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**ANALYSIS OF THE BABCOCK & WILCOX
PROTOTYPE STEAM GENERATOR
FOR A
SODIUM-WATER REACTION**

AEC Contract No. AT(11-1)-1280, Subcontract No. 1

Liquid Metal Cooled Reactors Branch

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ABSTRACT

An analysis of the effects of a sodium-water reaction in The Babcock & Wilcox Prototype Steam Generator was conducted. A leak in a tube in the Prototype would cause a sodium-water reaction which would result in the rapid generation of quantities of hydrogen and high temperatures. The mathematical model developed to analyze this accident is discussed and data are presented on the effect of (1) leak size, (2) paths for reaction relief, and (3) leak location on hydrogen pressure.

A maximum hypothetical accident consisting of the complete and simultaneous severance of all 25 tubes in the boiler section of the unit is discussed and illustrated with curves of the reaction data.

Recommendations are presented for (1) improving the method of analysis of a sodium-water reaction in the Prototype and (2) changing the structural design to improve the ability of the unit to withstand such a reaction.

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I. PREFACE

A. SCOPE

An analysis of the Prototype Steam Generator was conducted under subcontract for The Babcock & Wilcox Company. The proposed design was analyzed to determine whether the 25.5-Mw(t) unit had a high probability of withstanding the reaction resulting from a leak of water into sodium. From these analytical results, The Babcock & Wilcox Company will perform stress analysis on the unit.

B. RELATIONSHIP TO OTHER PROJECTS

This study is in direct support of the Sodium-Heated Steam Generator Development Contract awarded to The Babcock & Wilcox Company.
(AEC Contract No. AT (11-1)-1280)

II. INTRODUCTION

This report presents the results of an analysis of the Prototype Steam Generator, designed by The Babcock & Wilcox Company (B&W), for a sodium-water reaction. This study was conducted as part of a subcontract from B&W for the analysis of a sodium-water reaction in the proposed designs of the B&W Prototype and Full-Size Steam Generators. These sodium-heated steam generators are being designed by B&W under contract to the Atomic Energy Commission. The Prototype Steam Generator is a 25.5-Mw(t) unit which was designed as a model for the larger 682-Mw(t) Full-Size Steam Generator. The Prototype unit is scheduled to be tested in the Sodium Components Test Installation (SCTI) in 1967.

Under certain conditions, the reaction between sodium and water is characterized by the rapid generation of large volumes of hydrogen, the production of highly corrosive reaction products, and the liberation of heat. The reaction, therefore, is a potential hazard to both personnel and equipment due to the possibility of high temperatures and pressures being produced, and the nature of the reaction products. A general summary of sodium-water reactions can be found in "Literature Review of Sodium-Water Reactions," APDA-167, March 15, 1965.

The analysis presented herein is primarily devoted to predicting the pressures that would result from a sodium-water reaction in the Prototype Steam Generator. Included in the report is a brief description of the steam generator, the method of analysis, the results, and recommendations based on the results. The stress analysis of the Prototype for the conditions presented in this report was performed by B&W and can be found in the "Preliminary Prototype Design Report," BAW-1280-28.

III. SUMMARY

An analysis of the effects of a sodium-water reaction in The Babcock & Wilcox Prototype Steam Generator was conducted. The Prototype Steam Generator, a once-through-type unit, has sodium on the shell side and water in the helically coiled tube bundles. A 16-inch rupture disk and a 4-inch relief valve are provided at the top of the unit for reaction relief.

A leak in a tube in the Prototype would cause a sodium-water reaction which would result in the rapid generation of large volumes of hydrogen and high temperatures. To analyze this accident, a mathematical model was developed which would predict the hydrogen bubble pressure. The model takes into account the inertial effects of the sodium above the hydrogen bubble, compression of the gas in the gas space, the static head of sodium above the leak, the frictional drag on the sodium flowing away from the leak, and the pressure behavior of the bubble. With the exception of two, the assumptions used in the derivation and application of the model are conservative. These exceptions are a bubble temperature of 1800 F and an instantaneous water reaction. Applicable experimental data needed to evaluate these two assumptions are lacking.

In order to avoid the extensive and difficult analysis required to predict leak propagation rates, the maximum hypothetical accident consisting of the complete and simultaneous severance of all 25 tubes in the boiler section of the unit was emphasized. The steam generator operating mode that resulted in the highest water leak rate was used for the analysis and it was assumed, based on prior analyses by B&W, that the center pipe would collapse and not be available for reaction relief. Based on these criteria, a reaction in the boiler downcomer annulus resulted in the highest pressure. The pressure curve for this case is presented, together with additional data on the reaction. The stress analysis of the Prototype based on these results was performed by B&W and can be found in "Preliminary Prototype Design Report," BAW-1280-28.

