however, changes in the resistivity of the sodium due to voids or particulates are easily detectable. Recent work by APDA also indicated a potential gain in the sensitivity as a result of improvements in the temperature compensating features and the electronics package.⁵

The plugging meter lies somewhere between the hydrogen detector, the oxygen meter, and the Rhometer in sensitivity, assuming the secondary system can be maintained at moderately clean conditions (300 F plugging temperature). With better temperature programming and perhaps an improved understanding of the plugging mechanism, the plugging meter sensitivity may be significantly increased.

Leaks occurring very near the top of the steam generator or in the cover gas space may go undetected by the in-sodium instruments for a long time if the major release of reaction products occurs in the cover gas space or otherwise fails to enter the sodium system. For this reason it is important, also, to monitor the cover gas system. Here, the thermal conductivity cell provides good sensitivity to changes in the hydrogen concentration. This instrument has proved to be reliable in past applications and has a significantly shorter delay time than the gas chromatograph. Detection of hydrogen in the cover gas suffers from the large variations in hydrogen content of the cover gas resulting from temperature changes of tubing and structures in this region.¹⁵ This instrument will also detect leaks into the relatively stagnant sodium in the downcomer region.

Calibration of this instrument is possible using a span gas injected either directly at the detector or in the sample line where it leaves the steam generator.

Previous leak detection analyses show that the optimum leak detection device should be independent of sodium transport time and background levels of sodium impurities.¹⁶ The acoustic monitor has the potential of fulfilling these requirements and is considered to be the ultimate in detection devices. This detector has not been included in the proposed system since development of this instrument is not sufficiently advanced to demonstrate its performance. It is recommended, however, that provisions be made in the steam generator design for addition of transducers and wave guides to accommodate such an instrument should it become available in the future.

IV. DESCRIPTION OF LEAK DETECTION SYSTEM ANALYSIS

The leak detection system described in Section III was analyzed to determine its effectiveness in preventing propagation of small leaks in the B&W prototype steam generator. The method of analysis was similar to previous leak detection analyses performed by APDA.¹⁶ The reported state-of-the-art in instrumentation was reviewed and updated for this analysis. The system description was changed to coincide with the B&W prototype steam generator as installed in the SCTI, and the computer program has been improved to give a more complete and accurate simulation. Improvements in wastage rate information and reaction product distribution analyses were incorporated in addition to consideration of the effect of cold trap operation and diffusion of corrosion-generated hydrogen into the system.

A. DESCRIPTION OF MATHEMATICAL MODEL

1. General

For the analysis of the B&W steam generator in the SCTI secondary sodium system, a computer simulation of the system was devised as shown in Appendix A. The program, BAWSG, divides the sodium circuit into segments having a sodium residence time of 1 second each. As a leak occurs in the steam generator, the reaction products are distributed within the system as follows:

- A portion of the reaction products remains at the point of the leak as solid precipitate
- Another portion of the reaction products dissolves in the sodium at the point of the leak and is transported throughout the remainder of the system by bulk sodium flow
- A portion of the hydrogen rises in the steam generator to the cover gas space and enters the cover gas monitoring system
- The remaining hydrogen is carried by the sodium flow as hydrogen and dissolves farther along in the sodium circuit.

A block diagram of the mathematical model is shown in Figure 6; the flow chart for the program is shown in Figure 7. Each numbered block in Figure 6 represents that portion of the system having a 1 second residence time. The products of a sodium-water reaction are advanced, in slug flow, each second in the direction of the flow indicated. The sodium flow lines on Figure 6 represent the system at 100% power (0.8586×10^6 lb/hr).

FIG. 6 MODEL OF SYSTEM ANALYZED BY BAWSG PROGRAM

FIG. 7 FLOW CHART FOR BAWSG PROGRAM

If a flow other than this is specified, the model is automatically adjusted to reflect the system at the adjusted rate.

The sodium flow is simulated by an advance of the segment each second

$$C_n = C_{n+1} \quad (1)$$

which represents slug flow in the piping systems.* Mixing occurs in the various components of the systems: surge tank, pump tank, IHX inlet and outlet headers, steam generator inlet and outlet headers, and steam generator tube bundle.

In all of the above components, with the exception of the steam generator tube bundle, mixing is assumed complete and is described by the standard tank mixing equation:

$$C_{out} = (C_o - C_{in}) \exp(-(F/V)\Delta t) + C_{in} \quad (2)$$

In the steam generator tube bundle, partial mixing occurs only between two adjacent segments of the steam generator.

A cold trap is located across the pump so that the discharge of the cold trap enters the secondary system between the surge tank and the pump. A leak detection system is located at the outlet of the steam generator and consists of the following instrumentation: an in-sodium hydrogen detector, an electrochemical oxygen cell, a Rhometer, and a continuously operating plugging meter.

In addition to the in-sodium leak detection system, a thermal conductivity cell is located in a cover gas monitoring system that continuously samples the argon cover gas of the steam generator. The thermal conductivity cell is responsive to changes in the hydrogen concentration of the cover gas which are produced as a result of a sodium-water reaction.

The present plugging meter on the SCTI is remotely located from the steam generator, behind the sodium pump. The reaction products generated in a sodium-water reaction must pass through the surge tank, the sodium pump, and a long sodium flow path to get to the plugging meter. Because of the excessive transport time and the detection which accompanies passage through the surge tank, this location was neglected with respect to a proposed leak detection device.

* The terms in the equations shown in this section are defined in a list at the end of this section.

2. Steam Generator

The steam generator has been divided into three major sections: inlet header, tube bundle, and outlet header. The inlet and outlet headers are considered as mixing tanks with a time constant of 0.7 second each. The tube bundle is located between the headers and is subdivided into 32 segments (for 100% load conditions), each segment having a residence time of 1 second. Partial mixing occurs between each pair of adjacent segments as the time constant for mixing is specified at 0.5 second.

In addition to the standard tank mixing equation (Equation (2)), a term has been included to represent the influx of impurities. Two sources of impurities are considered for the steam generator:

- Hydrogen and oxygen that are dissolved in the sodium immediately at the specified location
- Hydrogen generated as a result of water-side corrosion which is subsequently diffused into the sodium through the tube walls; this source is evenly distributed throughout the tube bundle.

3. Reaction Product Distribution

Water leaking into a sodium system reacts with the sodium according to one or a combination of the following reactions:

It has been demonstrated that NaOH, when injected into a sodium circuit at 600 F, affects instrumentation as though the injection had been composed of equivalent amounts of Na₂O and NaH. From this, the primary reaction between the sodium and water can be represented by Equation (4), with gaseous hydrogen being released. The hydrogen, in turn, reacts further with the sodium according to Equation (5).

Observation of the target area following the water injection tests performed by APDA, indicates that a significant amount of the reaction products are deposited as solid chunks of material which are not readily soluble. For the purpose of this analysis, it was assumed that 40% of the primary reaction products, NaH and Na₂O, are not immediately dissolved and therefore are "lost" with respect to the leak detection system. The remaining

impurities, 60% of the total oxygen and 80% of the total hydrogen involved, are distributed throughout the secondary sodium circuit.

The Na_2O and NaH assumed to be dissolved are considered to dissolve instantaneously at the point of the leak.

The hydrogen gas which is formed with the NaH , or 50% of the total hydrogen involved, has two paths through which it may be distributed:

- Vertical rise through the tube bundle with a portion reaching the cover gas space
- Suspension and ultimate solution in the flowing sodium stream.

The possibility of a bubble rising through the steam generator is considered in Appendix B. The calculations indicate that approximately 6% of the hydrogen is released into the cover gas. As the hydrogen forming the bubble dissolves, the bubble becomes smaller, resulting in a reduced terminal velocity. At some point, then, the bubble may become entrained in the sodium flow, rather than rising through it and becoming dissolved completely in the sodium. The leak detection analysis assumes a 1% release to the cover gas, with 60% of the hydrogen dissolving immediately, 20% of the hydrogen precipitating, and the remaining 19% dissolving in the sodium flow circuit.

It is recognized that the amount and composition of deposits are a function of sodium flow rate, temperature, and leak rate; however, not enough is known about the manner in which these variables are related to predict the reaction product distribution for each specific situation considered. For this reason, a fixed ratio was used for all cases.

It has been reported that the water-side corrosion can materially contribute to influx of hydrogen to the sodium in the steam generator.¹¹ This hydrogen influx, if great enough, can seriously hinder the detectability of a water leak in the steam generator by maintaining a high background (the performance of the oxygen meter will probably be unaffected by this interference).

To determine the effect of the water-side corrosion, the following conditions are imposed:

- Corrosion rate = 1 mil/yr
- Reaction is

- All the hydrogen so generated diffuses through the tubing wall and becomes dissolved in the sodium (conservative)
- The cold trap is operating continuously at 250 F and 20 gpm and is 100% efficient
- The downcomer region does not contribute to the hydrogen effects.

The prototype steam generator consists of 17 tubes, each having five sections as shown in Table 1.

TABLE 1 - TUBING DIMENSIONS FOR THE B&W
PROTOTYPE STEAM GENERATOR

<u>Location</u>	<u>Length, ft</u>	<u>Inside Diameter, in.</u>
Economizer	16	1.086
Superheat 1	45	0.866
Superheat 2	19	0.778
Superheat 3	42	0.724
Outlet leg	30	0.806

The inside surface area is $1.197 \times 10^6 \text{ cm}^2$. The volume of iron removal per year is*

$$V = (\text{AREA})(\text{CORROSION RATE})(1 \text{ year}) \quad (8)$$

$$= 3.04 \times 10^3 \text{ cm}^3/\text{yr}$$

Since the density of iron is 7.86 g/cm^3 , the weight of iron removed is $23.9 \times 10^3 \text{ gm/yr}$. To compute the amount of hydrogen released using Equation (7)

$$\left(\frac{\text{Mass Fe}}{\text{Formula Wt Fe}} \right) = \left(\frac{\text{Mass H}_2}{\text{Formula Wt H}_2} \right) \quad (9)$$

$$\left(\frac{23.9 \times 10^3}{167.55} \right) = \frac{\text{Mass H}_2}{8}$$

$$\begin{aligned} \text{Mass H}_2 &= 1.14 \times 10^3 \text{ g/yr} \\ &= 2.87 \times 10^{-4} \text{ lb/hr} \end{aligned}$$

* This approximation introduces an error of only 0.5% over the correct equation:

$$V = \frac{\pi}{4} (D_1^2 - D_2^2)$$

At a sodium flow rate of 0.8586×10^6 lb/hr the incremental increase in the hydrogen content of the sodium will be

$$\frac{2.87 \times 10^{-4} \text{ lb/hr H}_2}{0.8586 \times 10^6 \text{ lb/hr Na}} \times 10^6 = 3.36 \times 10^{-4} \text{ ppm/pass} \quad (10)$$

and will not interfere in the detection of a leak. This continued influx can eventually build up the hydrogen level, reducing the effectiveness of the hydrogen detector and plugging meter unless the system is cold trapped.

For the case stated, i.e., continuous cold trap operation, the hydrogen level will continue to rise until the rate of removal using the cold trap is equal to the influx of hydrogen.

$$\text{H}_2 \text{ in} = \text{H}_2 \text{ out} \quad (11)$$

$$2.87 \times 10^{-4} \text{ lb/hr H}_2 = (8400 \text{ lb/hr Na})(\Delta \text{ Concentration})$$

$$\frac{2.87 \times 10^{-4}}{8400} \times 10^6 = 3.42 \times 10^{-2} \text{ ppm}$$

$$= 0.034 \text{ ppm}$$

A cold trap, therefore, operating at 250 F (H_2 saturation concentration = 0.040 ppm) will maintain the sodium system at a hydrogen concentration of 0.074 ppm and a plugging temperature of 275 F.

The model includes the influx of hydrogen from the water-side corrosion and sets the initial hydrogen concentration 0.034 ppm above the cold trap saturation concentration.

4. Wastage Rate

The wastage rate of Croloy 2-1/4 under the conditions of a sodium-water reaction has been studied in the sodium-water reaction test program conducted at APDA.¹⁷ A majority of the tests were conducted in the leak rate range of 10^{-3} to 1 lb/sec water into sodium at ~610 F. A few tests, however, were conducted at 900 F which indicated a significantly higher wastage rate than at 610 F. Assuming an Arrhenius-type relationship exists between the two sets of data, the temperature function

$$k = A \times \exp(-E/RT) \quad (12)$$

can be evaluated to predict the wastage rate at any temperature that may exist in the steam generator. The temperature function (k) is

$$k = \exp \left(7.44 - \frac{7890}{T} \right) \quad (12a)$$

The wastage rate data at 610 F was fitted to an equation that yields a conservative value of the wastage rate. This equation is

$$WR = 242 (LR)^{0.922} \quad (13)$$

The sodium temperature in the steam generator varies from 1000 F at the inlet to 650 F at the outlet. Assuming a linear temperature profile within the steam generator, the sodium temperature can be computed by

$$T = 650 + (1000 - 650) H/20 + 460 \quad (14)$$

Application of Equations (12a), (13), and (14) will predict the wastage rate as a function of leak rate and location. The time to penetrate versus leak rate at various positions in the steam generator is shown in Figure 8.

5. Tube Size

The dimensions of the tubing used in the steam generator also vary from one section to another. The computer model will select the tube dimensions according to Table 2. The critical wall thickness is defined as the minimum wall thickness capable of maintaining the integrity of water-steam system under the conditions imposed by a sodium-water reaction.

TABLE 2 - TUBE DIMENSIONS FOR VARIOUS
SECTIONS IN THE TUBE BUNDLE

<u>Location</u>	<u>Distance from Bottom of Tube Bundle, ft</u>	<u>Wall Size, mils</u>	<u>Critical Wall Thickness, mils</u>
Economizer	1 - 11	207	40
Superheat 1	12 - 14	317	50
Superheat 2	15	361	50
Superheat 3	16 - 18	388	50
Return Leg	19 - 20	347	50

6. Cover Gas

The variation in the cover gas hydrogen is strongly dependent on operational transients which may occur in a power generating plant. As a result of the reaction of sodium vapor with the hydrogen which coexists in the cover gas, quantities of solid NaH precipitate on the surfaces of the steam generator. A change in the plant operating conditions that could cause even a slight change in the temperature of the surfaces inside the steam generator would cause a shift in the equilibrium of the NaH, resulting in a large source

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FIG. 8 LEAK RATE VERSUS TIME-TO-FAILURE

or sink of hydrogen (for rising or lowering temperatures, respectively).¹⁵ This type of behavior severely limits cover gas monitoring as a potential leak detection method. Because of the uncertainties involved, these considerations were not integrated into the computer analysis.

7. Leak Detection System

The leak detection system consists of a 20-member array representing a maximum time delay of 20 seconds. The flow through this system is independent of the flow through the main system. Each of the leak detection instruments can be individually programmed to respond with delay times anywhere from 1 to 20 seconds in addition to the transport time inherent in the steam generator. For the purpose of this analysis, an average detection system delay time of 10 seconds was estimated.

The thermal conductivity cell is located in a side stream taken from the cover gas region (outer shroud) of the steam generator. The calculational routine takes into consideration the equilibrium pressure of hydrogen above the sodium in the upper plenum, a capacitance time delay (time constant = 2 minutes) to account for mixing, adsorption, etc., and an additional time delay of 100 seconds for transport time in the system.*

The minimum detection time for the cover gas system with no bubble transport is the transport time of the hydrogen from the leak area to the upper plenum, ~70 seconds at full flow, plus 100 seconds. If bubble transport is allowed, the system will normally respond in 100 seconds which is comparable to previous APDA experience.

8. Cold Trap Operation

The cold trap is programmed to operate continuously at 20 gpm unless nonoperation is specified by the data input. The cold trap is assumed to be 100% efficient in that the sodium leaving the cold trap is in equilibrium with Na_2O and NaH at the cold trap temperature.

Interaction between the Na_2O and NaH have been reported in the literature which affect their solubility;¹⁸ however, the nature of these interactions is not well understood at this time. Therefore, the solubilities of the elements that compose the two compounds, i. e., oxygen as given by Eichelberger¹⁹

$$\log C = 6.239 - 2447/T \quad (15)$$

* The 2-minute time constant approximates the shape of the hydrogen rise curve from tests previously run by APDA.

and hydrogen by Hill and Meacham,²⁰

$$\log C = 6.56 - 3140/T \quad (16)$$

are used to describe the cold trap function.

B. RESULTS

A leak of water into the steam generator will result in a sudden step change in the impurity level of the sodium flowing past the leak location. The magnitude of the resulting change in the concentration (ΔC) of the oxygen or hydrogen can be calculated knowing the influx of the impurity and the sodium flow rate:

$$\Delta C = L/F \quad (17)$$

The influx in this case is the leak rate of water multiplied by the stoichiometric ratio for oxygen or hydrogen (8/9 or 1/9) and multiplied by the fraction (FR) of the specific impurity dissolved.

$$L = (LR)(FR) (8/9 \text{ or } 1/9) \quad (18)$$

A leak detection station located at the outlet of the steam generator would respond to this step change if the leak were sufficiently large such that it resulted in a step change that exceeded the minimum detectable limits of the leak detection system. Combining Equations 17 and 18, the minimum detectable leak (first pass) can easily be determined.

$$LR = \frac{F \Delta C}{FR} (9/8 \text{ or } 9/1) \quad (19)$$

The value of ΔC is specified as the minimum detectable limit or the sensitivity of the detection system. Table 3 is a list of the minimum detectable leaks (first pass) at power levels of 20, 40, 60, 80, and 100% for the hydrogen detector, oxygen meter, and plugging meter.

A leak smaller than about 1×10^{-4} lb/sec of water, which cannot normally be detected on the first pass, will cause the impurity level of the secondary system to gradually increase in a series of step changes which result from the continuing leak and closed loop flow. The BAWSG program simulates the secondary sodium system for the purpose of describing the actual rise in the impurity level for subsequent passes. The oxygen concentration of the sodium at the leak detection station is shown in Figure 9 for a leak rate of 1×10^{-4} lb/sec. Also shown is the effect of the sodium flow rate (power level).

FIG. 9 OXYGEN CONCENTRATION VERSUS TIME FOR OPERATION AT VARIOUS POWER LEVELS

TABLE 3 - MINIMUM DETECTABLE LEAK, FIRST PASS

Power Level, %	Sodium Flow lb/hr x 10 ⁶	Minimum Detectable Leak, First Pass, lb/sec			Elapsed Time, sec
		H ₂ O Detector	O ₂ Meter	Plugging Meter	
100	0.8586	2.146 x 10 ⁻⁴	1.12 x 10 ⁻⁴	1.647 x 10 ⁻⁴	14-44
80	0.8040	2.010 x 10 ⁻⁴	1.045 x 10 ⁻⁴	1.540 x 10 ⁻⁴	14-52
60	0.6715	1.679 x 10 ⁻⁴	8.74 x 10 ⁻⁵	1.289 x 10 ⁻⁴	15-61
40	0.4698	1.175 x 10 ⁻⁴	6.11 x 10 ⁻⁵	9.00 x 10 ⁻⁵	15-79
20	0.2698	6.24 x 10 ⁻⁵	5.24 x 10 ⁻⁵	4.79 x 10 ⁻⁵	18-140

Apparent from Figure 9 is the tendency for all the lines to merge (except at 20% power), thus becoming independent of the sodium flow rate after about 500 seconds. The "softening" of the step change on the second and subsequent passes is due principally to the effect of the surge tank which is assumed to act as a perfect mixing tank.

For extended periods of time, then, the concentration of the sodium at the leak detection station can be calculated for the simplest case from the equation:

$$C = C_0 + (L/V)t \quad (20)$$

The analysis reported herein, however, considers two additional factors which tend to complicate the equation:

- An additional hydrogen source from the water-side corrosion of the tubes
- Continuous cold trapping

The modified equation describing the system then becomes

$$VdC = Ldt + Sdt - F_{ct} \Delta Cdt \quad (21)$$

Integrating Equation (21) between the limits

$$C_0 \rightarrow C \text{ and } 0 \rightarrow t,$$

$$C = (\Delta C_0 - \frac{S+L}{F_{ct}}) \exp(-F_{ct}/Vt) + \frac{L+S}{F_{ct}} + C_{ct} \quad (22)$$

where,

$$\Delta C_o = C_o - C_{ct} \quad (23)$$

Equation (22) is also plotted on Figure 9 as the dashed line (offset by 25 seconds or approximately the transport time from the leak to the detection station). The equation is slightly conservative and shows good correspondence to the computer analysis within the limits of the equation.

The time to detect a given leak falls into three categories:

- Leaks which can be detected on the first pass
- Leaks which can be detected only after an extended period of time (>10 min)
- Neither of the above.

In the first category, the time to detect is independent of leak size, but dependent on sodium flow rate and leak location within the tube bundle. The transport time, defined as the time for the reaction products to travel to the leak detection system is equal to the time to detect. The instrument response time is considered as a fixed unit of time in the leak detection system and is included as a portion of the transport time.

The B&W prototype steam generator has a relatively long sodium residence time (approximately 30 seconds) at full power. The transport time may vary from 14 seconds for a leak near the bottom of the tube bundle to 44 seconds for a leak near the top of the tube bundle. At 20% power, the comparative times are 18 and 140 seconds for these two locations. The long transport times involved are a serious restriction on the efficiency of the proposed leak detection system.