Recommendations are presented for (1) improving the method of analysis of a sodium-water reaction in the Prototype and (2) changing the structural design to improve the ability of the unit to withstand such a reaction.

IV. DESCRIPTION OF THE PROTOTYPE STEAM GENERATOR

A complete description of The Babcock & Wilcox Prototype Steam Generator can be found in the "Preliminary Prototype Design Report," BAW-1280-28. The Prototype Steam Generator is a once-through-type unit with the boiler and superheater sections in the same shell. The arrangement of the two sections is illustrated in Figure 1 which shows the sodium flowing over the helically coiled tubes of the superheater section and then passing over the boiler section, also composed of helically coiled tubes. The superheater and boiler regions are connected outside the unit by a manifold; a steam drum is not incorporated between the regions. Dimensions and operating conditions are presented in Table I.

Several aspects of the unit are important from a sodium-water reaction analysis standpoint. Single-walled tubes are used to separate the high pressure water and steam from the sodium. A leak, therefore, in a tube allows water or steam to flow directly into the sodium resulting in a reaction. A 16-inch rupture disk and a 4-inch relief valve are provided at the top of the unit for relief of the products of a sodium-water reaction. A gas annulus, 2-7/8 inches wide, is maintained between the shell of the unit and a liner which fits inside the shell. The liner extends from the sodium outlet at the bottom to 10-1/2 inches above the sodium level. A 30-inch-OD cylinder, in the center of the unit, is shown as the center pipe in Figure 1. This center pipe may be pressurized with gas to reduce the sodium inventory in the unit.

Vertical bar-type tube supports are used in both the boiler and superheater tube bundles. The placement of the bars are such that they divide the helical bundles into four quadrants allowing essentially no sodium flow circumferentially between quadrants. The boiler downcomer and riser tubes and the superheater downcomer tubes are housed in box-type channels located at various places in the annulus outside the superheater tube bundle. There are two boxes for the boiler downcomer tubes, one box for the boiler riser tubes, and one box for the superheater downcomer tubes. These boxes contain horizontal plate-type tube supports and convection baffles which are staggered along the length of the boxes. These supports and baffles are also present in the annuli outside the boiler and superheater bundle. Sodium flow upward through these regions, as a result of a reaction near the bottom of the steam generator, behaves much the same as the shell-side flow through a segmental, baffled heat exchanger with its correspondingly high pressure drop.

FIG. 1 BABCOCK & WILCOX PROTOTYPE STEAM GENERATOR

TABLE I - GENERAL INFORMATION ON THE
PROTOTYPE STEAM GENERATOR

SIZE AND WEIGHT

Over-All Length	40 ft-8-3/8 in.
Inside Diameter	72 in.
Weight, empty	131, 000 lb
Weight, filled to operating level	164, 000 lb

BOILER SECTION TUBES

Number of Tubes	25
Material	Croloy 2-1/4 T-22
Transverse Spacing	1. 625 in.
Parallel Spacing	1. 375 in.

Size

Downcomer Region	0. 625 in. OD x 0. 076 in. wall
Economizer and Nucleate Boiling Region	1. 0 in. OD x 0. 120 in. wall
Film Boiling Region	1. 0 in. OD x 0. 145 in. wall
Superheat Region	1. 0 in. OD x 0. 165 in. wall
Riser Region	1. 0 in. OD x 0. 165 in. wall

SUPERHEATER SECTION TUBES

Number of Tubes	45
Material	Type 316SS
Transverse Spacing	1. 5 in.
Parallel Spacing	1. 25 in.
Size	7/8 in. OD x 0. 120 in. wall

GAS SPACE VOLUME

418 cu ft

OPERATING CONDITIONS, 100% LOAD

Sodium Flow	583, 500 lb/hr
Water (Steam) Flow	88, 750 lb/hr

Boiler Section

Sodium Inlet Temp	1016 F
Sodium Outlet Temp	650 F
Feedwater Temp	530 F
Steam Outlet Temp	750 F
Feedwater Pressure	2610 psia
Steam Outlet Pressure	2507 psia