Leaks in the second category cover the range from approximately 3×10^{-5} lb/sec and smaller. As illustrated in Figure 9, as the impurity level in the sodium system increases, the curve loses its characteristic stepped shape after approximately 500 seconds, and portions of the curve may be represented by an analytical function of time. By solving Equation (22) for time

$$t = -\frac{V}{F} \ln \left(\frac{(L + S) - F \Delta C}{(L + S) - F \Delta C_o} \right) \quad (24)$$

$$\Delta C = C + MDC - C_t \quad (25)$$

and inserting the minimum detectable change, MDC, the time to detect a given size leak can be calculated. Figure 10, an extension of Figure 9,

FIG. 10 LEAK RATE VERSUS TIME TO PENETRATE

shows the results of this calculation for the three instruments: the hydrogen detector, the oxygen meter, and the plugging meter.

After approximately 5 hours, the system approaches a steady-state condition where cold trap operation is removing the reaction products from the system just as fast as they are being generated. This condition is illustrated by the dashed lines in Figure 10. The limit of detection is dependent on the instrument sensitivity and the cold trapping rate. A comparison is made for the time to detect with the cold trap off for the oxygen meter. As expected, in the absence of a sink (the cold trap), a lower limit of detection does not exist.

Leaks in the third category are too small to be detected on the first pass, yet large enough to be detected before 10 minutes. In general, these leaks range from 2.5×10^{-5} to 1×10^{-4} lb/sec. The graph of concentration versus time still exhibits rather sharp step changes which do not readily provide an analytical approach. Examination of Figure 9, however, indicates that the analytical solution expressed by Equation (22) is conservative and, therefore, the estimated time to respond is conservative. It was decided to treat third category leaks as second category leaks, recognizing that, in most cases, the performance of the leak detection system will be significantly more favorable than is indicated by the analysis.

The effect of initial sodium purity was tested using the computer simulation. Runs were made at three leak rates and two purity levels. Table 4 shows the effects of initial purity on the response time of the oxygen meter. As shown, a high initial impurity level seriously hinders the ability of the oxygen meter to give timely warning in case of a leak. The plugging meter is not quite as seriously affected, and the Rhometer and hydrogen detector are not affected by the initial condition in this range.

TABLE 4 - EFFECT OF INITIAL SODIUM PURITY ON THE
RESPONSE TIME OF THE OXYGEN METER

Leak Rate, lb/sec	Response Time, sec		
	Cold Trap		
	On	Off	
	250 F	300 F	350 F
1×10^{-4}	22	216	517
5×10^{-5}	210	458	1060
2.5×10^{-5}	420	928	2140

C. DISCUSSION

As shown in Figure 10, leaks below 1×10^{-4} lb/sec H_2O can readily be detected before serious damage from a secondary failure occurs. Assuming continuous cold trap operation, each of the instruments exhibits a limit of detection as the leak approaches 10^{-6} lb/sec. A limit of detection at this low leak rate is not considered to be a serious restriction to the adequacy of the leak detection system. The absence of wastage rate data at these low leak rates prevents a meaningful analysis of the situation.

Normally, on signal of a leak of less than 10^{-4} lb/sec, an orderly shut down of the system can be accomplished, preventing secondary failure.

A leak of the first category, characterized by a sudden, rapid rise in reaction products, will require an immediate dump of the steam generator water side, because the damage rate becomes very high.

Distinction of the leak category can readily be made by specification of a rate-of-rise alarm-and-dump system coupled with an absolute limit alarm. An alarm signal, in which the rate-of-rise criteria is not exceeded, can be followed by an orderly shut down rather than an emergency dump.

The effect of initial sodium purity on the instrument response can be quite serious, as demonstrated in the previous section. For a system of relatively high oxygen levels, for instance, the time available to take corrective action is significantly reduced. The same effect can be shown for the plugging meter which is inherently less responsive to a given change in concentration at higher impurity levels. The hydrogen detector is not as seriously affected because the calibration curve is nearly linear over the range of 0 to 1 ppm H_2 (<400 F plugging temperature).

As mentioned earlier, a leak occurring in the downcomer region of the steam generator is not detectable by the in-sodium instrumentation. These leaks must be detected by a bubble rise through the stagnant sodium, dispersion of the bubble in the cover gas, and detection by the thermal conductivity cell. Detection is expected to require 1-1/2 to 2 minutes from the start of the leak (0 to 20 seconds transport time through the sodium plus 100 seconds for dispersion and gas phase transport).

For a given leak rate, the wastage rate in the downcomer region is expected to be smaller than the wastage rate in the tube bundle. Two factors contribute to this reduced wastage rate: lower temperature and no sodium flow past the impingement area. The temperature effect on the wastage rate has been discussed earlier.

Wastage tests conducted by APDA have shown that the wastage rate in stagnant sodium is 1/3 to 1/2 the wastage rate in flowing sodium.¹⁷

Therefore, the overall effect of these two factors may reduce the damage rate by as much as 75%. A leak of 2.5×10^{-3} lb/sec which would result in a wastage rate of approximately 1 mil/sec at the bottom of the tube bundle may only cause damage at a rate of 0.25 mil/sec in the downcomer region. This would result in propagation in approximately 600 seconds (compared to 110 seconds 1 foot from the bottom of the tube bundle). With the delay time of 2 minutes indicated above, a leak of this size could be detected and the unit shut down before the leak propagated. This analysis has not been pursued in great detail since the amount of wastage rate information for no sodium flow is quite limited, and the effect of baffles and tube supports on bubble rise times is unknown.

Based on the above analysis, the following can be concluded:

- The leak detection system is adequate to protect the steam generator from leak propagation resulting from very small primary leaks
- Leaks greater than approximately 2×10^{-4} lb/sec, which can be detected on the first pass of sodium through the leak detection circuit, should result in an automatic isolation and dump of the steam generator. The critical parameter to use for initiation of the isolation and dump is the rate of rise of the impurity level.
- Leaks smaller than approximately 2×10^{-4} lb/sec may actuate an alarm requiring manual shutdown, thus avoiding severe thermal transients within the system; this function would be signaled by exceeding a previously defined upper limit without exceeding the rate-of-rise criteria
- Leaks of about 4×10^{-3} lb/sec and higher (depending on leak location and sodium flow rate) can potentially cause secondary failures regardless of the sensitivity or response time of the proposed leak detection system; the limiting factor in this situation is the transport time from the leak location to the detector system
- An instrument which does not rely on impurity transport, such as the acoustic detector developed by APDA, can significantly extend the range of the proposed detection system; however, the state-of-the-art is not sufficiently advanced in the area to permit an industrial application of this type of instrument.
- At reduced power levels, the lower sodium flow rates hinder the detection of larger small leaks (7.5×10^{-3} lb/sec) by increasing the sodium residence time in the steam generator thus increasing the transport time of the reaction products

- At reduced power levels, the lower sodium flow rates do not seriously hinder the detectability of very small leaks ($<10^{-3}$ lb/sec)
- The downcomer region appears to be protected against propagation of leaks of approximately 3×10^{-3} lb/sec or less.

D. RECOMMENDED PROCEDURES FOR LEAK DETECTION SYSTEM OPERATION

Due to the very limited experience with leak detection systems for steam generators, two preliminary phases of operation will be required before the system can be put into a normal, steady-state mode of operation. It is expected that these two preliminary phases could be eliminated on later plants as sufficient experience is gained with these systems on the demonstration plant.

Important to the interpretation and proper utilization of the proposed leak detection system is an understanding of the chemistry of the secondary system and confidence in the instrumentation. To date, there is practically no information regarding the chemistry of such a system under normal operating conditions. In the event of a sodium-water reaction, it is not known just how the reaction products will be distributed throughout the system or whether the devices are subject to false alarms as a result of normal transients in operating conditions, as is presently the case with typical cover gas monitoring systems.

1. Calibration and Testing

This phase of operation will be carried out during preoperational testing of the plant. Calibration and checkout of individual instruments will be performed as follows:

- In-sodium Hydrogen Meter - gaseous hydrogen injections using the hydrogen injector, sodium sample analyses, and response to variation in cold trap operation and temperature
- In-Sodium Oxygen Meter - sodium sample analysis, refractory metal tab analysis, and response to variation in cold trap operation and temperature
- Rhometer - sodium sample analyses, response to cold trap operation and temperature, and correlation with other in-sodium detectors
- Cover Gas Thermal Conductivity Cell - span gas injection into sample line and detector, as well as correlation with grab samples analyzed on gas chromatograph.

In addition to the calibration, the stability and drift of the detectors will be checked and the normal background level of impurities established for the system. This will be done during continuous cold trapping and during periods of no cold trapping to determine whether continuous cold trapping is required to maintain a steady and low background.

The system will then be calibrated in terms of its response to a water leak. This will be done by injecting controlled amounts of water into the cover gas and sodium in the steam generator. This will be accomplished in such a manner and in small enough quantities to preclude damaging the system and causing possible corrosion problems. Provisions should be made in at least one steam generator to insert a water injection tube in the center shroud at elevations corresponding to the cover gas, in the relatively stagnant sodium in the center shroud, and in the flowing sodium below the center shroud.

Also, testing the cover gas detector will be conducted to determine the effect of normal gas feed and bleed or purging on its response.

2. Initial Operation

Following preoperational testing, the system will be set up for initial operation. The actual setpoints of the alarms and interlocks described will be established from the results of the preoperational test phase.

- Leak alarm actuated by

- In-sodium hydrogen detector - absolute level and rate of rise

- In-sodium oxygen meter - rate of rise

- Rhometer - rate of rise

- Thermal conductivity cell - absolute level and rate of rise

- Automatic isolation and dump actuated by a coincidence of two of the following alarms:

- In-sodium hydrogen detector - rate of rise

- In-sodium oxygen meter - rate of rise

- Rhometer - rate of rise

- Thermal conductivity cell - absolute value and rate of rise.

The automatic alarm signals for isolation will be set at rather high values for this period of operation due to the uncertainty in the reliability of the detectors. The operator action upon receipt of a leak alarm from one of the above instruments will depend upon the experience with that instrument during preoperational testing, however, if several instruments are indicating that an increase in impurity level is occurring, a shutdown is warranted. A comparison with the behavior of the detectors on other loops

will indicate whether a leak is being indicated or whether it is an effect common to all three loops and is indicative of a change in operating conditions only. The rate-of-change of signal and preoperational test results will dictate whether an isolation and dump or controlled shutdown should be initiated.

3. Normal Operation

After sufficient initial operation, experience with the detectors will indicate their stability, reliability, and response as installed in the demonstration plant. Also, the background level of impurities attainable in the sodium and cover gas, as well as the variation of this level will be determined. Based on this operation, realistic setpoints for both the alarms and the automatic isolation and dump interlock will be set. The instruments to be used for these functions and the degree of coincidence in signals required will also be determined and set.

A periodic schedule for calibration will be established based on measurements of instrument drift and reliability. The instruments and detection system will now be operating in a mode consistent with a commercial plant environment and should require a minimum of special attention from plant operating personnel.

LIST OF TERMS USED IN EQUATIONS IN SECTION IV

A	=	Frequency factor
C	=	Impurity concentration entering cold trap
C _{ct}	=	Impurity concentration leaving cold trap
C _n	=	Impurity concentration at point n
C _{n+1}	=	Impurity concentration at point n+1
C _o	=	Initial concentration of impurity
C _{in}	=	Impurity concentration entering volume
C _{out}	=	Impurity concentration leaving volume
D	=	Diameter
E	=	Activation energy
F	=	Flow rate
F _{ct}	=	Sodium flow rate through cold trap
FR	=	Fraction of impurity dissolved
H	=	Distance from bottom of tube bundle
k	=	Rate constant
L	=	Influx of impurity
LR	=	Leak rate
MDC	=	Minimum detectable change
R	=	Gas constant
S	=	Influx of hydrogen from water-side corrosion
t	=	Time
T	=	Temperature
V	=	Total sodium

V. SODIUM-WATER REACTION PRESSURE ANALYSIS

The sodium-water reaction analysis of the B&W prototype steam generator was performed using the BUG-2 program, discussed in Section VI. The major parts of the analysis consist of simulating the steam generator hydraulic characteristics using the BUG-2 program, determining the worst location for a leak in both the tube bundle and downcomer regions, and providing sufficient data for reactions at these worst locations to enable B&W to evaluate the ability of the steam generator to withstand the forces generated during the reactions resulting from single and multiple tube ruptures.

A. DESCRIPTION OF THE MODEL FOR SIMULATING THE PROTOTYPE STEAM GENERATOR DESIGN

1. Selection of the Reaction Path Arrangements for BUG-2 Input

The B&W prototype steam generator was analyzed for leaks occurring in the downcomer annulus and in the tube bundle. The BUG-2 computer runs made use of the reaction path arrangements shown in Figure 11, Case A for a leak occurring in the downcomer, and Cases B and C for leaks occurring in the tube bundle.

For all three cases, the following statements held true:

- The temperature of sodium was assumed to be 600 F
- The single outer shroud and the gas annulus walls (designated as the double outer shroud) did not collapse
- The maximum sodium level was assumed to be 22 feet 1 inch above the bottom of the single outer shroud
- The height of the sodium in the gas annulus was assumed to be 5 feet above the bottom of the annulus
- At the point of rupture in both the downcomer annulus and tube bundle, (Figure 11 , Cases A, B, and C), the sodium was assumed to divide into two relief paths:

Channel 1 where the sodium flowed towards the bottom of the unit

Channel 2 where the sodium flowed towards the top of the unit

FIG. 11 REACTION PATHS FOR LEAKS IN THE DOWNCOMER ANNULUS AND TUBE BUNDLE

- The gas annulus was divided into two channels:

The lower channel which represented the height of the sodium in the gas annulus, e.g., Channels 3, 10, and 10 in Cases A, B, and C, respectively

The upper channel which represented the gas space in the gas annulus, e.g., Channels 8, 13, and 11 in Cases A, B, and C, respectively

- The tube bundle was divided into three sections because of a significant difference in the pressure drop through the different parts of the bundle:

The length of the lower section was equal to the distance between the bottom of the single outer shroud and the mean vertical location where the downcomer joined the coiled bundle, e.g., Channels 5; 4 and 6; and 1, 2, and 6 for Cases A, B, and C, respectively

The length of the middle section was equal to the length of the coiled tube bundle, e.g., Channels 6; 1, 2, and 7; and 3 and 7 for Cases A, B, and C, respectively

The length of the upper section was equal to the distance between the maximum sodium level and the mean vertical location where the risers joined the coiled bundle, e.g., Channels 3, 3, and 4 for Cases A, B, and C, respectively

For Case B, Channels 11 and 12 were introduced to allow the inclusion of the exit losses from the tube bundle

- The sodium was assumed to flow up the tube bundle, the center pipe (except as noted later), and the downcomer annulus into the gas space, causing the cover gas to compress and eventually burst the rupture disk, e.g., Channels 9, 14, and 12 for Cases A, B, and C, respectively.

The tube supports for the tube bundle effectively divide the tube bundle into four regions. For Case A, the four tube bundle regions were combined together and treated as one large relief path; for Cases B and C, the reaction was assumed to occur in one of the four tube bundle regions. The remaining three tube bundle regions were combined together and treated as one large relief path.

2. Development of Input for Channels

For each channel, the length and the effective cross sectional area were calculated, and the pressure drop formula(s) was obtained. For the downcomer annulus an effective length was calculated because of the crossflow effect due to the baffles. For the upper section of the tube bundle, the pressure drop was assumed to be equal to the pressure drop due to the tubes and tube hangers plus the pressure drop due to the tubes and tube supports. For the middle section of the tube bundle, the pressure drop was assumed to be that from the crossflow of sodium over the coiled tube bundle. For the lower section of the tube bundle, the pressure drop was assumed to be equal to the sum of the pressure drops due to the tubes and tube supports, the tubes and tube support brackets, and the tubes and spacers. For the downcomer annulus the pressure drop was assumed equal to the pressure drop due to the crossflow of sodium over the tubes plus the pressure drop due to sodium flowing over the baffles. For the center pipe, the gas annulus, and the relief system, the pressure drop was assumed equivalent to sodium flow through a smooth pipe.

The data obtained from B&W and used in this analysis is summarized in Table 5. This data, the calculated data, and the ΔP_f formulas were then used to obtain the a and b coefficients in the expression $\Delta P_f = aV^b$ for each channel and each leak location.

3. Selection of Leak Location

The nine locations in the tube bundle and three locations in the downcomer bundle chosen for analysis are listed in Table 6. Reactions in these areas were expected to yield greater bubble pressures than reactions in other regions of the steam generator. Initially, the hydrogen bubble pressure is primarily dependent upon the inertial effects of accelerating the sodium between the reaction zone and gas space. The magnitude of the pressure is then dependent on the area and length of the channels available for relief. Locations TB-5 and DC-2 were near the bottom of the tube bundle and downcomer bundle regions, respectively; therefore, the channel lengths were greatest for these two rupture positions. All locations were in regions of restricted cross section; therefore, higher pressures were needed to accelerate the sodium in these areas as opposed to other locations in the unit.

After the sodium accelerates to high velocities, frictional effects also exert a significant effect on the bubble pressure. Regions with small cross sectional areas and impediments to flow, such as the downcomer region which contains flow baffles and the tube bundle which contains tube supports, result in relatively high bubble pressures when frictional effects become controlling. The channels selected for analysis were also those having relatively high pressure drops.

TABLE 5 - B&W DATA FOR USE IN BUG-2 PROGRAM

Cover gas pressure, psig	40.0
Rupture disk setting, psig	125.0
Horizontal tube pitch, in.	2.000
Vertical tube pitch, in.	2.125
Number of tubes	17
Downcomer tube	
Outside diameter, in.	0.875
Inside diameter, in.	0.500
Leak rate, lb/sec/tube	34.6
Economizer, superheaters 1, 2, 3, and outlet leg	
Outside diameter, in.	1.5
Economizer	
Inside diameter, in.	1.086
Horizontal length of section, ft	11.00
Leak rate, lb/sec/tube	163.1
Superheater 1	
Inside diameter, in.	0.866
Horizontal length of section, ft	3.00
Leak rate, lb/sec/tube	103.7
Thickness of tube supports, in.	2.00
Mean vertical location where the risers join the coiled bundle	6.0 ft below the face of top flange
Mean vertical location where the downcomers join the coiled bundle	24.0 ft below the face of top flange

TABLE 6 - LEAK LOCATION

<u>Location</u>	<u>Case, Figure 11</u>	<u>Location from the Bottom of the Single Outer Shroud, in.</u>
TB-1	A	67.00
TB-2	A	124.50
TB-3	A	34.50
TB-4	A	164.50
TB-5	B	6.00
TB-6	A	90.00
TB-7	A	110.00
TB-8 and TB-9	A	132.00
DC-1	C	110.00
DC-2	C	12.00
DC-3	C	160.00

B. DISCUSSION OF RESULTS

Using the channel arrangements shown in Figure 11 and the single tube leak rate of 34.6 lb/sec in the downcomer and 103.7 and 163.1 lb/sec in the tube bundle, the hydrogen bubble pressure at time $T = 0.0001$ second was determined at nine different locations in the tube bundle and three locations in the downcomer. These bubble pressures are plotted in Figures 12 and 13. It can be seen from these figures that the worst leak location based upon the maximum bubble pressure at $T = 0.0001$ second is located in the tube bundle, 124.5 inches above the bottom of the tube bundle liner in the steam generator (the location is labeled TB-2). The discontinuity shown in Figure 12 is the result of a change in leak rate from 163.1 to 103.7 lb/sec at 132.0 inches. For this change the bubble pressure decreases, as expected, by the square root of the ratio of the leak rate. Figures 14 and 15 are curves of the hydrogen bubble pressure versus reaction time for the various leak locations in the tube bundle and downcomer, respectively. Table 7 summarizes the manner in which the various channels empty of sodium for the different leak locations. On Figure 14 the sharp change in slope near the end of a curve is the result of emptying the tube bundle into the larger total cross sectional areas of the four adjacent channels.

Figure 16 is a plot of the integrals of PdV and Pdt ; Figures 17 and 18 are plots of the reaction parameters for Channels 1 and 2, respectively. These latter figures are helpful in understanding the events in the various channels.

With the worst location determined, the BUG-2 program was rerun for simultaneous ruptures of 1, 4, 9, 16, and 17 tubes in both the tube bundle and downcomer. The results of these studies are shown in Figures 19 and 20.

TABLE 7 - SUMMARY OF SODIUM-WATER REACTIONS IN
STEAM GENERATOR - SINGLE TUBE RUPTURE

Location*	Bubble Pressure at T = 0.0001 Sec, psia	Channel No. and Time at Which Empty, Sec	Reason for Termination**	Cover Gas Pressure at Termination, psia
TB-5 (6.0)	5803.4	1; 0.005 10; 0.052	1	67.0
TB-3 (34.5)	7344.0	1; 0.006 4; 0.017 10; 0.061	1	70.6
TB-1 (67.0)	8776.8	1; 0.029 4; 0.039 10; 0.081	1	75.1
TB-6 (90.0)	9329.7	1; 0.050 4; 0.060 10; 0.101	1	79.4
TB-7 (110.0)	9564.6	1; 0.073 4; 0.083 10; 0.124	1	84.8
TB-2 (124.5)	9603.0	1; 0.0923 4; 0.1020 2; 0.1177 3; 0.1261	2	81.8
TB-8 (132.0)	9580.1	2; 0.103 1; 0.105 3; 0.110	2	70.1
TB-9 (132.0)	7638.9	2; 0.121 1; 0.104 3; 0.129	2	69.3
TB-4 (164.5)	7283.0	2; 0.072 3; 0.079	1	63.4
DC-2 (15.6)	2611.7	1; 0.026 3; 0.092	1	65.4
DC-1 (143.0)	3323.9	No Channel Empties	3; 0.3020 sec	
DC-3 (208.0)	3164.0	No Channel Empties	3; 0.2800 sec	

* Listed in order from bottom to top of tube bundle (TB) or downcomer (DC) annulus
Number in () is inches from bottom of tube bundle or downcomer
TB leak rates are 163.1 lb/sec, with the exception of TB-4 and TB-9 which are
103.7 lb/sec
DC leak rates are 34.6 lb/sec

- **1. Job terminated because channel emptied into the center pipe which already
contained gas. Although BUG-2 will not handle a channel with gas at both ends,
the job could have been continued by introducing a new channel arrangement or
making changes in the program.
2. Job terminated because the gas bubble emptied into the cover gas space.
3. Rupture disk failed at indicated time.

FIG. 12 INITIAL BUBBLE PRESSURE AT VARIOUS LEAK LOCATIONS IN THE TUBE BUNDLE

FIG. 13 INITIAL BUBBLE PRESSURE AT VARIOUS LEAK LOCATIONS IN THE DOWNCOMER ANNULUS

FIG. 14 HYDROGEN BUBBLE PRESSURE VERSUS REACTION TIME FOR VARIOUS LEAK LOCATIONS IN THE TUBE BUNDLE

FIG. 15 HYDROGEN BUBBLE PRESSURE VERSUS REACTION TIME FOR VARIOUS LEAK LOCATIONS IN THE DOWNCOMER ANNULUS

FIG. 16 INTEGRAL OF PdV AND Pd_t VERSUS REACTION TIME FOR A SINGLE TUBE LEAK IN THE TUBE BUNDLE

FIG. 17 REACTION PARAMETERS FOR CHANNEL 1 FOR A SINGLE TUBE LEAK IN THE TUBE BUNDLE

FIG. 18 REACTION PARAMETERS FOR CHANNEL 2 FOR A SINGLE TUBE LEAK IN THE TUBE BUNDLE

FIG. 19 HYDROGEN BUBBLE PRESSURE VERSUS REACTION TIME FOR MULTIPLE TUBE RUPTURES IN THE TUBE BUNDLE

FIG. 20 HYDROGEN BUBBLE PRESSURE VERSUS REACTION TIME FOR MULTIPLE TUBE RUPTURES IN THE DOWNCOMER ANNULUS

The data in Table 7 for single tube leaks at various locations in the tube bundle were obtained before Channels 11 and 12 of Case B were added to include the effect of the expansion losses from the tube bundle. Therefore, emptying of these two channels is not indicated. The inclusion of the expansion losses produced only a slight change in the results and, therefore, the data presented in this table are compatible with data presented elsewhere in the report.

Because the above-mentioned analyses of the prototype steam generator showed that the center pipe would probably collapse, it was decided to run two cases with the center pipe almost completely blocked. To simulate this blockage, the cross sectional area of the center pipe was decreased to 1.0% of its original value. This decreased area was assumed throughout the analysis, i. e., the initial conditions were calculated with this decreased area. The flow through the center pipe resulting from this change in area was between 1.3% and 1.4% of the open channel value. Figures 19 and 20 show that blocking the center pipe results in only a very slight change in the hydrogen bubble curve.

Collapsing of the center pipe will allow for communication between the tube bundle sections. The added relief paths produced by this collapsing would significantly decrease the hydrogen bubble pressure. However, the amount by which the pressure will be reduced cannot be easily estimated and can only be studied with the BUG-2 program after making major changes to the program and calculating new input information. It can be safely concluded, however, that the decrease in the bubble pressure resulting from the extra relief paths provided by the collapse of the center pipe would be much greater than the 2.0% increase in the bubble pressure that results from the loss of the center pipe as a relief path. The added relief path which communicates directly with the hydrogen bubble is much more important than the lost path which communicates with the end of the tube bundle and does not provide a bypass around the tube bundle with its high frictional resistance.

It can be concluded that neglecting the collapse of the center pipe is conservative in calculating the static pressure of the hydrogen bubble.

C. RECOMMENDATIONS FOR DESIGN CHANGES

1. Steam Generator

For a leak in the tube bundle, the major resistance to the expansion of the hydrogen bubble and the resulting decrease in bubble pressure is the frictional resistance and fluid inertia of that quarter of the bundle in which the leak is located. The fact that the frictional resistance and inertance of those relief paths which connect to the tube bundle region are of little significance compared to the riser region can be appreciated by the following:

- The hydrogen bubble voids both the upper and lower portion of the riser region at about the same time, even though the sodium leaving the upper portion passes directly to the cover gas space while the sodium leaving the lower portion must pass through the four parallel paths
- The frictional pressure drop through those paths connected to the riser region remain low relative to the frictional pressure drop in the riser
- The removal of the center pipe resulted in only a very slight increase in bubble pressure.

For a leak in the tube bundle region, the initial bubble pressure which is a function of the fluid inertance but not the frictional pressure drop, is determined largely by the riser region and not the connecting relief paths. This is apparent by noting that the worst leak location is located very near the center of the tube bundle.

The importance of the above is to show that the initial bubble pressure (initial pressure here means the pressure at time $T = 0.0001$ second) and the decrease of the bubble pressure with time can only be significantly improved by making design changes to the tube bundle region itself. If possible, decreasing the fluid inertance and frictional resistance of the down-comer annulus, gas annulus, and center pipe would only result in a marginal improvement.

There are only two general ways of modifying the design of a steam generator to improve its ability to handle sodium-water reactions. The first is to decrease the initial bubble pressure which is a function only of the inertance $\rho L/A$ of the relief paths; the second is to allow the bubble pressure versus time curve to reach a lower value before leveling off, i. e., before departing from the slope of $-1/2$, by decreasing the frictional pressure drop of the relief paths. Figure 14 illustrates these two points. The pressure at $T = 0.0001$ second is a function of the inertial terms only, and the curve always starts with a slope of $-1/2$ which is maintained until the frictional terms become dominate. At this point the curve levels off and the pressure drops off very slowly until the rupture disk bursts or the gas bubble breaks into a new channel(s) of significantly different geometry.

For the B&W prototype design, the initial bubble pressure and the bubble pressure after the frictional terms become important can be decreased by providing communication between the four quarters of the tube bundle. The best approaches would be to stagger the tube supports or make certain the center pipe collapses; placing vent holes in the tube supports would also help.

As mentioned above, the initial bubble pressure curve always has a slope of $-1/2$; however, a sharp decrease in the bubble pressure approaching a step change in the curve could be realized by allowing the gas to vent directly into the center pipe through some type of rupture disk located in the inner shroud at about the worst leak location. At the point this disk fails, the bubble pressure versus time curve would show a step decrease in the bubble pressure with the curve continuing with a slope of $-1/2$ after the rupture; however, the pressures would be much lower.

2. Relief System

Because it is planned to install the B&W steam generator in the SCTI, the adequacy of the presently installed relief system of the SCTI was studied. This study, which is included in Appendix E, showed that for a single tube rupture with a 17.4 lb/sec mass flow rate of hydrogen, the back pressure in the relief system would be about 100 psi. This is shown in Figure 21, a curve of the relief system pressure drop versus the mass flow rate of hydrogen.

Because the high back pressure would be undesirable from a structural standpoint, it was decided to study relief systems with larger pipe sizes. The results of this study are shown in Figure 22 and indicate that a pipe of 24 to 30 inches in diameter is required to handle a leak resulting from the rupture of many tubes simultaneously.

FIG. 21 PRESSURE DROP THROUGH SCTI RELIEF SYSTEM

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FIG. 22 PRESSURE DROP THROUGH SCTI RELIEF SYSTEM FOR VARIOUS PIPE SIZES

VI. DESCRIPTION AND USE OF THE BUG-2 PROGRAM

The BUG-2 program is used to study the effects of large leaks in sodium-heated steam generators by predicting the manner in which the hydrogen bubble produced by the reaction expels the sodium from the steam generator. The most important output from the program is the prediction of hydrogen bubble pressure as a function of reaction time.

The BUG-2 program is similar to other programs written to perform the transient solution of a piping network. It is a one-dimensional model, and, as such, the hydrogen bubble forces the sodium away from the reaction as a solid slug or piston. The program is quite flexible and provides various relief channel arrangements. The frictional pressure drop coefficients for the various channels are hand calculated and read as input by the program. Throughout the following discussion of the BUG-2 program, it is intended that the term frictional pressure drop include the true frictional effects and the form losses.

The following assumptions are inherent in the BUG-2 model. A discussion of each assumption is included to indicate whether it is conservative and to provide justification for the assumption.

1. Leak rate is instantaneous - This assumption is conservative since it leads to an infinite bubble pressure at time zero. In the actual case of a tube rupture it will take time for the leak to build up to the maximum rate. Previous attempts to account for leak rate build-up have given results which appear to be nonconservative, probably due to the fact that the reaction kinetics cannot be satisfactorily factored into the model.²¹
2. Leak rate is constant and not a function of the reaction back pressure - This assumption is also conservative since leak rate is dependent on the differential pressure between the water- and steam-side headers and the hydrogen bubble. As the bubble pressure rises, this differential should become much less than the initial ΔP of 2590 psi from which the leak rate was calculated. Also, for the cases considered where all tubes rupture, it is quite possible that the pressure in the header will not be maintained since the total leak rate of water from all the tubes greatly exceeds the normal water flow through the unit. Thus, the leak rate could be the greater water rate at the high pressure. Again, attempts were made to include this effect in the model; however, these were discontinued since the results appeared to be nonconservative.²¹
3. Reaction is instantaneous - This assumption is not representative of the actual case of a reaction since sodium-water reaction

experiments are characterized by sporadic pressure spikes soon after water injection, indicating that a significant amount of water may be injected into the sodium before reacting. This assumption, therefore, is probably nonconservative. Assumptions 1 and 2 may make up for this nonconservatism, since the results are pressure decays from infinity which somewhat simulate the high initial pressure peaks experienced in the experiments. Also, since the times involved for these peaks to occur are in terms of milliseconds, energy apparently becomes the controlling parameter for vessel strength considerations. The combination of Assumptions 1, 2, and 3 yields the maximum possible integrated mechanical energy release at any time from a reaction consistent with Assumption 4. It does not necessarily, however, give the maximum possible rate of energy release, since this is a function of the reaction kinetics.

4. Reaction is according to the equation $2 \text{ Na} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{O} + \text{H}_2\uparrow$ -
This equation is assumed since it represents the maximum hydrogen generation rate from a sodium-water reaction. Based on the comparison of mathematical models with results from large leak experiments, others have concluded that the reaction $\text{Na} + \text{H}_2\text{O} \rightarrow \text{NaOH} + 1/2 \text{ H}_2\uparrow$ more realistically describes the reaction.²² This assumption is, therefore, conservative.
5. The hydrogen is generated at a temperature of 1800 F - This temperature was chosen as the average expected in the bubble from experimental data for sodium-water reactions.²³ Since few experiments have been conducted in large quantities of sodium and/or at significant depths, the effect of these variables on temperature has not been determined. It is possible, however, that the temperature may be greater due to the higher saturation temperature of sodium at the higher pressures developed in large steam generators. If the theoretical maximum hydrogen temperature were used, the volumetric hydrogen generation rate would be increased by a factor of 1.55 and the bubble pressure increased by a factor of approximately 1.25. More recent correlation of mathematical models with large leak experiments indicates that bubble temperatures between 1400 F and 1830 F give the best agreement.²² Based on this data, it is expected that 1800 F is the best estimate of the bubble temperature that can be made at the present time.
6. Hydrogen bubble expanded isothermally - This gives the maximum pressure consistent with Assumption 5.
7. The hydrogen bubble instantaneously assumes the shape of the cross section of the region or regions being studied and forces the liquid above it to rise as a solid slug - This assumption is not

realistic, especially in regions with large horizontal dimension. Initially, the bubble probably approximates a sphere rather than a thin wafer. Also, penetration of the bubble through the liquid is possible; however, this cannot be predicted with the piston model.

A finite-difference model was developed to account for these weaknesses. Initial calculations using this model applied to a large steam generator indicated that the bubble pressure was not significantly different from the piston model during the early stages of bubble development. Also, as time progressed, bubble penetration through the liquid was predicted, thus lowering the bubble pressure. This indicates, therefore, that the piston model is conservative.

8. The full pressure drop of the sodium as it moves through each channel is distributed uniformly along the length of the sections considered. - The effect of this assumption on the bubble pressure is negligible.

Most of the calculations performed by the BUG-2 program are made in the mainline program designed for the IBM 360/85. One subroutine, BUGX, is called to calculate the initial conditions, and is also called to calculate the gas pressures during the transient analysis.* Plotting programs have been written for plotting the channel parameters, hydrogen bubble pressure, and integrals of the pressure-time and pressure-volume curves of the hydrogen bubble. These programs use an IBM 1130 computer connected with a Calcomp digital incremental plotter. Input from the 1130 program is from punched cards produced by two subroutines, DKON and DKOFF, of the BUG-2 program.

For many studies using the BUG-2 program, changes must be made to the mainline program to account for special features of the steam generator design being analyzed. Sections VI. A and VI. B include detailed discussions of the BUG-2 program so that these changes can be made more easily and with the minimum chance of upsetting the other parts of the program. Also, it is always necessary to write a new BUGX subroutine for each new channel arrangement to be analyzed. The procedure of doing this is discussed in Section VI-D.

* Actually, several BUGX subroutines are used where their real names are BUGX1, BUGX2, BUGX3, etc. Each subroutine serves a particular channel arrangement and the calling of the particular subroutine is determined from the input data.

A. DERIVATION OF THE EQUATIONS USED IN BUG-2

1. Fluid Velocity and Pressure Drop Equations

For incompressible fluid flow with constant viscosity, the Navier-Stokes equation for flow in the x direction is*

$$\begin{aligned} u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} + \frac{\partial u_x}{\partial t} \\ = g_c x - \frac{g_c}{\rho} \frac{\partial P}{\partial x} + \nu \frac{\partial^2 u_x}{\partial x^2} + \nu \frac{\partial^2 u_x}{\partial y^2} + \nu \frac{\partial^2 u_x}{\partial z^2} \end{aligned} \quad (26)$$

For the three-dimensional case, two more equations are necessary for flow in the y and z direction. These are omitted here since only one-dimensional flow is of interest. In addition, for one-dimensional flow the second and third terms of Equation (26) may be dropped because

$$u_y = u_z = 0 \quad (27)$$

The continuity equation for incompressible flow is

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \quad (28)$$

With $u_y = u_z = 0$, Equation (28) becomes

$$\frac{\partial u_x}{\partial x} = 0 \quad (29)$$

Thus, the first and seventh terms of Equation (26) can also be dropped. Finally, because of the very high pressure differences involved, BUG-2 ignores the gravity effects and, therefore, the fifth term may also be dropped. Equation (26) can now be rewritten as the Navier-Stokes equation for one-dimensional, constant viscosity, incompressible flow without gravity effects as

* The terms for the equations in this section are defined in a list at the end of the section.

$$\frac{\partial u_x}{\partial t} = - \frac{g_c}{\rho} \frac{\partial P}{\partial x} + \nu \left(\frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \quad (30)$$

The third term of Equation (30) accounts for the frictional pressure drop. If it is assumed that the frictional pressure drop is not a function of the fluid acceleration, this term will have the same value regardless of whether $\partial u_x / \partial t$ is or is not equal to zero. With $\partial u_x / \partial t = 0$, the steady-state case is obtained where

$$\frac{g_c}{\rho} \frac{\partial P}{\partial x} = \nu \left(\frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \quad (31)$$

However, the $\partial P / \partial x$ will be equal to the steady-state frictional pressure drop, or

$$\frac{g_c}{\rho} \frac{\partial P_f}{\partial x} = \nu \left(\frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \quad (32)$$

Because the frictional pressure drop is assumed to be independent of the fluid acceleration, Equation (30) can be written as

$$\frac{\partial u_x}{\partial t} = - \frac{g_c}{\rho} \frac{\partial P}{\partial x} + \frac{g_c}{\rho} \frac{\partial P_f}{\partial x} \quad (33)$$

For the finite-difference case, Equation 34 is obtained:

$$\frac{\Delta u_x}{\Delta t} = - \frac{g_c}{\rho} \frac{\Delta P - \Delta P_f}{\Delta x} \quad (34)$$

The expression used to calculate ΔP_f may be any of the many correlations relating the steady-state frictional pressure drop of a channel to the velocity of fluid within the channel. In BUG-2 the frictional pressure drop (including form losses) is calculated from an equation similar to

$$\Delta P_f = a u_x^b \quad (35)$$

The coefficients a and b are hand calculated for each channel of the steam generator. The calculated values are read by the program as input data during execution.

In BUG-2, a network of pipes or channels are analyzed where a channel of length Δx has a constant cross sectional area, friction factor, and fluid density. For such a channel, the change in the fluid velocity, ΔV , for a time step Δt can be found by writing Equation (34) as

$$\Delta V = \frac{g_c}{\rho \Delta x \epsilon} \left(P_{in} - P_{out} - \Delta P_f \right) \Delta t \quad (36)$$

The ϵ of Equation (36) is the volume fraction of fluid in the channel. It is multiplied by the channel length Δx to correct the channel length for the case when the channel has been partially voided of fluid by gas. The negative sign of Equation (34) is dropped in Equation (36) since in BUG-2 the convention is that the positive flow is in the direction of decreasing pressure. If during a transient study the flow in a channel reverses because the outlet pressure has become higher than the inlet pressure, the channel velocity will carry a negative sign. This may happen near the end of a run if the cover gas pressure becomes higher than the bubble pressure.

In BUG-2, Equations (35) and (36) are written as

$$PF(I) = COEF(1, I) * VV(I) * DABS(VV(I)) ** (COEF(2, I) - 1.) * SIG(I) \quad (37)$$

and

$$DV = C1 * DELT * (PP(J, JX1) - PP(J, JX2) - PF(I)) / XX(I) / SIG(I) \quad (38)$$

The form of Equation (37) differs slightly from Equation (35) to preserve the sign of the fluid velocity. Equation (37) also contains the fluid volume fraction $SIG(I)$ to account for a partially filled channel.

2. Equations for Resolution of the Node Pressure

At the beginning of each time step, BUG-2 must determine the total pressure at each node, i. e., junction of two or more channels. An equation similar to Equation (33) can be written in terms of volume flow rather than velocity:

$$\frac{dQ}{dt} = - \frac{g_c}{\rho} \cdot \frac{A}{\epsilon} \cdot \frac{\Delta P}{\Delta x} \quad (39)$$

The ϵ term is again added to account for a partially filled channel.

For a network of channels, volume flow continuity at each node requires that

$$\sum_{i=1}^n Q_i = 0 \quad (40)$$

Equation 40 applied to Equation (39) gives

$$\sum_{i=1}^n \left(\frac{A \Delta P}{\epsilon \Delta x} \right)_i = 0 \quad (41)$$

Because ΔP_i is the total pressure drop across channel i of length Δx , Equation (41) becomes

$$\sum_{i=1}^n \frac{A_i (P_{in} - P_{out} + \Delta P_f)_i}{\epsilon_i \Delta x_i} = 0 \quad (42)$$

All of the P_{in} 's must be equal; therefore, Equation (42) becomes

$$P_{in} = \frac{\sum_{i=1}^n \frac{A_i}{\epsilon_i \Delta x_i} (P_{out} + \Delta P_f)_i}{\sum_{i=1}^n \frac{A_i}{\epsilon_i \Delta x_i}} \quad (43)$$

In BUG-2 the numerator of Equation (43) is first obtained by solving the following equation n times:

$$SUM = SUM + C2(IX) * (PP(JXX) + PF(IX)) \quad (44)$$

where the initial value of SUM is zero. The sign of the PF(IX) term is positive when the flow is away from the node. The C2 term is

$$C2(I) = AREA(I) / SIG(I) / XX(I) \quad (45)$$

The denominator of Equation (43) is C3(J) which is the sum of all of the C2's for each channel associated with the node.