Superheater Section

Sodium Inlet Temp	1140 F
Sodium Outlet Temp	1016 F
Steam Inlet Temp	750 F
Steam Outlet Temp	1050 F
Steam Inlet Pressure	2478 psia
Steam Outlet Pressure	2440 psia

V. ANALYSIS OF REACTION PRESSURES

A. DESCRIPTION OF THE MATHEMATICAL MODEL

1. Equations

The mathematical model used to estimate the pressure effects of a sodium-water reaction in the steam generator has been referred to as a piston model because the column of sodium above a leak was assumed to remain as a solid slug with no penetration of hydrogen into the sodium. This model provides two paths through the steam generator for relief of the reaction. A multiple-path model was also used for several cases presented in this report; however, a detailed description of this model is omitted since the equations used are similar to those presented for the parallel-path model. The multiple-path model will be described in the report of the analysis of the Full-Size Steam Generator. The equations for the parallel-path model are given below.

α Path:

$$\begin{aligned}
 & \left(\frac{m}{A_1^2} \frac{d^2 V}{dt^2} \right)_\alpha + \frac{P_{og}(V_{og})^\eta}{(V_{og} - V_\alpha - V_\beta)^\eta} + P_s \\
 & \quad (a) \qquad \qquad (b) \qquad \qquad (c) \\
 & + \frac{\rho}{2g} \left[\frac{KN}{A_2^n} \left(\frac{dV}{dt} \right)^n \right]_\alpha = \frac{V_{ho} P_{at}}{V_\alpha + V_\beta} t \qquad (1) \\
 & \qquad \qquad \qquad (d) \qquad \qquad \qquad (e)
 \end{aligned}$$

β Path:

$$\begin{aligned}
 & \left(\frac{m}{A_1^2} \frac{d^2 V}{dt^2} \right)_\beta + \frac{P_{og}(V_{og})^\eta}{(V_{og} - V_\alpha - V_\beta)^\eta} + P_s \\
 & \quad (a) \qquad \qquad (b) \qquad \qquad (c) \\
 & + \frac{\rho}{2g} \left[\frac{KN}{A_2^n} \left(\frac{dV}{dt} \right)^n \right]_\beta = \frac{V_{ho} P_{at}}{V_\alpha + V_\beta} t \qquad (2) \\
 & \qquad \qquad \qquad (d) \qquad \qquad \qquad (e)
 \end{aligned}$$

The expressions in the equation are defined as:

- (a) The inertial effects of the column of sodium as it was accelerated upward by the hydrogen bubble
- (b) The compression of the gas in the gas space above the leak
- (c) The static head of sodium above the leak
- (d) The resistance to flow of the sodium created by various structures in the steam generator, and the reduction of this resistance as the sodium was projected beyond the high pressure drop areas
- (e) The pressure behavior of the hydrogen bubble

where:

A_1 = area of liquid slug above leak, ft^2

A_2 = effective liquid slug area for pressure drop calculation, ft^2

g = acceleration of gravity, ft/sec^2

K = pressure drop attenuation factor

$$\left(\frac{L - \frac{V}{A_2}}{L} \right) \text{ or } e^{-L}$$

L = length for pressure drop or exponent of e , ft

m = mass of liquid above leak, slugs

n = exponent for pressure drop expression

N = pressure drop coefficient

P_{at} = atmospheric pressure, lb/ft^2

P_{og} = initial cover gas pressure, lb/ft^2

P_s = static pressure from head of fluid, lb/ft^2

t = time, sec

V = gas bubble volume, ft^3

V_{og} = initial volume of cover gas, ft^3

V_{ho} = gas generation rate at atmospheric pressure and 1800 F, ft^3/sec

η = ratio of specific heats of cover gas

α = alpha path for reaction relief

β = beta path for reaction relief

ρ = liquid density, lb/ft^3

Solution of the model yielded the following data as a function of time:

Hydrogen bubble pressure
Volume of the hydrogen bubble
Velocity of the sodium slugs
Acceleration of the sodium slugs
Pressure drop of the sodium slugs
Cover gas pressure

2. Assumptions Inherent in the Model and its Application

The many assumptions made in the derivation and application of the mathematical model are listed and discussed below:

- (a) The leak rate of water and steam was instantaneous and constant, and not a function of the reaction back pressure.
- (b) The reaction was instantaneous according to the equation:
$$2 \text{ Na} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{O} + \text{H}_2$$
- (c) The hydrogen was generated at a temperature of 1800 F.
- (d) The hydrogen bubble expanded isothermally.
- (e) The hydrogen bubble instantaneously assumed the shape of a cross section of the region or regions being studied, and pushed the liquid above it as a solid slug or piston.
- (f) The sodium has either one or two flow paths for reaction relief.
- (g) The full pressure drop of the sodium as it moved upward was distributed uniformly along the length of the sections considered.
- (h) A rupture disk bursting pressure and relief valve setting of 60 psig were used, and it was assumed that the reaction relief system beyond the rupture disk was capable of relieving the products of a full rupture of all the tubes with a pressure drop less than 60 psi.

Assumption (a):

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.

Leak rate is constant and not a function of back pressure - This assumption is also conservative since the 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 that are considered where all the tubes rupture, it is quite possible that the pressure in the header will not be maintained because 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 reduced by the inability of the feedwater supply system to supply the increased water flow rate at the high pressure.

Assumption (b):

Reaction is instantaneous - This assumption is not representative of the actual reaction since sodium-water reaction experiments are characterized by sporadic pressure spikes soon after water injection, which indicate that a significant amount of water may be injected into the sodium before being reacted. This assumption, therefore, is probably not conservative. Assumption (a) however, may supplement this since the results are a pressure decay from infinity, which somewhat simulates the high initial pressure peaks experienced in the experiments. Also, since the times involved for these peaks are in the order of milliseconds, energy apparently becomes the controlling parameter for vessel strength considerations. The combination of Assumptions (a) and (b) yields the maximum possible integrated mechanical energy release at any time from a reaction that is consistent with Assumption (c). However, it does not necessarily give the maximum possible rate of energy release since this is a function of the reaction kinetics.

Reaction is according to equation $2 \text{ Na} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{O} + \text{H}_2$ - This equation is assumed for the reaction because it represents the maximum possible hydrogen generation rate from a sodium-water reaction.

Assumption (c):

The hydrogen was generated at a temperature of 1800 F - This temperature was chosen as a reasonable temperature to expect in the bubble from experimental data for sodium-water reactions.¹ Since no experiments have been conducted in large quantities of sodium at significant depths, the effect of these variables on temperature has never been determined. It is possible, however, that at significant depths the temperatures may be of a greater magnitude due to the higher saturation temperature of the sodium at the higher pressures developed. If the theoretical maximum hydrogen temperature were used, the volumetric hydrogen generation rate would be increased by a factor of 1.55.

Assumption (d):

Hydrogen bubble expanded isothermally - This gives the maximum pressure consistent with Assumption (c).

Assumption (e):

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 a sizeable horizontal dimension such as the boiler downcomer annulus. 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 in the boiler downcomer region of the Full-Size Steam Generator indicate that the bubble pressure is not significantly different from the piston model during the early stages of bubble development. Also, as the reaction time progresses, penetration of the bubble through the liquid is predicted by the finite-difference model and lower bubble pressures are obtained. This penetration cannot be predicted by the piston model.

Assumption (f):

The sodium has either one or two flow paths for reaction relief - Since more than two paths are available for relief, this assumption is conservative for most of the cases considered. However, the magnitude of this effect should not be too large since the paths chosen were those offering the least resistance to flow.

Assumption (g):

The full pressure drop of the sodium as it moved upward was distributed uniformly along the length of the sections considered - The effect of this assumption on the bubble pressure is negligible.

Assumption (h):

Relief System Parameters - These values were assumed since a design of the relief system for this unit is not available.

3. Method of Solution

The SWAG, "Sodium-Water Reaction Analysis in Steam Generators," Computer Program was used to solve the differential equations for

the piston mathematical model describing a sodium-water reaction. The equations were solved numerically using the Adams method² with automatic truncation error control.* This program was also used for solution of the mathematical models described in Section IV-D.

B. APPLICATION OF THE MODEL TO THE STEAM GENERATOR

1. Steam Generator Operating Conditions

The various operating modes of the unit were studied to determine which would result in the most severe reaction. The conditions prior to power operation of the unit were found to result in the maximum water leak rate for a tube rupture at any location. At this time, the boiler section was flooded with water at 350 F and pressurized to 2625 psig. The total water leak rate from both ends of a completely severed boiler tube as a function of the location of the break is presented in Figure 2. It was found that for the flooded condition, the water stayed as a liquid throughout the length of the tube and did not flash into steam until it left the broken end of the tube. The leak rate for the flooded condition was about 2-1/2 times the leak rate for operation of the unit at full load.