3. Equations for Calculating the Fluid Fraction and the Hydrogen Bubble and Cover Gas Pressures

The change in the fluid volume fraction for channels that are emptying and filling is determined by dividing the volume of fluid added to or taken from a channel during a time step by the channel volume, or

$$\Delta \epsilon = \frac{V A \Delta t}{A \Delta x} = \frac{V \Delta t}{\Delta x} \quad (46)$$

In BUG-2, Equation (46) is

$$\text{SIG(I)} = \text{SIG(I)} \pm (\text{VV(I)} - \text{DV}/2.) * \text{DELT}/\text{XX(I)} * 12.0 \quad (47)$$

The sign of the third term is negative when the outlet of the channel is full (therefore the inlet is empty), indicating the channel is emptying with a positive fluid velocity. The value of SIG(I) decreases, indicating an emptying channel if the outlet is full and the velocity is positive or the outlet is empty and the velocity is negative. The value of SIG(I) increases, indicating a filling channel if the inlet is full and the velocity is positive or the inlet is empty and the velocity is negative.

The cover gas pressure is calculated assuming adiabatic expansion of the cover gas

$$P_{cgt} = P_{cgi} (V_i/V_t)^{1.66} \quad (48)$$

The volume ratio of Equation (48) can be replaced by the ratio of the initial fraction of gas in the channel to the present fraction. Also, since by convention the highest numbered channel represents the cover gas space, Equation (48) is solved in the BUGX subroutine by

$$\text{PSTAT(2)} = \text{POG} * (\text{VOG}/(1. - \text{SIG(NCHN)})) ** 1.66 \quad (49)$$

The hydrogen injection rate is given as cubic feet per second at atmospheric pressure and 1800 F. The hydrogen bubble pressure is then determined from

$$\frac{\text{bubble pressure}}{\text{atmospheric pressure}} = \frac{\text{total volume injected}}{\text{bubble volume}} \quad (50)$$

In the BUGX subroutine, the bubble pressure equation is

$$\text{PSTAT(1)} = \text{VHOT} * \text{PAT} * 1728. / (\text{V1} + \text{V2}) \quad (51)$$

FIG. 23 FLOW CHART FOR BUG-2 PROGRAM

The V1 and V2 are the gas volumes of Channels 1 and 2, which by convention are adjacent to the leak location. When one of these two channels is almost empty ($\epsilon \leq 0.1$). The denominator is replaced by TX1, which is the sum of the gas volumes of those channels which have been partially or totally voided by the hydrogen bubble. The calculation of TX1 may at times be in error, and, therefore, changes must be made to the BUGX subroutine. This is discussed in Section VI.D.

4. Equation for Determining the Initial Bubble Pressure

In Reference 24 the initial hydrogen bubble volume for a single path model is given as

$$BV = \left(\frac{4g_c QP_a A^2}{3m} \right)^{1/2} \left(t^{3/2} \right) \quad (52)$$

This equation is for an instantaneous rupture of one or more tubes, which is represented as a setp change in leak rate from zero to some initial value. Defining the inertial resistance as

$$r = \rho L/A \quad (53)$$

Equation (52) can be rewritten as

$$BV = \left(\frac{4g_c QP_a}{3r} \right)^{1/2} \left(t^{3/2} \right) \quad (54)$$

The inertial resistance r is that resistance present in the network of channels between the hydrogen bubble and cover gas space or spaces. The calculation of r is not difficult, even for a system that has several cover gas spaces. This will be discussed in detail in Section VI.D. Equation (54) appears in the BUGX subroutine as

$$BV = \text{DSQRT} ((4.*32.2*3.58 \text{ E} + 7*\text{VHT}*\text{PAT})/(3.*\text{TOTR}))*\text{TIM}^{1.5} \quad (55)$$

B. ORGANIZATION OF THE BUG-2 PROGRAM

Figure 23 is a simplified flow chart for the BUG-2 program which will help in the understanding of this portion of the report.

1. Calculation of Initial Values

The BUG-2 program starts with reading input data, printing this data, and initializing various variables.* This is then followed by calling the BUGX subroutine to calculate the following:

* The variables are listed in Appendix C.

- The inertial resistance for
 - Each channel, R
 - The path from the leak through Channel 1 to cover gas spaces, $R1$
 - Same as above but through Channel 2, $R2$
 - The total network of pipes, $TOTR$
- The initial total bubble volume, BV , using Equation (55) and the bubble volume of Channels 1 and 2, $V1$ and $V2$
- The initial fluid velocity through each channel, VV
- The initial fluid volume fraction for Channels 1 and 2, using $V1$ and $V2$ from above
- The initial static pressure of the hydrogen bubble.

The next step in the mainline program is to assign the proper values to the $NEIP(JX, J)$ array used to describe the channel arrangement for the BUG-2 program. Specifically, the array

- Relates the node numbers to the channel identification (ID) numbers
- Relates the fluid flow direction relative to a particular node
- Relates each gas space to the proper channel.

Understanding of the use of $NEIP$ is necessary to understand the operation of the BUG-2 program. The variable integer JX of $NEIP(JX, J)$ is a counter, where for $JX = 1$ the value of $NEIP$ is for the first channel that connects to the node, for $JX = 2$ $NEIP$ is for the second channel, and so on. Which channel is considered the first and second is unimportant. J is the node number. The value assigned to $NEIP$ is the ID number of the channel which connects to the node number being considered with a positive value if the flow is toward the node. The use of $NEIP$ can most easily be understood by example. Referring to Figure 11, Case A, for $NEIP(1, 4) = -5$, the first channel which connects to node 4 is Channel 5, whose flow is away from node 4. For $NEIP(2, 4) = -11$, Channel 11 is the second channel to connect to node 4, and its flow is away from node 4. The fact that Channel 5 is considered before Channel 11 is not important; in fact, the BUG-2 program does not take the channels in this order.

The $NEIP$ array serves one additional purpose. The seventh row of the array, i.e., $NEIP(7, J)$ is used to relate each channel which contains gas to one of the gas spaces. For $NEIP(7, J)$ the J is the channel ID number and the value of $NEIP$ is the gas space ID number. For $NEIP(7, 2) = 1$, Channel 2 contains gas space No. 1. Actually, $NEIP(7, 1)$ and $NEIP(7, 2)$ are always equal to 1 since, by convention, Channels 1 and 2 are always adjacent to the leak and the hydrogen bubble is always identified as gas space No. 1.

For $NEIP(7,J) = 0$, Channel J is completely filled with fluid and does not make direct contact with any gas space. Initially $NEIP(7,J)$ will have nonzero values for Channels 1 and 2 and those channels that describe the cover gas spaces; all remaining $NEIP(7,J)$'s will be equal to zero. As the bubble expands, however, other channels will begin to empty, and their $NEIP(7,J)$ values will be redefined to nonzero values. The above assignment of the $NEIP$ values are made in the DO 21 loop for relating the gas space to the channels and the DO 40 loop for relating the channel ID numbers to the node numbers.

The next step is to call the BUGX subroutine again to calculate the initial changes in the bubble and cover gas pressures. After control returns to the mainline program from BUGX, the calculation of the frictional pressure drop, PF, for each channel and the total pressure at each node which contacts a gas space is made.

All of the above calculations are made once to provide the initial values for the first time step. The steps discussed in the next section are made for each time step.

2. Transient Calculations

The first operation of each time step is to determine the total pressure at each node using Equations (43) and (44) (statements 100 to 190). The iteration procedure is continued until no two successive iterations result in a change in pressure of more than 0.001 psi for any node. This can usually be obtained in 100 iterations, normally the limit; but for cases with channels of small length-to-area ratios, many more iterations may be required, and it may be necessary to redefine the limit of 0.001 to a larger value.

After printing the channel parameters, the program calculates the change in fluid velocity for each channel using Equation (38) and the new fluid fraction for the partially filled channels using Equation (47). If the new value of the fluid fraction $SIG(I)$ for a channel is negative, that channel has emptied during the time step, and its ID number is tagged by the variable $IOEVEC(IOE)$.

The next steps are to call the BUGX subroutine to calculate the new bubble and cover gas static pressures and to then use these pressures to calculate the total pressures for those nodes in gas spaces.

The DO 570 loop is next encountered. This is a loop with many calculations, all of which are involved with channels that have emptied during the time step. If no channels have emptied during the time step, this portion of the program is skipped and it is only necessary to calculate new values of PF and C2 before going to the next time step by returning to statement 100.

In the DO 570 loop, the program performs the following for each channel which has emptied:

- Computes the volume by which the channel has overemptied, AH1
- Calculates the total flow leaving the node, ARG2
- Distributes the excess gas volume, AH1, to each of the adjacent channels according to its fraction of the total flow through the node
- Sets up new node numbers for the new gas-fluid interfaces produced when one channel empties into two or more channels
- Redefines NEIP(7, J) for the adjacent channels which now contain gas.

C. DATA INPUT

Tables 8 and 9 provide the information necessary to understand the data input required for the BUG-2 code. Special requirements and limitations for the code are as follows:

Channel Numeration

- Channels 1 and 2 must be located adjacent to the hydrogen bubble
- The highest numbered channel must represent the cover gas space
- The second highest numbered channel must represent the second cover gas space, if one exists; for the B&W steam generator discussed in this report, the second cover gas space was the gas space in the center pipe
- No more than six channels may enter one node
- No numbers may be skipped in identifying channels.

Node Numeration

- Nodes 1 and 2 must be next to the hydrogen bubble
- The highest numbered node must be the outlet of the cover gas space
- The second highest numbered node must be the outlet of the second cover gas space, if one exists
- No numbers may be skipped in identifying nodes.

Limits

- Thirty channels – If more than 30 channels are requested, the program will skip the job and go to the next with a message printed. However, if a gross error has been made in this regard, an addressing exception may result and the entire run may fail.

TABLE 8 - INPUT FOR BUG-2

Card	Columns	Format	Variable	Description
1	1-40	10A4	JOB	Title to appear on printed and plotted output
	41-50	F10.2	RHO	Fluid density, lb/ft ³
	51-55	I5	NTIM	One job may be divided into several time segments in which the size of the time step and/or frequency of printed and plotted output may be changed from one segment to the next; NTIM is total number of such segments that are to be defined.
	56-60	I5	NCHN	Total number of channels in system, ≤ 30
	61-65	I5	NPP	Total number of nodes in system, ≤ 30
	66-70	I5	NPSTAT	Those nodes which are initially located in the cover gas or hydrogen bubble are considered as nodes with known static pressures; NPSTAT is the total number of nodes with such known pressures; NPSTAT = 3 for no second gas space because one node is in the cover gas and two are in the hydrogen bubble; NPSTAT = 4 for the case with a second gas space
	71-80	F10.2	TIM	TIM is the initial time; if this field is blank or < 0.0001 , TIM will be set equal to 0.0001 by the program
2	1	I1	NOPT	NOPT determines which BUGX subroutine is to be called to calculate the initial conditions and the gas pressures at each time step; for example, when NOPT = 1, BUGX1 is called
	2	I1	IPLOT	IPLOT = 0 No punching = 1 Punch bubble data only = 2 Punch all data
3	1-5	I5	NDEL T	This third card is used to specify the job segments mentioned above (Card 1, Columns 51-55) NDEL T is the total number of times the time step of this segment is to be repeated
	6-10	I5	NPRNT	NPRNT is the frequency of printing the channel data, e.g., NPRNT = 30, then print every 30 time steps
	11-15	I5	NPLOT	NPLOT is the frequency of providing the channel and hydrogen bubble information for plotting
	16-20	F5.5	TIMX	TIMX is the time step to be used for this segment
The above set of four pieces of data for Card 3 must be repeated in the indicated field widths of five as required, to specify the number of job segments, NTIM (Card 1, Columns 51-55). Continue on this card to Column 80, then go to a new card, if necessary.				
4	1-5	I5	NNEI(1, I)	Those nodes which are located in the known static pressure regions (above, Card 1, Columns 66-70) must be related to the particular pressure to be entered later on Card 6; NNEI(1, I) is the node number and NNEI(2, I) is the identification number of the pressure; these pressure ID numbers are: NNEI = 1 = hydrogen bubble NNEI = 2 = cover gas NNEI = 3 = second gas space (if any)
	As for Card 3, the above variables on Card 4 must be defined as many times as necessary in field widths of five to locate NPSTAT number of nodes (Card 1, Columns 66-70) in the proper gas space.			
5	1-10	F10.2	XX	Channel length, in.
	11-20	F10.2	AREA	Channel area, in. ²
	21-30	F10.2	COEFF(1, I) = a	The channel frictional pressure drop in psi will be calculated from $P_f = av^b$ where v is in ft/sec
	31-40	F10.2	COEFF(2, I) = b	
	41-45	I5	NNEI(1, I)	The node number at the channel inlet-inlet is towards the hydrogen bubble and is not related to the normal sodium flow through the steam generator
	46-50	I5	NNEI(2, I)	The node number at the channel outlet
	51-60	F10.2	SIG	SIG is the initial volume fraction of fluid in the channel. SIG = 1.0 for all channels except those which contain cover gas or the hydrogen bubble. A value of zero or < 0.0001 will be taken by the program as 0.0001. The initial value of SIG for the channels adjacent to the bubble (Channels 1 and 2) can be calculated by the BUGX subroutine if it is so written.
	61-70	F10.2	VV	The initial velocity of the fluid in the channel; this is the initial velocity resulting from the sodium-water reaction, not the normal fluid velocity, which is neglected in BUG-2; the velocities for all channels may also be calculated by the BUGX subroutine
Card 5 is repeated as necessary to define all the channels (NCHN, Card 1, Columns 56-60). The above data is read by the mainline program.				
The following data is read by the BUGX subroutine:				
6	1-10	F10.2	POG	Cover gas pressure, psia
	11-20	F10.2	POG1	Center pipe gas pressure (any pipe), psia
	21-30	F10.2	PGMAX	Rupture disk relief pressure, psia
	31-40	F10.2	PAT	Atmospheric pressure, psi
	41-50	F10.2	PB	Initial bubble pressure, psia; may be calculated by BUGX subroutine
	51-60	F10.2	VHO	Hydrogen release rate at one atmosphere and 1800 F for a single tube, ft ³ /sec
	61-70	I10	NTUBE	No total number of tubes assumed to rupture

TABLE 9 - INPUT FORMAT FOR BUG-2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																						
JOB TITLE																																									RHO lb/ft^3				NTIM				NCHM				NPP				NPSTAT				TIM																																																																																																																																																																																								
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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																						

$$* \Delta P = a V^b \text{ PSI, } V \text{ IN FT/SEC}$$

- Thirty nodes - However, since the number of nodes may increase as channels empty, the job may stop and the message may occur after the run has started. These protections have been added because exceeding the 30-node limit would result in unpredictable results; possibly results which appear correct, but are not.
- A request for punched output for subsequent plotting can only be made 200 times for each channel. After this, punched output will stop, but the program will continue. A message is printed to this effect the first time more than 200 data points are requested.

The fields for the initial time, TIM, and the fluid fractions, SIG, can be left blank and would be read as zero values by an IBM 360 computer. BUG-2 will set these equal to 0.0001 for these zero values or for any value less than 0.0001.

D. PROGRAMMING BUGX

The BUG-2 program begins its analysis at some time greater than $t = 0.0$. Before the analysis is begun, it is necessary to know the hydrogen bubble volume and pressure, as well as the fluid velocity and fluid fraction of all channels at this initial time, usually $t = 0.0001$. These initial values may be hand calculated and read as input or calculated by the BUGX subroutine if it has been so written. In this section, the procedure for writing the BUGX subroutine to calculate the initial conditions will be discussed. The subroutine has not been written in a general manner; therefore, it is necessary to write a new subroutine for each channel arrangement.

The parameters to be calculated are

- The inertial resistance of each channel, R
- The inertial resistance from the hydrogen bubble to the gas spaces in both directions, i. e., through Channels 1 and 2, R1 and R2
- The total inertial resistance, TOTR
- The bubble volume, BV
- The fluid velocity in each channel in ft/sec, VV
- The initial fluid fraction of Channels 1 and 2.

The initial bubble volume is found from Equation (54), which is rewritten as

$$BV = \left(\frac{4g_c QP_a}{3r} \right)^{1/2} t^{3/2} \quad (54)$$

To calculate the initial bubble volume, it is only necessary to calculate the total inertial resistance r . The resistance of the individual channels is calculated from Equation (53)

$$r = \rho L/A \quad (53)$$

The total resistance can be calculated from individual resistances by considering the inertial resistance to be analogous to the resistances of an electrical network. The procedure does not become complex when several gas spaces are considered because the gas spaces can always be considered as one, since their pressures are much less than the initial bubble pressure. The channel arrangement for a leak in the tube bundle of the B&W prototype steam generator was rather complex and serves as a good example of how to calculate the total inertial resistance and the other resistances that are required. For this case, the resistance of the channels which included the cover gas space and center pipe were neglected in the calculation of the total resistance. The channel arrangement is shown in Figure 11 and the listing of the corresponding BUGX subroutine is included in Appendix D.

With the initial bubble volume calculated, the initial fluid velocity in Channels 1 and 2 is calculated by

$$BV = \frac{\text{volume displaced in channel}}{\text{channel area} \times \text{time} \times 12.0} \times 1.5 \quad (56)$$

Without the factor of 1.5 the equation would calculate the average velocity over the time step rather than the velocity at the end of the time step. The time step here is the time from true zero to the initial time used in the analysis. The velocities in the remaining channels can be calculated by considering the need for volume flow continuity if the channel with a known velocity does not branch into two or more channels. When the flow does split into two or more branches, it is necessary to weight the volume of fluid displaced by the ratio of the inertial resistance presented by each branch to the total resistance of the branches.

The initial fluid fraction for Channels 1 and 2 are calculated from the bubble volume of each channel and the total channel volume.

The BUGX subroutine contains one calculation which must be watched. When the fluid fractions of Channels 1 and 2 are both above 0.10, the bubble volume during the transient analysis is calculated directly from the fluid fractions of these two channels. When the fluid fraction of either channel

approaches zero, the bubble volume calculation must consider that the bubble may be present in other channels. The bubble volume is then calculated by adding the total void volumes of all the channels except the last one (the highest numbered channel) which contains the cover gas space or the last two if there is a second cover gas space. If, however, the bubble pressure has become very low, the second cover gas space may empty into its adjacent channel and part of its gas volume would be considered by the program to be from the hydrogen bubble. If either of the cover gas spaces does empty into its adjacent channel, the NCHN2 of the DO 30 I = 1, the NCHN2 statement must be changed and the job rerun.

The BUGX subroutine listed in Appendix D has been written for a steam generator with a second cover gas space in the region of the steam generator. For a unit with no second cover gas space, the following changes should be made:

- VOG1, R(NCHN1), and PSTAT(3) need not be calculated
- The DO 30 loop mentioned above should be changed to
DO 30 I = 1, NCHN1

If more gas spaces are added, corresponding changes should be made.

DEFINITION OF TERMS USED IN EQUATIONS IN SECTION VI

- a = Frictional pressure drop coefficient
 A = Channel flow area
 b = Frictional pressure drop coefficient
 BV = Bubble volume
 ϵ = Volume fraction of fluid in channel
 g_c = Gravitational conversion factor between force and mass
 L = Channel Length
 $m = \rho AL$
 n = Number of channels leading to a node
 ν = Viscosity
 P = Total pressure
 P_a = Atmospheric pressure
 P_f = Frictional pressure drop
 P_{in} = Total pressure at inlet to channel
 P_{out} = Total pressure at outlet of channel
 P_{cgi} = Initial hydrogen bubble pressure
 P_{cgt} = Instantaneous bubble pressure
 Q = Channel volume flow
 $r = \rho L/A$
 ρ = Fluid density
 t = Time
 u_x, u_y, u_z = Velocity components
 V = Fluid velocity
 V_i = Initial hydrogen bubble volume
 V_t = Instantaneous hydrogen bubble volume
 x, y, z = Coordinate axes

APPENDIX A: LEAK DETECTION ANALYSIS COMPUTER CODE

To facilitate the small leak analysis, a computer code was written which simulates the demonstration plant secondary system. The code, written in Fortran IV, is compatible with the IBM 360/85, and is shown in Table A.1.

Following initiation of a leak in the steam generator, the concentration of H_2 and O_2 in the sodium at the leak detection station is recorded on a second-to-second basis. In addition, the response of a Rhometer and a plugging meter at that location are computed and printed out; the hydrogen concentration of the cover gas of the steam generator as monitored by a thermal conductivity cell is also printed out. At the same time, the code records the wall thickness of the adjacent tube which is being attacked as a result of the leak.

At the end of each run, a summary sheet is printed listing the instrumentation; the estimated sensitivity of the device; the time required for detection; the total wastage occurring during that time period; and the minimum sensitivity required in order that detection, isolation, and dump of the unit can be accomplished preventing propagation of the leak. Summary sheets produced by the code for the analysis performed are shown in Table A.2.

Program control is effected by replacing the variables of the X-array with the desired values. Table A.3 lists the variables of the X-array and defines them. Eight variables can be entered per data card by first listing the X-array location (1-15) on an I2 format then giving the value to be entered at that location (F8.3). If the array location is read in as zero or left blank, the analysis will begin with the values already read in.

On completion of the run, the next data set is read in on the same format. Only those variables which are changed need to be read in, the rest will carry over from the previous case. To terminate the job, the X-array location is specified as -1.