As outlined in BAW-1280-28, the superheater section of the Prototype will be empty during startup and will contain superheated steam during normal operation. Although this region should never contain liquid water, analyses were made for leaks in the superheater tubes with water at 350 F under 2625-psig pressure. The leak rate for a completely severed tube in the superheater region as a function of the location of the break is presented in Figure 3. Since the superheater tubes are much shorter than the boiler tubes, the leak rate is higher.

2. Size of Accident

Most of the cases chosen for analysis were the simultaneous and complete severance of all the tubes in the boiler or superheater regions. Although these are highly incredible events, they were emphasized because the extensive analysis of leak propagation for the Prototype can be eliminated if it can withstand these maximum accidents. The simultaneous rupture of various numbers of tubes (from one tube to all the tubes) was also analyzed for purposes of comparison; there are 25 tubes in the boiler section and 45 tubes in the superheater section.

* This method is programmed as a General Motors Corporation subroutine.

FIG. 2 TOTAL WATER LEAK RATE FROM BOTH ENDS OF A SEVERED TUBE IN THE BOILER SECTION

FIG. 3 TOTAL WATER LEAK RATE FROM BOTH ENDS OF A SEVERED TUBE IN THE SUPERHEATER SECTION

3. Locations Chosen for Analysis

The five locations chosen for analysis are shown in Figure 4. 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 the gas space. The magnitude of the pressure, then, is dependent upon the area and length of the channels available for relief. Locations (A) and (D) are the lowest points in the steam generator for the boiler and superheater tubes, respectively; therefore, the channel lengths should be greatest for these rupture positions. Locations (B), (C), and (E), although closer to the sodium surface, are in regions of restricted cross-sectional area which require higher pressures to accelerate the sodium.

After the sodium has been accelerated to significant velocities, frictional effects begin to exert a significant effect on the bubble pressure. Regions with small cross-sectional areas and impediments to flow, such as the downcomer and riser boxes and annuli which contain tube supports and convection baffles, produce high bubble pressures when frictional effects become controlling. Locations (B), (C), and (E) are in these high pressure drop regions.

The paths chosen for reaction relief offered the least resistance to flow of sodium away from the reaction zone. All the cases examined for the Prototype are summarized in Table II, including the location of the rupture, the paths used for reaction relief, the number of tubes ruptured, and the total leak rate of water.

C. RESULTS

Hydrogen bubble pressure predictions using the piston model as described previously are presented in Figures 5 through 10. The smallest time shown on the curves is 0.1 millisecond; however, because the mathematical model predicts an infinite bubble pressure at time zero, the value of 0.1 millisecond is chosen only as a convenient point for starting the graph. The curves are terminated when either path has emptied of sodium, providing a direct channel for reaction products to reach the relief devices at the top of the unit. The bubble pressure should then attain a value determined by the pressure drop of the hydrogen as it flows up this path.

1. Leak Size

The effect of various leak sizes on the hydrogen bubble pressure for leaks in the boiler downcomer tubes, both at the bottom of the unit (Location (A)) and in the boiler downcomer annulus (Location (B)), is illustrated in Figure 5. It can be seen from the curves that, at any particular time, the

FIG. 4 LOCATION OF SODIUM-WATER REACTIONS IN THE B & W PROTOTYPE STEAM GENERATOR

TABLE II - DESCRIPTION OF PRESSURE ANALYSES
IN THE PROTOTYPE STEAM GENERATOR

<u>Case</u>	<u>No. of Tubes Ruptured</u>	<u>Water Leak Rate (lb/sec)</u>	<u>Comments</u>
<u>Location</u> (A) - Reactions at the Boiler Downcomer Tubes at the Bottom of the Unit			
I	1	22.75	Relief: Up the center pipe
Ia	13	295.5	Up through the boiler and
Ib	25	568	superheater tube bundles
Ic	25	568	Same as Case Ib except gas in center pipe
IX	25	568 max	Same as Case Ib except leak rate is function of bubble pressure
XIV	25	568	Center pipe collapses blocking flow Relief: Up through the boiler and superheater tube bundles Up through the boiler downcomer annulus and boiler downcomer boxes
III	25	568	Internals of steam generator ignored (single-path mathematical model)
IIIa	25	568 max	Same as Case III except leak rate is function of bubble pressure
IIIf	25	568 max	Same as Case III except water leak rate buildup considered
<u>Location</u> (B) - Reactions at the Top of the Boiler Downcomer Annulus			
II	1	25.4	Relief: Down the boiler downcomer
IIa	13	330	annulus and up the center pipe
IIb	25	635	Up both boiler downcomer boxes
Iic	25	635	Same as Case IIb except gas in the center pipe
VII	25	635 max	Same as Case IIb except leak rate is function of bubble pressure

TABLE II - DESCRIPTION OF PRESSURE ANALYSES
IN THE PROTOTYPE STEAM GENERATOR (Continued)

<u>Case</u>	<u>No. of Tubes Ruptured</u>	<u>Water Leak Rate (lb/sec)</u>	<u>Comments</u>
XIII	25	635	Center pipe collapses blocking flow Relief: Down the center pipe and up the boiler and superheater tube bundles Up both boiler downcomer boxes
XVI	25	635	Same as Case XIII except both boiler downcomer boxes rupture
<u>Location</u> (C) - Reactions in One or Both Boiler Downcomer Boxes			
VI	14	371	Reaction in one box Relief: Up the boiler downcomer box Down the boiler downcomer box and annulus and up the center pipe
IVa	25	662	Same as Case IV except reactions in both boxes and both boxes rupture
VIII	25	662	Same as Case IVa except leak rate is function of bubble pressure
<u>Location</u> (D) - Reaction at the Superheater Downcomer Tubes at the Bottom of the Superheater Section			
X	45	1755	Relief: Up through the superheater tube bundle Up through the annulus outside the superheater tube bundle
<u>Location</u> (E) - Reaction in the Superheater Downcomer Box			
XII	45	1845	The box ruptures Relief: Up through the superheater tube bundle Up through the annulus outside the superheater tube bundle

FIG. 5 EFFECT OF LEAK SIZE ON HYDROGEN BUBBLE PRESSURE

ratio of bubble pressures at two different leak rates is approximately equal to the square root of the ratio of leak rates.

2. Paths for Reaction Relief

The accuracy of the pressure analysis for reactions in a steam generator is no better than the techniques used in determining the paths through which the sodium will be forced by the reaction products. The choice of paths for a reaction at any location markedly effects the bubble pressure, as is illustrated in Figures 6, 7, and 8.

Figure 6 shows the effect on bubble pressure of four different paths chosen for reaction on relief for the severance of the boiler downcomer tubes at the bottom of the unit (Location (A)). Curve III (Figure 6) illustrates the lowest possible bubble pressure for this location (and the normal sodium level in the unit) which results from ignoring the internals of the unit and employing the complete area of the shell for reaction relief. This case is unrealistic since most of the internals of the steam generator will remain intact and will inhibit the flow of sodium away from the reaction zone. Curve Ib is the bubble pressure for the case where the internals of the unit were assumed to remain intact, and the two paths offering the least resistance to flow were used for reaction relief. These paths were up the center pipe and up through the boiler and superheater tube bundles. A third path up the boiler downcomer annulus and up through the boiler downcomer boxes was also available for reaction relief; however, this path was not considered since its resistance was large compared to the other two paths. As expected, the bubble pressure for Case Ib is significantly higher than that for Case III.

When the possibility arose that the center pipe might be pressurized with gas to within a short distance of its base to reduce the sodium inventory in the steam generator, Case Ic was run using the same paths as in Case Ib with only 1 foot of sodium present in the center pipe. Thus, the inertial and frictional resistance to sodium flow up the center pipe was very small. The curve for this case (Ic), therefore, is even lower than the curve for the case where the internals of the unit were ignored.

B&W has concluded from analyzing the pressures predicted from these cases that the center pipe may collapse locally from reactions in the boiler section and would not be available as a path for relief of the reaction. Case XIV was run to determine the effect of a blocked center pipe on the bubble pressure. The absence of the center pipe for relief of the reaction increased the bubble pressure significantly as illustrated by Curve XIV (Figure 6) and, therefore, must be considered as a valid expression of bubble pressure for a reaction at the bottom of the steam generator.