TABLE A.1 BASIC BAWSG PROGRAM

DATE 70.282/11.05.43

LEVEL 18 (SEPT 69)

OS/360 FORTRAN H

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=53,SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,
NOEDIT,ID,NOXREF

```

ISN 0002      DIMENSION X(15),CO(150),CH(150),CSO(120),CSH(120),GH(120),OO(120),
1CDO(20),CDH(20),CG(100),V(9),IT(9),A(6),IX(8),XT(8)
ISN 0003      DIMENSION SUMH(4),SUMO(4),SUMR(4),SUMP(4),SUMT(4)
ISN 0004      DIMENSION D1(10),D2(10),D3(10),D4(10),D5(10),D6(10)
ISN 0005      EQUIVALENCE (X(1),CNO),(X(2),F),(X(3),ALR),(X(4),ALOC),(X(5),TEMP),
1,(X(6),ACT),(X(7),FRH1),(X(8),FRH2),(X(9),FRH3),(X(10),FRO),(X(11)
2,ALIM),(IT(1),IT1),(IT(2),IT2),(IT(3),IT3),(IT(4),IT4),(IT(5),IT5)
3,(IT(6),IT6),(IT(7),IT7),(IT(8),IT8),(X(12),CTT),(X(14),ACAR),
4(IT(9),IT9),(X(13),ANT)
ISN 0006      DATA V,X /9.5,19.1,20.7,34.6,35.8,37.,39.,31.6,22.5,0.0,.8584,1.E-
13,10.,250.,1.,.6.,19.,.01,.6,5000.,250.,1.0,2.0,0.0/
ISN 0007      DATA NIN,NOUT,K5,IP,IPC/5,6,1,50,2/
ISN 0008      1000 FORMAT(8(I2,F8.3))
ISN 0009      1001 FORMAT('HYDROGEN CONCENTRATION,PPM')
ISN 0010      1010 FORMAT(1H ,I4,3F8.3,2F8.1,F12.4)
ISN 0011      1011 FORMAT('OXYGEN CONCENTRATION,PPM')
ISN 0012      1020 FORMAT(65H1TIME IMPURITY CONC. RHOMETER PLUG. WALL H2 CONC I
1N PAGE 12,/8X,'H2',6X,'O2',5X,'CHANGE TEMP. SIZE COVER GA
2S CASE 'F4.1,/' SEC.'7X,'PPM'6X,'PERCENT R 'F'6X,'MILS'5X,'VPM'
3/)
ISN 0013      1021 FORMAT('RHOMETER, PERCENT R')
ISN 0014      1030 FORMAT(1H1,30X,'SUMMARY',20X,F4.1,/,26X,'HABCOCK AND WILCOX',/,25X,
1'SMALL LEAK ANALYSIS',/,2X,'AT ',F4.2,' MILLION LBS/H2 SODIU
2M FLOW, A LEAK OF ',1PE9.3,' LBS/SEC',/' OF WATER OCCURS ',0PE4.1
3,' FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF',/' UNDETECTED, AN
4 ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN ',/10,
5 ' SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK',/
6' DETECTION INSTRUMENTATION.')
ISN 0015      1032 FORMAT('PLUGGING TEMPERATURE,F')
ISN 0016      1040 FORMAT(/24X,'EST1' ,
1MATED TIME TO TOTAL REQUIRED'/23X,'SENSITIVITY DETECTION
2WASTAGE SENSITIVITY'/38X,'SEC'6X,'MILS',/, ' HYDROGEN'/ ' R
3DETECTOR, PPM'11X,F5.3,7X,F4.0,6X,F5.1,6X,F5.3,/' OXYGEN METER, PPM
4'8X,F6.3,7X,F4.0,6X,F5.1,5X,F6.3,/' RHOMETER CHANGE,/' PERCENT
5R'14X,F6.4,6X,F4.0,6X,F5.1,6X,F6.4)
ISN 0017      1042 FORMAT('WALL THICKNESS, MILS')
ISN 0018      1050 FORMAT(' PLUGGING METER, F'9X,F5.1,7X,F4.0,6X,F5.1,6X,F5.1,/' THICK
1MAL CONDUCTIVITY'/ ' CELL, VPM'13X,F9.3,5X,F4.0,6X,F5.1,4X,F9.3)
ISN 0019      1051 FORMAT('HYDROGEN CONCENTRATION,VPM')
ISN 0020      1060 FORMAT('HABCOCK AND WILCOX SMALL LEAK ANALYSIS',38X,F4.1)
ISN 0021      2307 FORMAT(10F8.3)
ISN 0022      2308 FORMAT(1P10E8.2)
ISN 0023      ICAR=2
ISN 0024      115 READ(NIN,1000)(IX(I),XT(I),I=1,8)
ISN 0025      IPC=2
ISN 0026      K5=1
ISN 0027      IP=50
ISN 0028      DO 110 I=1,8
ISN 0029      IF(IX(I)) 99,120,105
ISN 0030      105 J=IX(I)
ISN 0031      110 X(J)=XT(I)

```

TABLE A.1 BASIC BAWSG PROGRAM (CONT'D)

```

ISN 0032      GO TO 115
ISN 0033      120 LIM=IFIX(ALIM)
ISN 0034      ICAR=IFIX(ACAR)
ISN 0035      INT=IFIX(ANT+0.001)
ISN 0036      IF(LIM/INT.LT.2001) GO TO 396
ISN 0038      WRITE(6,2396) LIM
ISN 0039      2396 FORMAT('1LIM TOO BIG,=',I10)
ISN 0040      GO TO 115
ISN 0041      396 CONTINUE
ISN 0042      IF(ALOC.GT.11.1) GO TO 400
ISN 0044      WALL=207.
ISN 0045      DAM=40.
ISN 0046      GO TO 410
ISN 0047      400 WALL=347.
ISN 0048      IF(ALOC.LT.18.1)WALL=388.
ISN 0050      IF(ALOC.LT.15.1)WALL=361.
ISN 0052      IF(ALOC.LT.14.1)WALL=317.
ISN 0054      DAM=50.
ISN 0055      410 W=WALL
ISN 0056      GO TO (350,351),ICAR
ISN 0057      350 DO 300 IA=1,6
ISN 0058      NW=IA+12
ISN 0059      300 REWIND NW
ISN 0060      351 CONTINUE
ISN 0061      FF=.8586/F
ISN 0062      ICT=IFIX(ACT)
ISN 0063      FS=F*1.E6/3600.
ISN 0064      DO 1 I=1,9
ISN 0065      1 IT(I)=IFIX(V(I)*FF+0.501)
ISN 0066      IA=IT7+1
ISN 0067      IB=IT8+1
ISN 0068      DO 180 I=1,IB
ISN 0069      QD(I)=0.0
ISN 0070      180 QH(I)=8.F-8/(FS*FLOAT(IT8))
ISN 0071      TCT=(CTT+460.)/1.8
ISN 0072      TPM=(TEMP+460.)/1.8
ISN 0073      CIO=EXP(2.302585*(6.239-2447./TPM))*1.E-6
ISN 0074      CIH=EXP(2.302585*(6.56-3140./TPM))*1.E-6+0.0342E-6
ISN 0075      CTO=EXP(2.302585*(6.239-2447./TCT))*1.E-6
ISN 0076      CTH=EXP(2.302585*(6.56-3140./TCT))*1.E-6
ISN 0077      DO 2 I=1,IA
ISN 0078      CO(I)=CIO
ISN 0079      2 CH(I)=CIH
ISN 0080      DO 3 I=1,IB
ISN 0081      CSO(I)=CIO
ISN 0082      3 CSH(I)=CIH
ISN 0083      DO 4 I=1,20
ISN 0084      CDO(I)=CIO
ISN 0085      4 CDH(I)=CIH
ISN 0086      DO 5 I=1,100
ISN 0087      5 CG(I)=(((CIH*1.E6)/131.5)**2)*1.E6/2.18

```

TABLE A.1 BASIC BAWSG PROGRAM (CONT'D)

```

ISN 0088      CXO=CIO
ISN 0089      CXH=CIH
ISN 0090      LOC=IFIX(IT8*ALOC/20.)
ISN 0091      IF(LOC) 7,7,8
ISN 0092      7 LOC=1
ISN 0093      8 QH(LOC)=ALR*FRH1/(9.00*FS)+8.E-8/(FS*ELCAT(IT8))
ISN 0094      QO(LOC)=ALR*FRH2/(9.00*FS)
ISN 0095      R=ALR*FRH3/(9.00*FS)
ISN 0096      H2=ALR*FRH3*359.1*3.67*1200.E6/(192.*492.)
ISN 0097      SF=1110.+350.*ALOC/20.
ISN 0098      SF=EXP(7.44-7890./SF)
ISN 0099      WR=242.*SF*ALR*.922
ISN 0100      DO 230 I=2,4
ISN 0101      SUMH(I)=-1000.
ISN 0102      SUMO(I)=-1000.
ISN 0103      SUMR(I)=-1000.
ISN 0104      SUMP(I)=-1000.
ISN 0105      230 SUMT(I)=-1000.
ISN 0106      SUMH(1)=0.06
ISN 0107      SUMO(1)=CIO*0.2E6
ISN 0108      SUMR(1)=0.03
ISN 0109      SUMP(1)=20.
ISN 0110      SUMT(1)=5.
ISN 0111      B1=CIH*1.E6+SUMH(1)
ISN 0112      B2=CIO*1.E6+SUMO(1)
ISN 0113      B3=CIH*1.E6*0.0558+CIO*1.E6*0.0043+SUMR(1)
ISN 0114      B4=SUMP(1)+(3140./(6.56-(ALOG(CIH*1.E6)/2.3026)))*1.8-460.
ISN 0115      B5=DAM+WP*10.
ISN 0116      B6=CG(1)+SUMT(1)
ISN 0117      FF=1./FF
ISN 0118      IPEN=IFIX((WALL-DAM)/WR)
ISN 0119      DO 100 I=1,LIM
ISN 0120      IF(W-WR-0.01) 15,15,10
ISN 0121      10 W=W-WR
ISN 0122      15 CXH=(CXH-CH(IT1))*EXP(-FF*1.5)+CH(IT1)
ISN 0123      CXO=(CXO-CO(IT1))*EXP(-FF*1.5)+CO(IT1)
ISN 0124      CH(IT1)=(CH(IT1-1)-CXH)*EXP(-FF*1.5)+CXH
ISN 0125      CO(IT1)=(CO(IT1-1)-CXO)*EXP(-FF*1.5)+CXO
ISN 0126      CH(IT2)=(CH(IT2-1)-CH(IT2))*EXP(-FF)+CH(IT2)
ISN 0127      CO(IT2)=(CO(IT2-1)-CO(IT2))*EXP(-FF)+CO(IT2)
ISN 0128      CH(IT5)=(CH(IT5-1)-CH(IT5))*EXP(-FF*.5)+CH(IT5)
ISN 0129      CO(IT5)=(CO(IT5-1)-CO(IT5))*EXP(-FF*.5)+CO(IT5)
ISN 0130      CH(IT7)=(CH(IT7-1)-CH(IT7))*EXP(-FF*.27)+CH(IT7)
ISN 0131      CO(IT7)=(CO(IT7-1)-CO(IT7))*EXP(-FF*.27)+CO(IT7)
ISN 0132      CH(IT9)=(CH(IT9-1)-CH(IT9))*EXP(-FF*.068)+CH(IT9)
ISN 0133      CO(IT9)=(CO(IT9-1)-CO(IT9))*EXP(-FF*.068)+CO(IT9)
ISN 0134      CSH(18)=CH(IT6)
ISN 0135      CSO(18)=CO(IT6)
ISN 0136      DO 20 J=1,IT8
ISN 0137      CSH(J)=(CSH(J)-CSH(J+1)-QH(J))*EXP(-2.)+CSH(J+1)+CH(J)
ISN 0138      20 CSO(J)=(CSO(J)-CSO(J+1)-QO(J))*EXP(-2.)+CSO(J+1)+CO(J)

```

TABLE A.1 BASIC BAWSG PROGRAM (CONT'D)

```

ISN 0139      CH(IT6)=CSH(1)
ISN 0140      CO(IT6)=CSO(1)
ISN 0141      DO 30 J=1,IT7
ISN 0142      CH(J)=CH(J+1)
ISN 0143      30 CO(J)=CO(J+1)
ISN 0144      CH(1A)=CH(1)
ISN 0145      CO(1A)=CO(1)
ISN 0146      DO 40 J=1,19
ISN 0147      CDH(J)=CDH(J+1)
ISN 0148      40 CDO(J)=CDO(J+1)
ISN 0149      CDH(20)=CH(IT4)
ISN 0150      CDO(20)=CO(IT4)
ISN 0151      DO 50 J=1,99
ISN 0152      50 CG(J)=CG(J+1)
ISN 0153      CG(100)=(((CH(IT7)*1.E6)/131.5)**2)*1.E6/2.1E+02
ISN 0154      GO TO (55,60),ICT
ISN 0155      55 CH(IT3)=(CH(IT3)*FS+CTH*2.33)/(FS+2.33)
ISN 0156      CO(IT3)=(CO(IT3)*FS+CTO*2.33)/(FS+2.33)
ISN 0157      60 CH(IT4-1)=CH(IT4-1)+R
ISN 0158      CG(2)=(CG(1)-CG(2))*EXP(-0.00433)+CG(2)
ISN 0159      A(1)=CDH(10)*1.E6
ISN 0160      A(2)=CDO(10)*1.E6
ISN 0161      A(3)=A(1)*0.0553+A(2)*0.0043
ISN 0162      A(5)=X
ISN 0163      A(6)=CG(1)
ISN 0164      TH=(3140./(6.56-(ALOG(CDH(10)*1.E6)/2.3026)))*1.8-446.
ISN 0165      TO=(2447./(6.239-(ALOG(CDO(10)*1.E6)/2.3026)))*1.8-460.
ISN 0166      IF (TH-TO) 130,130,135
ISN 0167      130 A(4)=TO
ISN 0168      GO TO 140
ISN 0169      135 A(4)=TH
ISN 0170      140 IF(MOD(1,INT).NE.0) GO TO 156
ISN 0172      IF(IP-50) 160,165,165
ISN 0173      165 IP=0
ISN 0174      WRITE(NOUT,1020)IPC,CND
ISN 0175      IPC=IPC+1
ISN 0176      160 IP=IP+1
ISN 0177      WRITE(NOUT,1010) I,A
ISN 0178      GO TO(141,155),ICAR
ISN 0179      141 CONTINUE
ISN 0180      D1(K5)=A(1)
ISN 0181      D2(K5)=A(2)
ISN 0182      D3(K5)=A(3)
ISN 0183      D4(K5)=A(4)
ISN 0184      D5(K5)=A(5)
ISN 0185      D6(K5)=A(6)
ISN 0186      IF(10-K5) 150,150,155
ISN 0187      150 WRITE(20) D1
ISN 0188      WRITE(21) D2
ISN 0189      WRITE(22) D3
ISN 0190      WRITE(23) D4

```

TABLE A.1 BASIC BAWSG PROGRAM

```

ISN 0191      WRITE(24) D5
ISN 0192      WRITE(25) D6
ISN 0193      K5=0
ISN 0194      155 K5=K5+1
ISN 0195      156 CONTINUE
ISN 0196      IF(SUMH(2)) 200,200,202
ISN 0197      200 IF(A(1)-B1) 202,201,201
ISN 0198      201 SUMH(2)=FLOAT(I)
ISN 0199      SUMH(3)=WALL-W
ISN 0200      202 IF(SUMH(2)) 205,205,207
ISN 0201      205 IF(A(2)-B2) 207,206,206
ISN 0202      206 SUMO(2)=FLOAT(I)
ISN 0203      SUMO(3)=WALL-W
ISN 0204      207 IF(SUMR(2)) 210,210,212
ISN 0205      210 IF(A(3)-B3) 212,211,211
ISN 0206      211 SUMR(2)=FLOAT(I)
ISN 0207      SUMR(3)=WALL-W
ISN 0208      212 IF(SUMP(2)) 215,215,217
ISN 0209      215 IF(A(4)-B4) 217,216,216
ISN 0210      216 SUMP(2)=FLOAT(I)
ISN 0211      SUMP(3)=WALL-W
ISN 0212      217 IF(A(5)-B5) 220,220,221
ISN 0213      220 SUMH(4)=A(1)-B1+SUMH(1)
ISN 0214      SUMT(4)=A(6)-B6+SUMT(1)
ISN 0215      IF(SUMT(4).LT.1.E-4) SUMT(4)=0.0
ISN 0217      SUMP(4)=A(4)-B4+SUMP(1)
ISN 0218      SUMR(4)=A(3)-B3+SUMR(1)
ISN 0219      SUMO(4)=A(2)-B2+SUMO(1)
ISN 0220      B5=0.0
ISN 0221      221 IF(SUMT(2)) 225,225,227
ISN 0222      225 IF(A(6)-B6) 227,226,226
ISN 0223      226 SUMT(2)=FLOAT(I)
ISN 0224      SUMT(3)=WALL-W
ISN 0225      227 CONTINUE
ISN 0226      100 CONTINUE
ISN 0227      WRITE(NOUT,1030)CNO,F,ALR,ALOC,IPEN
ISN 0228      WRITE(NOUT,1040)SUMH,SUMO,SUMR
ISN 0229      WRITE(NOUT,1050)SUMP,SUMT
ISN 0230      GO TO (340,331),ICAR
ISN 0231      340 CONTINUE
ISN 0232      WRITE(7,1060) CNO
ISN 0233      IMAX=LIM/10
ISN 0234      DO 330 IA=1,6
ISN 0235      NW=IA+19
ISN 0236      REWIND NW
ISN 0237      GO TO (301,302,303,304,305,306),IA
ISN 0238      301 WRITE(7,1001)
ISN 0239      GO TO 307
ISN 0240      302 WRITE(7,1011)
ISN 0241      GO TO 307
ISN 0242      303 WRITE(7,1021)
ISN 0243      GO TO 307
ISN 0244      304 WRITE(7,1032)
ISN 0245      GO TO 307
ISN 0246      305 WRITE(7,1042)
ISN 0247      GO TO 307
ISN 0248      306 WRITE(7,1051)
ISN 0249      307 CONTINUE
ISN 0250      DO 329 IE=1,IMAX
ISN 0251      READ(NW) D1
ISN 0252      IF(IA.LT.6) WRITE(7,2307) D1
ISN 0254      IF(IA.EQ.6) WRITE(7,2308) D1
ISN 0256      329 CONTINUE
ISN 0257      330 CONTINUE
ISN 0258      331 CONTINUE
ISN 0259      GO TO 115
ISN 0260      99 STOP
ISN 0261      END

```


TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG

SUMMARY

1.0

BADCOCK AND WILCOX
SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000E-04$ LBS/SEC OF WATER OCCURS 3.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 1751 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	128.	12.2	0.623
OXYGEN METER, PPM	0.217	22.	2.1	2.431
RHOMETER CHANGE, PERCENT R	0.0300	974.	92.9	0.0512
PLUGGING METER, F	20.0	105.	10.0	106.6
THERMAL CONDUCTIVITY CELL, VPM	0.500E-01	142.	13.5	0.267E-02

COLD TRAP RUNNING AT 250 F

SUMMARY

2.0

BADCOCK AND WILCOX
SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000E-04$ LBS/SEC OF WATER OCCURS 3.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 1751 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	126.	12.0	0.684
OXYGEN METER, PPM	0.217	22.	2.1	4.169
RHOMETER CHANGE, PERCENT R	0.0300	924.	88.1	0.0561
PLUGGING METER, F	20.0	105.	10.0	111.2
THERMAL CONDUCTIVITY CELL, VPM	0.500E-01	142.	13.5	0.284E-02

COLD TRAP OFF

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG (CONT'D)

SUMMARY

3.0

**BABCOCK AND WILCOX
SMALL LEAK ANALYSIS**

AT 0.80 MILLION LBS/HR SODIUM FLOW, A LEAK OF 1.0000×10^{-4} LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN DETECTOR, PPM	0.060	141.	25.7	0.335
OXYGEN METER, PPM	0.217	37.	6.7	2.079
RHOMETER CHANGE, PERCENT R	0.0300	990.	180.3	0.0276
PLUGGING METER, F	20.0	123.	22.4	78.5
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.194E 02

COLD TRAP RUNNING AT 250 F

SUMMARY

4.0

**BABCOCK AND WILCOX
SMALL LEAK ANALYSIS**

AT 0.67 MILLION LBS/HR SODIUM FLOW, A LEAK OF 1.0000×10^{-4} LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN DETECTOR, PPM	0.060	151.	27.5	0.338
OXYGEN METER, PPM	0.217	39.	7.1	2.106
RHOMETER CHANGE, PERCENT R	0.0300	981.	178.7	0.0279
PLUGGING METER, F	20.0	135.	24.6	78.9
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.194E 02

COLD TRAP RUNNING AT 250 F

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG (CONT'D)

SUMMARY

5.0

**BARCOCK AND WILCOX
SMALL LEAK ANALYSIS**

AT 0.47 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000\text{E}-04$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN DETECTOR, PPM	0.060	182.	33.1	0.337
OXYGEN METER, PPM	0.217	50.	9.1	2.118
RHOMETER CHANGE, PERCENT R	0.0300	982.	178.9	0.0279
PLUGGING METER, F	20.0	55.	10.0	78.8
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.192E 02

COLD TRAP RUNNING AT 250 F

SUMMARY

6.0

**BARCOCK AND WILCOX
SMALL LEAK ANALYSIS**

AT 0.25 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000\text{E}-04$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN DETECTOR, PPM	0.060	86.	15.7	0.336
OXYGEN METER, PPM	0.217	81.	14.8	2.203
RHOMETER CHANGE, PERCENT R	0.0300	991.	180.5	0.0282
PLUGGING METER, F	20.0	84.	15.3	78.7
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.190E 02

COLD TRAP RUNNING AT 250 F

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG (CONT'D)

SUMMARY

7.0

BABCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 1.23 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000E-04$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	152.	27.7	0.342
OXYGEN METER, PPM	0.217	85.	15.5	2.106
RHOMETER CHANGE, PERCENT R	0.0300	971.	176.8	0.0281
PLUGGING METER, F	20.0	113.	20.6	79.4
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.195E 02

COLD TRAP RUNNING AT 250 F

SUMMARY

8.0

BABCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $2.000E-05$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 4043 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	803.	33.2	0.257
OXYGEN METER, PPM	0.217	455.	18.8	1.566
RHOMETER CHANGE, PERCENT R	0.0300	****	*****	0.0211
PLUGGING METER, F	20.0	586.	24.2	67.9
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	1380	124.7	0.585E 01

COLD TRAP RUNNING AT 250 F

**** NO DETECTION

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG (CONT'D)

SUMMARY

9.0

BABCOCK AND WILCOX
SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000E-04$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	138.	25.1	0.354
OXYGEN METER, PPM	0.555	216.	39.3	2.175
RHOMETER CHANGE, PERCENT R	0.0300	936.	170.5	0.0291
PLUGGING METER, F	20.0	221.	40.3	55.6
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.209E 02

COLD TRAP OFF

SUMMARY

10.0

BABCOCK AND WILCOX
SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $1.000E-04$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 916 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	138.	25.1	0.354
OXYGEN METER, PPM	1.265	517.	94.2	2.175
RHOMETER CHANGE, PERCENT R	0.0300	936.	170.5	0.0291
PLUGGING METER, F	20.0	496.	90.3	32.6
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	142.	25.9	0.244E 02

COLD TRAP OFF

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG (CONT'D)

SUMMARY

11.0

BARCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $5.000E-05$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 1737 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	304.	29.2	0.340
OXYGEN METER, PPM	1.265	1060	101.8	2.052
RHOMETER CHANGE, PERCENT R	0.0300	1870	179.3	0.0278
PLUGGING METER, F	20.0	986.	94.8	31.6
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	205.	19.7	0.172E 02

COLD TRAP OFF

SUMMARY

12.0

BARCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $5.000E-05$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 1737 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	304.	29.2	0.340
OXYGEN METER, PPM	0.555	458.	44.0	2.052
RHOMETER CHANGE, PERCENT R	0.0300	1870	179.3	0.0278
PLUGGING METER, F	20.0	455.	43.7	54.2
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	207.	19.9	0.133E 02

COLD TRAP OFF

TABLE A.2 SUMMARY OF ALL CASES PERFORMED BY BAWSG

SUMMARY

13.0

BABCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $2.500E-05$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 3291 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	597.	30.3	0.329
OXYGEN METER, PPM	0.555	928.	47.1	1.938
RHOMETER CHANGE, PERCENT R	0.0300	1870	187.2	0.0267
PLUGGING METER, F	20.0	889.	45.1	53.1
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	985.	50.0	0.937E 01

COLD TRAP OFF

SUMMARY

14.0

BABCOCK AND WILCOX SMALL LEAK ANALYSIS

AT 0.86 MILLION LBS/HR SODIUM FLOW, A LEAK OF $2.500E-05$ LBS/SEC OF WATER OCCURS 10.0 FEET FROM THE BOTTOM OF THE TUBE BUNDLE. IF UNDETECTED, AN ADJACENT TUBE(S) WILL BE COMPLETELY PENETRATED IN 3291 SEC. THE FOLLOWING TABLE IS A SUMMARY OF THE AVAILABLE LEAK DETECTION INSTRUMENTATION.

	ESTIMATED SENSITIVITY	TIME TO DETECTION SEC	TOTAL WASTAGE MILS	REQUIRED SENSITIVITY
HYDROGEN				
DETECTOR, PPM	0.060	597.	30.3	0.329
OXYGEN METER, PPM	1.265	2140	108.4	1.938
RHOMETER CHANGE, PERCENT R	0.0300	3690	187.2	0.0267
PLUGGING METER, F	20.0	1940	98.4	30.8
THERMAL CONDUCTIVITY CELL, VPM	0.500E 01	611.	31.0	0.134E 02

COLD TRAP OFF

TABLE A.3 - LIST OF INPUT VARIABLES

<u>X-Array Location</u>	<u>Variable Name</u>	<u>Description</u>
1	CNØ	Case number
2	F	Sodium flow, lb/hr x 10 ⁶
3	ALR	Water leak rate, lb/sec
4	ALØC	Location of leak measured from bottom of the tube bundle, ft (LØC)
5	TEMP	Initial plugging temperature of the secondary system, F
6	ACT	Cold trap option (ICT) ACT = 1 - Cold trap on ACT = 2 - Cold trap off
7	FRH1	Fraction of hydrogen dissolved in the sodium at the leak location
8	FRH2	Fraction of hydrogen dissolved in the sodium as it is carried along with the sodium flow; this fraction is not available to the leak detection system on the first pass
9	FRH3	Fraction of hydrogen released to the cover gas via bubble transport
10	FRØ	Fraction of oxygen dissolved in the sodium at the leak location
11	ALIM	Duration of run, sec (LIM)
12	CTT	Cold trap temperature, F
13	ANT	Time increment for printed output, sec (INT)
14	ACAR	Card punch option (ICAR) ACAR = 1 - Sort and punch data on cards ACAR = 2 - By-pass sort and card punch
15	----	Unassigned

APPENDIX B: HYDROGEN BUBBLE MOVEMENT STUDY

A brief analysis was performed to estimate the potential of hydrogen bubbles to reach the cover gas space of the steam generator. If the bubbles were swept along with the sodium flow, they would go only as far as the surge tank which is located schematically just behind the steam generator. Alternately, the bubbles may rise vertically in the steam generator against the downward flow of sodium. The residence time of the sodium in the steam generator is approximately 30 seconds at full power and the sodium velocity, therefore, would be approximately 0.7 ft/sec. The following simplifying assumptions were made to facilitate the analysis:

- The terminal velocity of the bubble is constant at 1 ft/sec
- The rate controlling step for the reaction

is the liquid phase diffusion of the solute in the solvent

- The solute is assumed to be nonionic in character and may be represented as a neutral atom of hydrogen.

From the first assumption, it may be concluded that the bubble does rise vertically in the steam generator.

The diffusivity can be estimated by two methods as shown in Reference 25, assuming that liquid sodium approximates the characteristics of water. Using Figure B.1 and the equations given below:*

$$D_L = \frac{T}{\mu F} (F = 1.4 \times 10^7) \quad (\text{B.2})$$

where

$$\begin{aligned} &= 1.4 \times 10^{-4} \text{ cm}^2/\text{sec} \\ D_L &= \frac{0.00014}{\mu^{1.1} V_A^{0.6}} = 0.67 \times 10^{-4} \text{ cm}^2/\text{sec} \quad (\text{B.3}) \end{aligned}$$

For simplifying purposes, the diffusivity was chosen as $1.4 \times 10^{-4} \text{ cm}^2/\text{sec}$.

* A list of terms used in the equations in this appendix is given at the end of the appendix.

FIG. B.1 DIFFUSION OF NONIONIC SOLUTES IN DILUTE AQUEOUS SOLUTION

The liquid mass transfer coefficient can be estimated by a correlation given by Johnson, et al.²⁶

$$k = 1.13 \left(\frac{D_L U}{0.45 + 0.2 d_e} \right)^{1/2} \quad (\text{B.4})$$

The mass transfer rate can then be calculated:

$$dN/dt = kA(C_2 - C_1) \quad (\text{B.5})$$

Figure B.2 shows the results of this calculation starting with an effective bubble diameter of 5 cm. A bubble having an effective diameter of 5 cm will last approximately 130 seconds.

As a check on the accuracy of the analysis, the computation was checked against the data gathered on some water injections performed in a steam generator at the Enrico Fermi Atomic Power Plant. An average bubble diameter of 2.5 to 3 cm was chosen. The transport time around the secondary circuit was approximately 45 seconds. The point of the injections was at the steam generator outlet; therefore, it was quite probable that the hydrogen bubbles traveled around the circuit rather than upward through the steam generator. The amount of hydrogen reaching the cover gas is calculated to be equal to 1.3% to 7% of that hydrogen which is originally present in the bubble. However, only one-half of the hydrogen constituting the water will form the bubble. The total release fraction, therefore, is 0.65% to 3.5%. This value compares favorably with the results of the injections at the Fermi plant.

Now repeating the analysis for the B&W prototype steam generator, it can be assumed that the leak occurs midway in the unit or about 10 feet from the top. The difference between the terminal velocity and the sodium velocity is 0.3 ft/sec and the total travel time is approximately 30 seconds. The bubble diameter starting at 2.5 cm diminishes to 1.98 cm, and 12.8% of the bubble enters the gas space. This is one-half of the total hydrogen available; therefore, for full flow, the release fraction to the cover gas is 6.4%. The same type of analysis can be performed for less than full flow conditions in which case the bubble will rise faster than for the 100% flow condition and will result in a higher fractional release to the cover gas.

The deficiencies and limitations of the above analysis are recognized; the analysis serves only to present some rational to the release fraction and could be the first step in performing a more detailed analysis which was not undertaken in the performance of this job.

FIG. B.2 BUBBLE SIZE VERSUS TIME FOR A HYDROGEN BUBBLE RISING IN SODIUM AT 660 F

LIST OF TERMS USED IN EQUATIONS IN APPENDIX B

- A = Diffusing area, cm^2
- C₁ = Hydrogen concentration distant from the bubble - assumed to be negligible
- C₂ = Saturation concentration, 13×10^{-6} g-moles H₂/cm³
- D_L = Diffusivity in liquid system, cm^2/sec
- d_e = Effective diameter of bubble, cm
- F = Value read from Figure B.1, $\frac{(^{\circ}\text{K})(\text{sec})}{\text{Centipoise (cm)}^2}$
- k = Mass transfer coefficient, cm/sec
- μ = Viscosity of the sodium, 0.314 cp
- N = Amount of hydrogen diffusing, g-moles
- t = Unit time, sec
- T = Temperature, $^{\circ}\text{K}$, 622K (660 F)
- V_a = Solute molal volume at the normal boiling point, 28.56 cm³/g-mole

APPENDIX C: LIST OF VARIABLES FOR BUG-2

AH1	- Amount of over-emptying of a channel, in. ³
AH2	- Amount of gas distributed to a particular channel, in. ³
AH4	- Total amount of distributed gas, in. ³
AH5	- Flow through a particular channel, ft ³ /sec
AH6	- Total flow through the just emptied node, ft ³ /sec
AREA	- Channel cross sectional flow area (input), in. ²
ARG2	- Total flow through the just emptied channel, ft-in. ² /sec
BV	- Hydrogen bubble volume, in. ³
COEFF(1, I)	Friction pressure drop coefficients (including form losses); for $\Delta P_f = aV^b$, $a = \text{COEFF}(1, I)$ and $b = \text{COEFF}(2, I)$ (input)
COEFF(2, I)	
C1	- $g \cdot 1728 / \rho$, ft-in. ³ /lb-sec ²
C2	- $\text{AREA} / (\text{XX} \cdot \text{SIG})$, in.
C3	- Summation for C2, in.
C4	- $\rho / (2 \cdot 32.2 \cdot 144)$ lb-sec ² /(ft ² -in. ²)
DELT	- Δt time step, sec
DV	- Change in fluid velocity, ft/sec, for the time step (not rate of change)
END	- When END = 2.0, job will stop because the total specified number of time steps has been made; any other reason to terminate the run will set END = 1.0; for END = 0, job continues.
IOE	- Total number of channels which emptied during time step
IOEVEC	- ID number of channel which emptied during time step
IPLLOT	- Specifies punching of cards for later plotting, (input)
IVEC1	- Total number of partially filled channels
IVC1	- ID number of partially filled channel
JOB	- Title to appear on printed and plotted output (input)
NCHN	- Total number of channels, input
NCHN1	- ID number of cover gas channel
NCHN2	- ID number of center pipe, if any
NDELT	- Number of times a time step is to be repeated, input
NEIP(7, JX)	- Static pressure ID number for node JX

NEIP(JX, J) - This variable is used to relate each node to each of its adjacent channels and also the flow direction in the adjacent channel relative to the node
 JX is a counter, where JX = 1 for the first channel that connects to the node, JX = 2 for the second, etc., which channel is considered the first and second, etc., is not important
 J is the number of the node
 The value assigned to NEIP(JX, J) is the ID number of the adjacent channel being considered, i.e., first, second, etc., with a sign which is (-) if flow is away from the node and (+) if towards the node; see example Section VI

NNEI(1, I) - Inlet node number of Channel I; NNEI also serves to read input data for static pressure

NNEI(2, I) - Outlet node number of Channel I; as above, also serves for input

NOPT - Specifies which BUGX subroutine to call

NPLMX - Running total of the number of time steps

NPLOT - Frequency of punching cards for later plotting

NPP - Total number of nodes (input), but may increase during analysis as channels empty

NPRNT - Frequency of printing channel parameters

NPSTAT - For reading input, NPSTAT is the total number of nodes having a known static pressure, but is redefined as the total number of known static pressure regions

NTIM - Total number of time-step segments (input)

NTUBE - Number of tube ruptures (input)

PAT - Atmospheric pressure (input), psia

PDV - Integral of PdV, ft-lb

PDT - Integral of Pdt, psia-sec

PB - Hydrogen bubble pressure (input), or calculated by BUGX, psia

PF - Frictional pressure drop, psi

PGMAX - Rupture disk relief pressure (input), psia

POG - Initial pressure of first cover gas space (input), psia

POG1 - Initial gas pressure of second cover gas space, if any, (input), psia

PSI - Inlet static pressure, psia

PSO - Outlet static pressure, psia

PTSTAT(1) - Static pressure of hydrogen bubble, psia

PTSTAT(2) - Static pressure of first cover gas space, psia

PTSTAT(3) - Static pressure of second cover gas space, if any, psia

PF - Frictional pressure drop, psi

PP - Total node pressure, psi

R	- Inertial resistance of channels, $\text{lb}/(\text{ft}^3\text{-in.})$
R1	- Inertial resistance from bubble through Channel 1 to gas spaces, $\text{lb}/(\text{ft}^3\text{-in.})$
R2	- Same as R1, but through Channel 2
RHO	- Fluid density, input, lb/ft^3
SIG	- Volume fraction of fluid in channel
TIM	- Time, read as input for initial time and then increases during analysis to indicate time of reaction
TIMX	- Size of time step (input)
TOTR	- Total inertial resistance, $\text{lb}/(\text{ft}^3\text{-in.})$
TX1	- Total gas bubble volume, in.^3
VHO	- Single tube gas generation rate at 1 atmosphere and 1800 F, (input), ft^3/sec
VHOT	- Total gas released ($\text{VHO} \times \text{NTUBE} \times \text{TIM}$), in.^3
VHOTR	- Rate of gas injection, ft^3/sec
VV	- Fluid velocity, negative if flow is opposite that defined by the node number convention, ft/sec
XX	- Channel length (input), in.