Figure 7 presents a similar analysis for leaks at the top of the boiler downcomer annulus (Location (B)). Curve IIb represents the bubble

**FIG. 6 EFFECT OF PATHS CHOSEN FOR RELIEF ON HYDROGEN
BUBBLE PRESSURE—REACTIONS AT BOTTOM OF STEAM GENERATOR**

**FIG. 7 EFFECT OF PATHS CHOSEN FOR RELIEF ON HYDROGEN BUBBLE PRESSURE—
REACTIONS IN BOILER DOWNCOMER ANNULUS**

FIG. 8 EFFECT OF PATHS CHOSEN FOR RELIEF ON HYDROGEN BUBBLE PRESSURE—REACTIONS IN BOILER DOWNCOMER BOXES

pressure for the case where all the internals of the unit remain intact and the paths for reaction relief are up both boiler downcomer boxes, down the boiler downcomer annulus, and up the center pipe. Curve Ic results if the center pipe is pressurized with gas to within 1 foot of its base. Case XIII is the result of the analysis assuming the center pipe collapses and is no longer available as a path for sodium flow. From the pressures developed in Case XIII, B&W concluded that both boiler downcomer boxes would rupture. To account for this circumstance, Case XVI was run in which it was assumed that both the 11- and 14-tube downcomer boxes rupture between the two lowest tube supports providing access to the superheater bundle. The bubble pressure resulting from this case is considered to be the most valid for reactions at Location (B); however, since a simultaneous severance of all the tubes is highly unlikely, these results are very pessimistic.

The bubble pressures for tube ruptures at Location (C) are presented in Figure 8. Curve IV is the result of the case for a full-tube severance in the downcomer box containing 14 tubes and assuming the box does not rupture. B&W determined that the box, in fact, would rupture immediately under pressures of the magnitude shown. Consequently, an analysis was made of a complete simultaneous severance of all the tubes in both downcomer boxes, assuming both boxes ruptured allowing access to the superheater bundle and the annulus outside the superheater bundle. The results of this analysis are shown as Curve IVa which represents a more realistic approach to a maximum accident in this area.

3. Leak Location

In order to determine the locations that would yield the maximum reaction pressure in the boiler and superheater sections, cases involving a simultaneous rupture of all the tubes in these sections were compared. One case, representing the most valid choice of paths for reaction relief, was chosen for each location. The pressures for locations in the superheater section are presented in Figure 9 and those for locations in the boiler section are given in Figure 10.

A reaction at Location (E) results in the maximum bubble pressure for cases in the superheater section as shown in Figure 9. However, the possibility of a reaction of the magnitude considered for the superheater section is extremely remote, and was discussed in Section IV B. In the boiler section of the steam generator, Figure 10, Case XVI yielded the maximum bubble pressures during the first 5 milliseconds of the reaction. Although a higher pressure is generated in Case XIV than in Case XVI after 5 milliseconds, the pressure at this point is below the static strength of the vessel (2545 psi as stated by B&W). Case XVI, therefore, was chosen as the maximum accident for the steam generator. This case is the simultaneous severance of all 25 tubes at the top of the boiler downcomer annulus.

FIG. 9 EFFECT OF LEAK LOCATION ON HYDROGEN BUBBLE PRESSURE— SUPERHEATER SECTION—CASES X AND XII

FIG. 10 EFFECT OF LEAK LOCATION ON HYDROGEN BUBBLE PRESSURE—BOILER SECTION—CASES IV_a, XIV, AND XVI

The pressure from the bubble will cause the two boiler downcomer boxes to burst providing relief through the superheater bundle. The other path for relief is down the boiler downcomer annulus and up through the boiler and superheater tube bundles. It was assumed that the center pipe had collapsed, blocking flow up the central area of the steam generator.

Since Case XVI was chosen as the maximum accident for the steam generator, additional information is presented which shows, in detail, the progress of the hydrogen bubble through the steam generator. A schematic of the channels selected for relief of a reaction in the boiler downcomer annulus is presented in Figure 11. Figure 11 also illustrates the hydrogen bubble pressure and volume as a function of time. Figures 12 through 18 indicate the fraction of sodium in the channel, the sodium volume, the sodium velocity, the frictional pressure drop, and the total pressure at the inlet and exit of the channel for each of the seven channels shown in Figure 11. As can be seen from the figures, the channels emptied in the following sequence: a, b, and c. Channels d, e, and f were partially filled when the bubble reached the gas space through Channel c and Channel g was still completely full.

Channel b is a combination of both boiler downcomer boxes between the boiler downcomer annulus and the point at which the boxes rupture. This channel represents a length of about 24 inches and includes one set of tube supports. Channels d and e, the boiler downcomer boxes between the rupture point and gas space, contain nine sets of tube supports or convection baffles. Channel a represents a length of about 0.2 inch in the downcomer annulus and, therefore, empties quite rapidly.