APPENDIX D: BUG-2 PROGRAM

```

C      BUG2 -- TRANSIENT PIPING NETWORK
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION NDELT(10),IVC1(10),NPLT(10),NPRNT(10),IOEVEC(10)
      DIMENSION C2(30),TIMX(10),C3(30),VOLC(30)
      COMMON/BUGXX/VHO,PAT,VHOT,R1,R2,TOTR,V1,V2,BV,CDEF(2,30)
      COMMON/DSK/PDT,PDV,C4,IPLT,NCHH(30)
      COMMON TIM,DELT,RHO,END,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
      1PF(30),PP(30),TX1,JOB(10)
      COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
      DKUSE=0.0

C
      10 PRINT 2000
      2000 FORMAT(1H1/'1BUG2-TRANSIENT PIPING NETWORK'//)
      DO 12 I=1,30
      12 NCHH(I)=0
      IPR3=0
      ICONV=0
      READ(5,1400) JOB,RHO,NTIM,NCHN,NPP,NPSTAT,TIM
      1400 FORMAT(10A4,F10.2,4I5,F10.6)
      IF(TIM.LT.0.0001) TIM=0.0001
      IF(RHO.NE.0.) GO TO 14
      PRINT 2014, RHO
      2014 FORMAT('1JOB COMPLETE, RHO=',F9.2)
      STOP
      14 PRINT 1420,JOB,RHO
      1420 FORMAT(3X,10A4/'ORHO=',F6.2)
      PRINT 2116, NTIM,NCHN,NPP,NPSTAT,TIM
      2116 FORMAT('0 NTIM NCHN NPP NPSTAT TIM' / 15,1X,2I5,2X,15,F9.5)
      READ 2113, NOPT,IPLT
      2113 FORMAT(5I1)
      PRINT 2115, NOPT
      2115 FORMAT('0 NOPT=',I2)
      IF(IPLT.EQ.0) PRINT 2117
      2117 FORMAT('0 NO PUNCHING')
      IF(IPLT.EQ.1) PRINT 2118
      2118 FORMAT('0 PUNCH BUBBLE AND INTEGRALS PDT AND PDV DATA')
      IF(IPLT.EQ.2) PRINT 2119
      2119 FORMAT('0 PUNCH ALL DATA')
      IF((NOPT.GT.0).AND.(NOPT.LE.4)) GO TO 15
      PRINT 2114,NOPT
      2114 FORMAT('0NOPT SPECIFYING BUGX OPTION NOT EQUAL TO 1,2,OR 3')
      STOP
      15 CONTINUE
      IF(DKUSE.EQ.0.) GO TO 18
      DKUSE=0.0
      DO 16 I=1,NCHN1
      NW=I+19
      16 REWIND NW
      REWIND 16
      REWIND 17
      18 NCHN1=NCHN
      DO 20 J=1,30
      PP(J)=0.
      DO 20 JX=1,7
      20 NEIP(JX,J)=0
      READ 2403, (NDELT(ITIM),NPRNT(ITIM),NPLT(ITIM),TIMX(ITIM),ITIM=1,
      1NTIM)
      2403 FORMAT(4(3I5,F5.5))
      PRINT 2404,(NDELT(ITIM),NPRNT(ITIM),NPLT(ITIM),TIMX(ITIM),ITIM=1,

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

INTIM)
2404 FORMAT('O NDELT NPRNT NPLDT TIMX'/ 3(I5,2X),F8.6)
READ (5,1402) (NNEI(1,I),NNEI(2,I),I=1,NPSTAT)
1402 FORMAT(16I5)
WRITE (6,1429) (NNEI(1,I),NNEI(2,I),I=1,NPSTAT)
J=1
DO 21 I=1,NPSTAT
JX=NNEI(1,I)
NEIP(7,JX)=NNEI(2,I)
21 IF(NEIP(7,JX).GT.J) J=NEIP(7,JX)
NPSTAT=J
1401 FORMAT(4F10.2,2I5,2F10.2)
READ (5,1401) (XX(I),AREA(I),COEF(1,I),COEF(2,I),NNEI(1,I),NNEI(2,
I),SIG(I),VV(I),I=1,NCHN)
DO 22 I=1,NCHN
22 IF(SIG(I).LT.0.0001) SIG(I)=0.0001
IF(NOPT.GT.1) GO TO 602
WRITE (6,1421) (I,XX(I),AREA(I),COEF(1,I),COEF(2,I),NNEI(1,I),NNEI
1(2,I),SIG(I),VV(I),I=1,NCHN)
1421 FORMAT(5HOCHAN 3X 6HLENGTH 6X 4HAREA 7X 4HCOEF 6X 3OHEXP P IN P
IOUT SIGMA VEL/(I5,1P3E11.3,0PF6.2,I5,I7,F8.4,F9.2))
GO TO 603
602 WRITE (6,3421) (I,XX(I),AREA(I),COEF(1,I),COEF(2,I),NNEI(1,I),NNEI
1(2,I),I=1,2)
3421 FORMAT(5HOCHAN 3X 6HLENGTH 6X 4HAREA 7X 4HCOEF 6X 3OHEXP P IN P
IOUT SIGMA VEL/(I5,1P3E11.3,0PF6.2,I5,I7))
WRITE (6,2421) (I,XX(I),AREA(I),COEF(1,I),COEF(2,I),NNEI(1,I),NNEI
1(2,I),SIG(I),VV(I),I=3,NCHN)
2421 FORMAT (I5,1P3E11.3,0PF6.2,I5,I7,F8.4,F9.2)
C
603 IF(NCHN.LE.30) GO TO 24
PRINT 2211
2211 FORMAT('NUMBER OF CHAN OR NODES GT 30')
GO TO 10
24 IF(NPP.LE.30) GO TO 28
PRINT 2211
GO TO 10
28 CONTINUE
IT=0
ITIM=1
DELT=TIMX(1)
IF(NOPT.EQ.1) CALL BUGX1(0)
IF(NOPT.EQ.2) CALL BUGX2(0)
IF(NOPT.EQ.3) CALL BUGX3(0)
IF(NOPT.EQ.4) CALL BUGX4(0)
PRINT 2023
2023 FORMAT('//T23,'INITIAL CALCULATED VALUES'/ )
PRINT 2024, R1,R2,TOTR
2024 FORMAT('OINERTIAL RESISTANCES LB/FT3-IN'6X'R1'10X'R2'9X'TOTR'/
1T33,1P3E12.4)
PRINT 2020,V1,V2,BV,SIG(1),SIG(2)

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

2020 FORMAT(1H0,T23,'CHAN 1'6X'CHAN 2'7X' TOTAL'/' RUEBLE VOL IN3'3X
11P3E12.4,
2/' SIG',T18,OP2F12.7)
PRINT 2052,(VV(I),I=1,NCHN)
2052 FORMAT('OVLOCITIES FT/SEC '6(1P5E13.5/))
DO 29 I=1,NCHN
29 VOLC(I)=VV(I)*AREA(I)*12.0
PRINT 2029,(VOLC(I),I=1,NCHN)
2029 FORMAT('OVOLUME FLOWS IN3/SEC'6(1P5E13.5/))
NPRNTX=NPRNT(1)
NPLMX=0
NPLTX=NPLQT(1)
END=0.
C1=32.2*1728./RHO
C4=RHO/(2.*32.2*144.)
ISIGN=1
DO 40 I=1,NCHN
DO 40 IX=1,2
J=NNEI(IX,I)
ISIGN=-ISIGN
DO 30 JX=1,6
IF(NEIP(JX,J).NE.0) GO TO 30
NEIP(JX,J)=I*ISIGN
GO TO 40
30 CONTINUE
WRITE (6,1422) J,I
GO TO 10
40 CONTINUE
IF(NOPT.EQ.1) CALL BUGX1(1)
IF(NOPT.EQ.2) CALL BUGX2(1)
IF(NOPT.EQ.3) CALL BUGX3(1)
IF(NOPT.EQ.4) CALL BUGX4(1)
PDV=216.*VHO*PAT*TIM
PDT=2.*PSTAT(1)*TIM
TIML=TIM
PSTAL=PSTAT(1)
VHGT=VHGT
TX1L=TX1
PRINT 2410,PDT,PDV
2410 FORMAT('GINTEGRALS'4X'PDT='1PE10.3,' PSI-SEC '4X'PDV='10.3,
1' FT-LB')
DO 60 I=1,NCHN
PF(I)=COEF(1,I)*VV(I)*DABS(VV(I))*((COEF(2,I)-1.)*SIG(I)
C2(I)=AREA(I)/XX(I)/SIG(I)
IF((SIG(I).GE.1.0).OR.(SIG(I).LE.0.)) GO TO 60
DO 59 IX=1,2
J=NNEI(IX,I)
IF(NEIP(2,J).NE.0) GO TO 59
NEIP(1,J)=0
JX=NEIP(7,J)
PP(J)=PSTAT(JX)+C4*VV(I)**2
59 CONTINUE
60 CONTINUE
C
C
C
PRINT 2999,JOB
2999 FORMAT('1BEGIN TRANSIENT CALC'4X,10A4,/' UNITS'/'PX'PRESS'2X'PDT'4X
1'PDV'4X'VOL'4X'VEL'2X'VHO*T'/

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

28X'PSIA'2X'PSI-S'2X'FT-LB'2X'CU-IN'2X'FT/S'2X'CU-FT'///)
100 DO 120 J=1,NPP
    C3(J)=0.
    IF (NEIP(1,J).EQ.0) GO TO 120
    DO 110 JX=1,6
        I=IABS(NEIP(JX,J))
        IF (I.EQ.0) GO TO 120
    110 C3(J)=C3(J)+C2(I)
    120 CONTINUE
    ITR=0
C
    130 IF (ITR.LT.100) GO TO 131
C    PRINT 1423
C    END=1.0
    ICONV=ICONV+1
    GO TO 9320
    131 ITR=ITR+1
7131 FORMAT(I5,E15.6)
    SUMAX=1.0E-10
    DO 290 J=1,NPP
        IF (NEIP(1,J).EQ.0) GO TO 290
        SUM=0.
        DO 260 JX=1,6
            IX=NEIP(JX,J)
            IF (IX) 240,270,250
        240 IX=-IX
            JXX=NNEI(2,IX)
            SUM=SUM+C2(IX)*(PP(JXX)+PP(IX))
            GO TO 260
        250 JXX=NNEI(1,IX)
            SUM=SUM+C2(IX)*(PP(JXX)-PP(IX))
        260 CONTINUE
        270 SUM=SUM/C3(J)
            IF (DABS(SUM-PP(J)).GT.SUMAX) SUMAX=DABS(SUM-PP(J))
        280 PP(J)=SUM
        290 CONTINUE
            IF (SUMAX.GT.0.001) GO TO 130
C
9320 IF (IT.LT.NDELT(ITIM)) GO TO 310
    ITIM=ITIM+1
    IF (ITIM.LE.MTIM) GO TO 305
    END=2.0
    GO TO 320
    305 DELT=TIMX(ITIM)
    IT=0
    NPLOTX=NPLET(ITIM)
    NPRNTX=NPRNT(ITIM)
    GO TO 320
    310 CONTINUE
    IF (NPRNTX.NE.NPRNT(ITIM)) GO TO 334
    320 PRINT 2424, TIM, (PSTAT(J),J=1,NPSTAT)
2424 FORMAT('GTIME=',F8.5,' STATIC PRESSURES=',7F7.1)
    PRINT 2425, PDT,PDV,FX1,DTX1
2425 FORMAT(' PDT=',1PE10.3,3X'PDV=',1E10.3,3X'VE=',1E10.3,3X'DVB=',1E10.3
1)
    PRINT 2426, VHOT,VH-ITR,ITR
2426 FORMAT(' VHO*T=',1PE10.3,3X'VHOTR=',1E10.3,110)
    WRITE (6,1430)
1430 FORMAT('OCHAN'4X'SIGMA'4X'VOLUME'6X'VEL'5X'P F'2X'PT IN'2X
1'PT OUT'3X'PS IN' 2X'PS OUT'4X'FLOW')
    DO 330 I=1,NCHN
        IF (SIG(I).LE.0.) GO TO 330
        JX1=NNEI(1,I)
        JX2=NNEI(2,I)
        VVX=SIG(I)*AREA(I)*XX(I)
        PSI=PP(JX1)-C4*VV(I)**2

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

      PS0=PP(JX2)-C4*VV(1)**2
      FLOW=VV(1)*AREA(1)*12.0
      WRITE (6,1425) I,SIG(1),VVX ,VV(1),PF(1),PP(JX1),PP(JX2),PS1,PS0
      1, FLOW
1425  FORMAT(14,F11.6,1PE11.3,OPF8.1,3F7.1,2X,2F7.1,1PE12.3)
      330  CONTINUE
            IF(END.EQ.0.) GO TO 336
      332  CONTINUE
            IF(END.EQ.1.0) PRINT 2336, JOB
            IF(END.EQ.2.0) PRINT 2337, JOB
2336  FORMAT('O RUN COMPLETE TIME LIMIT NOT REACHED'/1X,20A4)
2337  FORMAT('O RUN COMPLETE SPECIFIED NUMBER OF TIME STEPS SATISFIED'
      1/1X,20A4)
      PRINT 9337,ICONV
9337  FORMAT(I10)
      IF(DKUSE.EQ.1.0) CALL DKOFF
      GO TO 10
      336  NPRNTX=0
      334  IF ((IPLT.EQ.0).OR.(NPLT(ITIM).EQ.0).OR.(NPLTX.NE.NPLT(ITIM)))
      1GO TO 340
      DKUSE=1.
      IF(NPLMX.LE.199) CALL DKON
      NPLTX=0
      340  TIM=TIM+DELT
      IT=IT+1
      NPLTX=NPLTX+1
      NPRNTX=NPRNTX+1
      IF(END.NE.0.) GO TO 320

C
      IOE=0
      IVEC1=0
      DO 450 I=1,NCNV
      IF(SIG(I).LE.0.) GO TO 450
      JX1=NNEI(1,I)
      JX2=NNEI(2,I)
      DV=C1*DELT*(PP(JX1)-PP(JX2)-PF(1))/XX(I)/SIG(I)
      VV(1)=VV(1)+DV
      IF(NCIP(1,JX1).NE.0) GO TO 410
      SIG(1)=SIG(1)-(VV(1)-DV/2.)*DELT/XX(1)*12.
      GO TO 420
410  IF (NCIP(1,JX2).NE.0) GO TO 450
      SIG(1)=SIG(1)+(VV(1)-DV/2.)*DELT/XX(1)*12.
420  IF(SIG(1).LE.1.) GO TO 430
      WRITE (6,1426)I
      END=1.0
      GO TO 320
430  IF(SIG(1).GT.0.) GO TO 440
      IOE=IOE+1
      IOVEC(IGF)=I
      GO TO 450
440  IVEC1=IVEC1+1
      IVC1(IVEC1)=I
450  CONTINUE

C
      IF(NOPT.EQ.1) CALL BUGX1(1)
      IF(NOPT.EQ.2) CALL BUGX2(1)
      IF(NOPT.EQ.3) CALL BUGX3(1)
      IF(NOPT.EQ.4) CALL BUGX4(1)

C
      PDT=PDT+0.5*(TIM-TIML)*(PSTAL+PSTAT(1))
      PDV=PDV+(TX1-TX1L)*(PSTAL+PSTAT(1))/24.
      DTX1=(TX1-TX1L)/(TIM-TIML)
      VHOTR=(VHOT-VHOTL)/(TIM-TIML)
      TIML=TIM
      PSTAL=PSTAT(1)
      TX1L=TX1

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

VHOTL=VHOT
IF (IVEC1.EQ.0) GO TO 480
DO 470 IVECX=1,IVEC1
I=IVC1(IVECX)
JX1=NNEI(1,I)
JX2=NNEI(2,I)
IF(NEIP(1,JX1).EQ.0) GO TO 460
JXX=NEIP(7,JX2)
PP(JX2)=PSTAT(JXX)+C4*VV(I)**2
GO TO 470
460 JXX=NEIP(7,JX1)
PP(JX1)=PSTAT(JXX)+C4*VV(I)**2
470 CONTINUE
C
480 IF(IDE.EQ.0) GO TO 580
DO 570 IDEX=1,IDE
I=IOVEEC(IDEX)
AH4=0.
AH1=XX(I)*AREA(I)*DABS(SIG(I))
PRINT 2021, I,TIM
2021 FORMAT('OCHAN',I3,' OVER EMPTIED    TIME=',I9.5)
PRINT 2022, I,AH1,SIG(I)
2022 FORMAT(' EX VOL(IN3)'5X'SIG(',I2,')'4X'MODE FLOW(FT3/S)'/E12.4,3X,
IF10.7)
IF(VV(I).GE.0.) GO TO 510
JX1=NNEI(2,I)
JX2=NNEI(1,I)
GO TO 520
510 JX1=NNEI(1,I)
JX2=NNEI(2,I)
520 JSTAT=NEIP(7,JX1)
ARG2=0.
DO 505 JX=1,6
IX=-NEIP(JX,JX2)
IXA=IABS(IX)
IF(VV(IXA).LT.0.) IX=-IX
505 IF(IX.GT.0) ARG2=ARG2+DABS(VV(IX)*AREA(IX))
AH6=ARG2/144.
PRINT 2032,AH6
2032 FORMAT(1H+,T30,E13.6)
PRINT 2028
2028 FORMAT(5X,'CHAN',RX,'SIG(I)' 10X,'GAS VOL '10X'FLOW')
IF(ARG2.NE.0.) ARG1=-SIG(I)*XX(I)*AREA(I)/ARG2
SIG(I)=0.
ICOUNT=0
DO 550 JX=1,6
IX=NEIP(JX,JX2)
IXA=IABS(IX)
IF(IXA.EQ.0) GO TO 560
IF(IXA.EQ.1) GO TO 550
ICOUNT=ICOUNT+1
530 IF(VV(IXA)*DPLUAT(IX).LE.0.) IF (ICOUNT-2) 531,532,533
WRITE (6,1427) I,IXA,JX2
VV(IXA)=0.
ICOUNT=ICOUNT-1
GO TO 550
531 J=JX2
GO TO 534
532 J=JX1
GO TO 534
533 NPP=NPP+1
J=NPP
IF(NPP.LE.30) GO TO 534
PRINT 2211
END=1.
GO TO 320

```


APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

534 ARG2=XX(IXA)*AREA(IXA)
   IF(SIG(IXA).EQ.1.000) GO TO 535
   PRINT 2535,IXA
2535 FORMAT('ONEIGHBORING CHAN',I3,' ALREADY CONTAINS GAS'/' AT THE END
1 OPPOSITE THE JUST EMPTIED NODE'/' )
   END=1.
535 CONTINUE
   SIG(IXA)=(ARG2-ARG1*DABS(VV(IXA)*AREA(IXA)))/ARG2
   AH2=XX(IXA)*AREA(IXA)*(1.-SIG(IXA))
   AH4=AH4+AH2
   AH5=VV(IXA)*AREA(IXA)/144.
   PRINT 2030,IXA,SIG(IXA),AH2,AH5
2030 FORMAT(6X,I2,6X,F11.8,5X,E12.5,5X,E11.4)
   NEIP(7,J)=JSTAT
   NEIP(1,J)=0
   PP(J)=PSTAT(JSTAT)+C4*VV(IXA)**2
   IF(IX.LT.0) GO TO 540
   NNEI(2,IXA)=J
   GO TO 550
540 NNEI(1,IXA)=J
550 CONTINUE
560 IF(ICOUNT-1) 561,562,570
561 WRITE (6,1422) JX2,IXA
   END=1.
   GO TO 320
1422 NEIP(1,JX1)=0
570 CONTINUE

C
C
C
   PRINT 2040,AH4
2040 FORMAT( 2X'TOTAL DISTRIBUTED VOL=' ,E11.4,' IN3')
580 CONTINUE
7580 DO 590 I=1,NCIN
   IF(SIG(I).LE.0.) GO TO 590
   PF(I)=COEF(1,I)*VV(I)*DABS(VV(I))*(COEF(2,I)-1.)*SIG(I)
   C2(I)=AREA(I)/SIG(I)/XX(I)
590 CONTINUE
   IF(END.EQ.1.0) GO TO 332
   GO TO 100
1422 FORMAT( 7H0 POINT I3,35H HAS TOO MANY NEIGHBORS-LAST ONE IS I3)
1423 FORMAT(24H0PRESSURES NOT CONVERGED)
1426 FORMAT(8H0CHANNEL I3,16H HAS OVER-FILLED)
1427 FORMAT(8H0CHANNEL I3,19H OVER-EMPTIED. FLOW I3,19H NOT AWAY FROM N
1ODEI3)
1428 FORMAT(31H0THERE ARE NO NEIGHBORS TO NODE I3,15H EXCEPT CHANNELI3)
1429 FORMAT(22H0STATIC PRESSURE NODES/15H NODE,P NC. .../12(I6,I3))
   END

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

C      SUBROUTINE BUGX2(M)
C
C      BW TUBE BUNDLE  STRAIGHT SECTION  BUGX2
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/BUGXX/VHD,PAT,VHOT,R1,R2,TOTR,V1,V2,BV,COFF(2,30)
      COMMON TIM,DELT,RHO,END,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
1PF(30),PP(30),TX1,JDR(10)
      COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
      DIMENSION DEL(2),R(30)
      IF(M.NE.0) GO TO 10
      READ 1400, PDG,POG1,PGMAX,PAT,VHD,NTUBE
1400 FORMAT(4F10.2,10X,F10.2,I10)
1403 FORMAT(8F10.2)
      WRITE(6,1401) PDG,POG1,PGMAX,PAT,VHD,NTUBE
1401 FORMAT('C PDG POG1 PGMAX PAT VHD 7X NTUBE'
1/4F8.2,F12.2,I7)
      NCHN1=NCHN-1
      NCHN2=NCHN-2
      VOG=1.-SIG(NCHN)
      VOG1=1.-SIG(NCHN1)
      IF(TIM.LE.0.01) GO TO 5
      DUM=1.
      RETURN
5 CONTINUE
      DO 6 I=1,NCHN2
6 R(I)=RHO*XX(I)/AREA(I)
      R(NCHN1)=RHO*XX(NCHN1)*SIG(NCHN1)/AREA(NCHN1)
      R(NCHN)=RHO*XX(NCHN)*SIG(NCHN)/AREA(NCHN)
      R3=1./(1./R(10)+R(11))+1./R(9))
      R4=1./(1./R(5)+1./R(6)+R(7)+R(8))
      R1=R(1)+R3*R4/(R3+R4)
      R2=R(2)+R(3)+R(4)
      TOTR=R1*R2/(R1+R2)
      VHT=VHD*DELT/PAT*(NTUBE)
      BV=DSORT((4.*32.2*3.5FE+7*VHT*PAT)/(3.*TOTR))*TIM**1.5
      V1=BV*TOTR/R1
      V2=EV*TOTR/R2
      V3=V1*(R1-R(1))/R3
      V4=V1*(R1-R(1))/R4
      VV(1)=V1/(AREA(1)*TIM*12.0)*1.5
      VV(2)=V2/(AREA(2)*TIM*12.0)*1.5
      VV(4)=VV(2)*AREA(2)/AREA(4)
      VV(5)=V4*R4/R(5)
      VV(5)=VV(5)/(AREA(5)*TIM*12.0)*1.5
      VV(6)=V4*R4/(R(6)+R(7)+R(8))
      VV(6)=VV(6)/(AREA(6)*TIM*12.0)*1.5
      VV(7)=VV(6)*AREA(6)/AREA(7)
      VV(8)=VV(6)*AREA(6)/AREA(8)
      VV(9)=V3*R3/R(9)
      VV(9)=VV(9)/(AREA(9)*TIM*12.0)*1.5
      VV(10)=V3*R3/(R(10)+R(11))
      VV(10)=VV(10)/(AREA(10)*TIM*12.0)*1.5
      VV(11)=VV(10)*AREA(10)/AREA(11)
      VV(3)=VV(2)*AREA(2)/AREA(3)
      VV(12)=(VV(3)*AREA(3)+VV(5)*AREA(5)+VV(9)*AREA(9)+VV(8)*AREA(8))/
1AREA(12)
      SIG(1)=1.-V1/AREA(1)/XX(1)
      SIG(2)=1.-V2/AREA(2)/XX(2)
      C1=32.2*1728./RHO

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

DUM=-1.
RETURN
10 PSTAT(2)= PUG*(VOG/(1.-SIG(NCHN)))*1.66
PSTAT(3)=POG1*(VOG1/(1.-SIG(NCHN1)))*1.66
VHT=VHO*TIM
VHOT=VHT*DFLOAT(NTURE)
IF(PSTAT(2).LT.PGMAX) GO TO 11
END=1.
PRINT 2040, TIM, JOB
2040 FORMAT(////' RUPTURE DISK FAILED AT',F8.4,' SEC'/1X,10A4////)
11 IF(DUM.LT.0.) GO TO 37
IF((SIG(1).LT.0.1).OR.(SIG(2).LT.0.1)) GO TO 21
DO 36 I=1,2
JX1=NNEI(1,I)
JX2=NNEI(2,I)
DV=C1*DELT*(PP(JX1)-PP(JX2)-PF(I))/XX(I)/SIG(I)
DEL(I)=(VV(I)-DV/2.)*DELT/XX(I)*12.
36 CONTINUE
V1=V1+DEL(1)*AREA(1)*XX(1)
V2=V2+DEL(2)*AREA(2)*XX(2)
37 PSTAT(1)=VHOT*PAT*1728./(V1+V2)
VHOT=VHO*TIM
DUM=1.
TX1=V1+V2
RETURN
21 CONTINUE
20 TX=TIM
TX1=0.
DO 30 I=1,NCHN2
30 TX1=TX1+AREA(I)*XX(I)*(1.-SIG(I))
VHOT=VHO*TX
PSTAT(1)=VHOT*PAT*1728./TX1
RETURN
END

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

SUBROUTINE BUGX3(M)
C
C BW DOWNCOMER   BUGX3
C
  IMPLICIT REAL*8 (A-H,O-Z)
  COMMON/BUGXX/VHO,PAT,VHOT,R1,R2,TOTR,V1,V2,BV,COEF(2,30)
  COMMON TIM,DELT,RHO,END,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
  1PF(30),PP(30),TX1,JOB(10)
  COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
  DIMENSION DEL(2),R(30)
  IF(M.NE.0) GO TO 10
  READ 1400, POG,POG1,PGMAX,PAT,VHO,NTUBE
1400 FORMAT(4F10.2,10X,F10.2,I10)
  WRITE(6,1401) POG,POG1,PGMAX,PAT,VHO,NTUBE
1401 FORMAT('O  POG  POG1  PGMAX      PAT      VHO'7X'NTUBE'
  1/4F8.2,F12.2,I7)
  NCHN1=NCHN-1
  NCHN2=NCHN-2
  VOG=1.-SIG(NCHN)
  VOG1=1.-SIG(NCHN1)
  IF(TIM.LE.0.01) GO TO 5
  DUM=1.
  RETURN
5 CONTINUE
  DO 6 I=1,NCHN2
6 R(I)=RHO*XX(I)/AREA(I)
  R(NCHN1) = RHO*XX(NCHN1)*SIG(NCHN1)/AREA(NCHN1)
  R(NCHN)=RHO*XX(NCHN)*SIG(NCHN)/AREA(NCHN)
  R1=1./((1./(R(3)+R(8))+ 1./(R(5)+R(6)+R(7))+ 1./R(4) )
  1+R(1)
  R2=R(2)
  TOTR=R1*R2/(R1+R2)
  VHT=VHO*DFLOAT(NTUBE)
  BV=DSQRT((4.*32.2*3.58E+7*VHT*PAT)/(3.*TOTR))*TIM**1.5
  V1=BV*TOTR/R1
  V2=BV*TOTR/R2
  VV(1)=V1/(AREA(1)*TIM*12.0)*1.5
  VV(2)=V2/(AREA(2)*TIM*12.0)*1.5
  VV(3)=V1*(R1-R(1))/(R(3)+R(8))
  VV(3)=VV(3)/(AREA(3)*TIM*12.0)*1.5
  VV(8)=VV(3)*AREA(3)/AREA(8)
  VV(5)=V1*(R1-R(1))/(R(5)+R(6)+R(7))
  VV(5)=VV(5)/(AREA(5)*TIM*12.0)*1.5
  VV(6)=VV(5)*AREA(5)/AREA(6)
  VV(4)=V1*(R1-R(1))/R(4)
  VV(4)=VV(4)/(AREA(4)*TIM*12.0)*1.5
  VV(7)=VV(5)*AREA(5)/AREA(7)
  VV(9)=(VV(2)*AREA(2)+VV(7)*AREA(7)+VV(4)*AREA(4))/AREA(9)
2000 FORMAT(1H0,6E15.5)
  SIG(1)=1.-V1/AREA(1)/XX(1)
  SIG(2)=1.-V2/AREA(2)/XX(2)
  C1=32.2*1728./RHO
  DUM=-1.
  RETURN
10 PSTAT(2)= POG*(VOG/(1.-SIG(NCHN)))*1.66
  PSTAT(3)=POG1*(VOG1/(1.-SIG(NCHN1)))*1.66
  VHT=VHO*TIM
  VHOT=VHT*DFLOAT(NTUBE)
  IF(PSTAT(2).LT.PGMAX) GO TO 11

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

END=1.
PRINT 2040, TIM, JOB
2040 FORMAT('////' RUPTURE DISK FAILED AT', F8.4, ' SEC'/'1X, 10A4'////)
11 IF(DUM.LT.0.) GO TO 37
   IF((SIG(1).LT.0.1).OR.(SIG(2).LT.0.1)) GO TO 21
   DO 36 I=1,2
   JX1=NNEI(1,I)
   JX2=NNEI(2,I)
   DV=C1*DELT*(PP(JX1)-PP(JX2)-PF(I))/XX(I)/SIG(I)
   DEL(I)=(VV(I)-DV/2.)*DELT/XX(I)*12.
36 CONTINUE
   V1=V1+DEL(1)*AREA(1)*XX(1)
   V2=V2+DEL(2)*AREA(2)*XX(2)
37 PSTAT(1)=VHOT*PAT*1728./(V1+V2)
   DUM=1.
   TX1=V1+V2
   RETURN
21 CONTINUE
20 TX=TIM
   TX1=0.
   DO 30 I=1,NCHN2
30 TX1=TX1+AREA(I)*XX(I)*(1.-SIG(I))
   PSTAT(1)=VHOT*PAT*1728./TX1
   RETURN
END

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

SUBROUTINE BUGX4(M)
C
C BW TUBE BUNDLE BUGX4
C
  IMPLICIT REAL*8 (A-H,O-Z)
  COMMON/BUGXX/VHO,PAT,VHOT,R1,R2,TOTR,V1,V2,BV,COEF(2,30)
  COMMON TIM,DELT,RHO,END,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
  1PF(30),PP(30),TX1,JOB(10)
  COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
  DIMENSION DEL(2),R(30)
  IF(M.NE.0) GO TO 10
  READ 1400, POG,POG1,PGMAX,PAT,VHO ,NTUBE
1400 FORMAT(4F10.2,10X,F10.2,I10)
  WRITE(6,1401) POG,POG1,PGMAX,PAT,VHO,NTUBE
1401 FORMAT('0 POG POG1 PGMAX PAT VHO'7X'NTUBE'
  2/4F8.2,F12.2,I7)
  NCHN1=NCHN-1
  NCHN2=NCHN-2
  VOG=1.-SIG(NCHN)
  VOG1=1.-SIG(NCHN1)
  IF(TIM.LE.0.01) GO TO 5
  DUM=1.
  RETURN
5 CONTINUE
  DO 6 I=1,NCHN2
6 R(I)=RHO*XX(I)/AREA(I)
  R(NCHN1) = RHO*XX(NCHN1)*SIG(NCHN1)/AREA(NCHN1)
  R(NCHN)=RHO*XX(NCHN)*SIG(NCHN)/AREA(NCHN)
  R3=1./ ( 1./(R(10)+R(13))+ 1./R(9) )
  R4=1./ ( 1./R(5)+ 1./(R(6)+R(7)+R(8)) )
  R1=R(1)+R(4)+ R3*R4/(R3+R4)
  R2=R(2)+R(3)
  TOTR=R1*R2/(R1+R2)
  VHT=VHO*DFLOAT(NTUBE)
  BV=DSQRT((4.*32.2*3.58E+7*VHT*PAT)/(3.*TOTR))*TIM**1.5
  V1=BV*TOTR/R1
  V2=BV*TOTR/R2
  V3=V1*(R1-R(1)-R(4))/R3
  V4=V1*(R1-R(1)-R(4))/R4
  VV(1)=V1/(AREA(1)*TIM*12.0)*1.5

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

VV(2)=V2/(AREA(2)*TIM*12.0)*1.5
VV(3)=VV(2)*AREA(2)/AREA(3)
VV(4)=VV(1)*AREA(1)/AREA(4)
VV(5)=V4*R4/R(5)
VV(5)=VV(5)/(AREA(5)*TIM*12.0)*1.5
VV(6)=V4*R4/(R(6)+R(7)+R(8))
VV(6)=VV(6)/(AREA(6)*TIM*12.0)*1.5
VV(7)=VV(6)*AREA(6)/AREA(7)
VV(8)=VV(6)*AREA(6)/AREA(8)
VV(9)=V3*R3/R(9)
VV(9)=VV(9)/(AREA(9)*TIM*12.0)*1.5
VV(10)=V3*R3/(R(10)+R(13))
VV(10)=VV(10)/(AREA(10)*TIM*12.0)*1.5
VV(11)=VV(4)*AREA(4)/AREA(11)
VV(12)=VV(3)*AREA(3)/AREA(12)
VV(13)=VV(10)*AREA(10)/AREA(13)
VV(14)=(VV(3)*AREA(3)+VV(5)*AREA(5)+VV(9)*AREA(9)+VV(8)*AREA(8))/
IAREA(14)
SIG(1)=1.-V1/AREA(1)/XX(1)
SIG(2)=1.-V2/AREA(2)/XX(2)
C1=32.2*1728./RHO
DUM=-1.
PSTAT(1)=VHT*PAT*1728./BV*TIM
PSTAT(3)=POG1
C4=RHO/(2.*32.2*144.)
7010 FORMAT(/5E15.6)
RETURN
10 PSTAT(2)= POG*(VDS/(1.-SIG(NCHN)))*1.66
PSTAT(3)=POG1*(VDS1/(1.-SIG(NCHN1)))*1.66
VHT=VHO*TIM
VHOT=VHT*DELCAT(NTG1)
IF(PSTAT(2).LT.PSMAX) GO TO 11
END=1.
PRINT 2040, TIM, JDS
2040 FORMAT('///// RUPTURE DISK FAILED AT',F8.4,' SEC'/1X,10A4/////')
11 IF(DUM.LT.0.) GO TO 37
IF((SIG(1).LT.0.1).OR.(SIG(2).LT.0.1)) GO TO 21
DO 36 I=1,2
JX1=NNFI(1,I)
JX2=NNFI(2,I)
BV=C1*DELT*(PP(JX1)-PP(JX2)-PF(1))/XX(1)/SIG(1)
DEL(1)=(VV(1)-BV/2.)*DELT/XX(1)*12.
36 CONTINUE
V1=V1+DEL(1)*AREA(1)*XX(1)
V2=V2+DEL(2)*AREA(2)*XX(2)
37 PSTAT(1)=VHOT*PAT*1728./(V1+V2)
IF(DUM.LT.0.) PRINT 7010,VHOT,PAT,V1,V2,TIM
DUM=1.
TX1=V1+V2
RETURN
21 CONTINUE
20 TX=TIM
TX1=0.
DO 30 I=1,NCHN2
30 TX1=TX1+AREA(I)*XX(I)*(1.-SIG(I))
PSTAT(1)=VHOT*PAT*1728./TX1
RETURN
END

```

APPENDIX D: BUG-2 PROGRAM (CONT'D)

```

SUBROUTINE DKON
  IMPLICIT REAL*8 (A-H,O-Z)
  REAL*4 A1,VVX,A3,A4,A5,A6
  COMMON/DSK/PDT,PDV,C4,IPLOT,NCHH(30)
  COMMON TIM,DELT,RHO,END,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
  1PF(30),PP(30),TX1,JDR(10)
  COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
  NPLMX=NPLMX+1
  IF(NPLMX.LE.200) GO TO 10
  IF(NPLMX.EQ.201) PRINT 2010
2010 FORMAT('OPUNCHED OUTPUT STOP.  NPLMX GT 200')
  RETURN
10  A1=TIM
    A3=PSTAT(1)
    A4=PSTAT(2)
    A5=PSTAT(3)
    WRITE(16) A1,A3,A4,A5
    A4=PDT
    A5=PDV
    WRITE(17) A1,A4,A5
    IF(IPLOT.EQ.1) RETURN
    DO 100 I=1,NCHN
      IF(SIG(I).EQ.0.) GO TO 100
      NCHH(I)=NPLMX
      JX1=NNEI(1,I)
      JX2=NNEI(2,I)
      VVX=SIG(I)*AREA(I)*XX(I)/1728.
      NW=I+19
      A1=SIG(I)
      A3=VV(I)
      A4=PF(I)
      A5=PP(JX1)-C4*VV(I)**2
      A6=PP(JX2)-C4*VV(I)**2
      WRITE(NW) A1,VVX,A3,A4,A5,A6
100 CONTINUE
    RETURN
  END

```


APPENDIX D: BUG-2 PROGRAM

```

SUBROUTINE DKOFF
  IMPLICIT REAL*8 (A-H,O-Z)
  REAL*4      ASIG(200),AVVX(200),AVV(200),APF(200),APP1(200),APP2(200
1),TIMM(200),PTSTA1(200),PTSTA2,PTSTA3
  DIMENSION ITIM(200),IPST1(200)
  COMMON/DSK/PDT,PDV,C4,IPLT,NCHH(30)
  COMMON TIM,DELT,RHO,CND,PSTAT(10),XX(30),AREA(30),SIG(30),VV(30),
1PF(30),PP(30),TX1,JOB(10)
  COMMON NCHN,NPP,NPSTAT,NNEI(2,30),NEIP(7,30),NPLMX
  PRINT 2112, NCHN,NPLMX,JOB
2112 FORMAT('CENTER DKOFF  NCHN=',I3,4X'NPLMX=',I4,3X,10A4)
2222 FORMAT(1H0,10A4,2I5)
  WRITE(7,2210) JOB,NCHN,NPLMX
2210 FORMAT(10A4,2I5,'HYDROGEN BUBBLE PRESS',T74,'16*****')
  REWIND 16
  DO 200 J=1,NPLMX
  READ(16) TIMM(J),PTSTA1(J),PTSTA2,PTSTA3
  IPST1(J)=IFIX(2500.*ALOG10(PTSTA1(J)*.10))
  ITIM(J)=IFIX(2500.*ALOG10(TIMM(J)*1.E4))
  200 CONTINUE
  WRITE(7,2111) (IPST1(I),ITIM(I),I=1,NPLMX)
2111 FORMAT(16I5)
  WRITE(7,2630)
2630 FORMAT(///)
2000 FORMAT(6E13.5)
  WRITE(7,2410) JOB,NCHN,NPLMX
2410 FORMAT(10A4,2I5,'INTEGRALS PDT,PDV',T74,'17*****')
  REWIND 17
  DO 220 I=1,NPLMX
  220 READ(17) TIMM(I),ASIG(I),AVVX(I)
  ASIG=PDT  AVVX=PDV
  WRITE(7,2220) (TIMM(I),AVVX(I),ASIG(I),I=1,NPLMX)
2220 FORMAT(1P8E10.4)
  IF(IPLT.EQ.1) GO TO 101
  WRITE(7,2630)
  PRINT 2142,(NCHH(I),I=1,NCHN)
2142 FORMAT(1H0
1/' NO. OF DATA POINTS PUNCHED FOR EACH CHAN'/3(10I5/))
  WRITE(7,2510) JOB,NCHN,NPLMX
2510 FORMAT(10A4,2I5,'CHAN DATA' ,T74,'20*****')
  WRITE(7,2000)(TIMM(I),I=1,NPLMX)
  DO 100 IK=1,NCHN
  IF(NCHH(IK).LE.0) GO TO 100
  WRITE(7,2610) JOB,IK,NCHH(IK),NPLMX
2610 FORMAT(10A4,3I5)
  NW=IK+19
  NPLMM=NCHH(IK)
  REWIND NW
  DO 80 J=1,NPLMM
  80 READ(NW) ASIG(J),AVVX(J),AVV(J),APF(J),APP1(J),APP2(J)
  WRITE(7,2000)(APP1(I),I=1,NPLMM)
  WRITE(7,2000)(APP2(I),I=1,NPLMM)
  WRITE(7,2000)(AVVX(I),I=1,NPLMM)
  WRITE(7,2000)(AVV(I),I=1,NPLMM)
  WRITE(7,2000)(APF(I),I=1,NPLMM)
  WRITE(7,2000)(ASIG(I),I=1,NPLMM)
  100 CONTINUE
  WRITE(7,2630)
  101 PRINT 2132
2132 FORMAT('OEXIT DKOFF')

  RETURN
  END

```

APPENDIX E: RELIEF SYSTEM DESIGN ANALYSIS

In the event of a sodium water reaction in the steam generator, the hydrogen produced will be relieved through the rupture disk and the relief system to the atmosphere. In this appendix the pressure drop of the hydrogen flowing through the relief system is determined as a function of hydrogen flow.

It was assumed that the hydrogen was at 1800 F, and the steam generator was connected to the existing relief system of the SCTI. The connection was assumed to be as shown in Figure E.1. The rest of the system, beyond the rupture disk tank, is shown in Figure E.2.

The B&W steam generator has a 12-inch-diameter rupture disk, and the SCTI relief system piping is also 12 inches in diameter. Hydrogen flowing through this system must pass through two expansions, four bends, two contractions, and 101 feet of 12-inch-diameter piping. To simplify this, an equivalent length was desired for the expansions, bends, and contractions.

The equivalent length is determined from the equation:*

$$L = K \frac{D}{f} \quad (E.1)$$

For expansions, the resistance coefficient K is determined by

$$K = \left(1 - \frac{D_1^2}{D_2^2} \right)^2 \quad (E.2)$$

However, for bends and contractions, K must be determined experimentally, and the accuracy is extremely limited. Table E.1 describes the expansions, bends, and contractions encountered in the relief system piping. The K values listed for each were determined from References 27 through 30.

Using the K values listed in Table E.1, the equivalent length of 12-inch-diameter pipe for the system can be calculated provided the friction

* The terms used in the equations in this appendix are defined in a list at the end.

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FIG. E.1 STEAM GENERATOR AND UPPER RUPTURE DISK TANK

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FIG. E.2 RELIEF SYSTEM BEYOND UPPER RUPTURE DISK TANK

TABLE E.1 - RESISTANCE COEFFICIENTS FOR PIPING IN
B&W STEAM GENERATOR RELIEF SYSTEM

<u>Description</u>	<u>Dimensions</u>	<u>Resistance Coefficient, K</u>
Contraction	6 feet to 1 foot	~ 0.40
Bend	long radius 90°	~ 0.30
Expansion	1 foot to 6 feet	~ 0.94
Contraction	6 feet to 1 foot (entrance is re-entrant)	~ 0.90
Bend	38°	~ 0.40
Bend	90°	~ 0.80
Bend	41°	~ 0.40
Expansion	to atmosphere	1.00

factor f is known. For the case studied, f was determined using the smooth pipe formula:²³

$$\frac{1}{\sqrt{f}} = 2 \log (Re_D \sqrt{f} - 0.8) \quad (E.3)$$

The pressure drop was then found by means of the formula²³

$$P_1^2 - P_2^2 = \rho_1 (V_1)^2 \left[f \frac{L}{D} - 2 \ln \frac{P_2}{P_1} \right] \quad (E.4)$$

which applies to isothermal flow of a compressible fluid in a pipe. Since solution of these two equations requires an iterative process, the problem was programmed for computer solution. To relate the pressure drop to the mass flow of hydrogen, the relationship

$$\dot{m} = \rho VA \quad (E.5)$$

was used to give the formulas:

$$\frac{1}{\sqrt{f}} = 2 \log \frac{\dot{m} \sqrt{f}}{0.0000113} - 0.8 \quad (E.6)$$

$$P_1^2 - P_2^2 = 4.24 \left(\frac{\dot{m}}{D^2} \right)^2 \left(f \frac{L}{D} - 2 \ln \frac{P_2}{P_1} \right) \quad (E.7)$$

If all expansions, bends, and contractions are based on the same reference pipe size, as they are in this case, the coefficients are additive. Thus, the total resistance coefficient is

$$K_{\text{tot}} = 0.40 + 0.30 + 0.94 + 0.90 + 0.40 + 0.80 + 0.40 + 1.00 = 5.14$$

and the total equivalent length of the entire relief system is

$$L_{\text{tot}} = 101 + \frac{5.14D}{f}$$

The results of this analysis are shown graphically in Figure 21, along with the curve for incompressible flow through the same system for comparison, assuming a constant friction factor and an average density. Also indicated is the sonic velocity through the system at the exit to the atmosphere. Below the sonic velocity (which corresponds to a mass flow rate of 8.44 lb/sec of hydrogen) the exit pressure was assumed to be atmospheric or 14.7 psia. Above the sonic velocity, the exit pressure was assumed to be the pressure necessary to give a density great enough to move the given mass flow through the exit at sonic velocity. Thus, the pressure is given by the solution of:

$$\dot{m} = \rho VA \quad (\text{E. 5})$$

and,

$$\rho = \frac{2P}{RT} \quad (\text{for hydrogen}) \quad (\text{E. 8})$$

where the sonic velocity at 1800 F is 8890 ft/sec, and the area is that of the 12-inch pipe. These equations thus reduce to

$$\begin{aligned} P &= \frac{1}{2} RT \left(\frac{\dot{m}}{VA} \right) \quad (\text{E. 9}) \\ &= \frac{(10.73) (2260)}{2(8890) \left(\frac{\pi}{4} D^2 \right)} \dot{m} \\ &= 1.74 \frac{\dot{m}}{D^2} \end{aligned}$$

This is the exit pressure (P2) used in the computer solution above sonic velocity.

Since the pressures determined were rather large for comparatively small leak rates, the problem was rerun with larger pipe sizes. These results are shown in Figure 22.

Several points should be made concerning the assumptions made to obtain this solution:

- The temperature was assumed to be 1800 F, the average temperature expected in the hydrogen bubble from experimental data for sodium-water reactions.²³ In actuality, the gas may be at a lower temperature than this, due to heat loss from the gas before it reaches the relief system. This affects the solution in several ways:

For a given mass flow rate, a lower temperature gives a greater density, and hence a lower flow velocity at a given pressure. Thus, the pressure loss would be less, and the solution conservative. A lower temperature also gives a lower sonic velocity. Since achievement of sonic velocity slightly decreases the rate of pressure increase with flow rate, this is also conservative.

- Hydrogen is generated according to the reaction

Thus if the reaction is 100% efficient, 9 lb of water is needed to produce 1 lb of hydrogen. Thus assumption is conservative also.

- Losses due to the method used for gas containment on the relief system were not taken into account in the analysis because the nature of the containment was not known. This is nonconservative. Use of the smooth pipe friction factor may also be nonconservative.

LIST OF TERMS USED IN EQUATIONS IN APPENDIX E

A	=	Flow area
D	=	Diameter
f	=	Friction factor
K	=	Resistance coefficient
L	=	Equivalent length
$\dot{m}$	=	Mass rate of hydrogen flow
P	=	Pressure
P_1	=	Inlet pressure
P_2	=	Outlet pressure
R	=	Gas constant
ρ	=	Density
ρ_l	=	Fluid Density
Re_D	=	Reynolds Number
T	=	Temperature
V	=	Velocity
V_1	=	Fluid velocity

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