D. ADDITIONAL PRESSURE ANALYSES

To eliminate both the unrealistic infinite bubble pressure at time zero and several of the assumptions inherent in the model, several modifications were made to the piston mathematical model which are discussed in this section, together with the results. Also included is a discussion of shock waves and their effect on the reaction pressure.

1. Leak Rate Buildup

The existing model assumes a stepwise change in leak rate from zero to the final value when the tube or tubes are ruptured. This is not realistic since the inertia of the water in the tube and the elasticity of the tube itself cause the leak rate to increase over a finite time rather than instantaneously. An analysis of the surge characteristics of ruptured tubes at the bottom of the Prototype Steam Generator (Location (A)) indicates that the leak rate buildup can be closely approximated by the function:

FIG. 11 BUBBLE PRESSURE AND VOLUME FOR A REACTION IN THE BOILER DOWNCOMER ANNULUS—CASE XVI

FIG. 12 REACTION DATA FOR RELIEF CHANNEL α -CASE XVI

FIG. 13 REACTION DATA FOR RELIEF CHANNEL b—CASE XVI

FIG. 14 REACTION DATA FOR RELIEF CHANNEL c—CASE XVI

FIG. 15 REACTION DATA FOR RELIEF CHANNEL d—CASE XVI

FIG. 16 REACTION DATA FOR RELIEF CHANNEL e—CASE XVI

$$\tanh\left(\frac{t}{T_f}\right)$$

where: t = time, seconds

T_f = inertial time constant of the water in the tube, seconds

To simplify the equation for this model, only the inertial term was included and a single path chosen for reaction relief. The expression for the leak rate buildup was applied to the equation as follows:

$$\begin{aligned} \frac{m}{A^2} \frac{d^2 V}{dt^2} &= \frac{P_{at}}{V} \int_0^t V_{ho} \\ &= \frac{P_{at}}{V} \left[V_{ho_1} \int_0^t \tanh\left(\frac{t}{T_{f_1}}\right) + V_{ho_2} \int_0^t \tanh\left(\frac{t}{T_{f_2}}\right) \right] \\ &= \frac{P_{at}}{V} \left[\begin{matrix} V_{ho} & T_f & \ln \left(\cosh \frac{t}{T_f} \right) \end{matrix} \right]_1 \\ &\quad + \left[\begin{matrix} V_{ho} & T_f & \ln \left(\cosh \frac{t}{T_f} \right) \end{matrix} \right]_2 \end{aligned} \quad (3)$$

where:

A = area of sodium column, ft²

m = mass of liquid above leak, slugs

P_{at} = atmospheric pressure, lb/ft²

V = gas bubble volume, ft³

V_{ho} = gas generation rate at atmospheric pressure and 1800 F, ft³/sec

The inertial time constants, T_f , of the two ends of the severed tube at Location (A) were 0.02884 and 0.0424 seconds. This input, combined with the same conditions used for Case III, yielded the results shown in Figure 19. The curve for Case III is included in the figure for reference.

FIG. 19 EFFECT OF WATER LEAK RATE BUILDUP ON HYDROGEN BUBBLE PRESSURE

A bubble pressure of approximately 480 psia is obtained over most of the duration of the reaction. Although this new model is probably a more realistic treatment of the problem than the unmodified model, the results do not duplicate the initial sharp pressure peaks actually experienced in sodium-water reaction experiments. Since this model did not duplicate the experimental results and since the leak rate buildup was automatically taken into consideration in the modification to the model discussed below, it was not used for any further analysis.

2. Variation of Leak Rate with Bubble Pressure

The mathematical model described in Section IV-A was modified to include the effect of the bubble pressure on the water leak rate. Since the leak rate is a function of the pressure differential between the water and steam reservoirs and the broken ends of the tube, the rate of discharge of water can be expressed as a function of the pressure in the bubble (assuming a constant reservoir pressure).

Although factoring in this effect results in a more realistic treatment of the reaction, the results from this back-pressure model may be optimistic since the effects of reaction kinetics have not been included. The results are indicative, however, of what would happen in the steam generator if the sporadic reaction rate from the kinetics were suppressed. Most of the reaction test data confirms that the reaction proceeds in a highly sporadic manner; however, most of these reactions occurred very close to the surface of the excess reactant. However, one test conducted by MSA, in which sodium was injected into a pond of water at a depth of ten feet yielded results that indicated the reaction was continuous, except for flows in the laminar-turbulent transition region.^{3,4} Nevertheless, the results of one test should by no means be considered as conclusive evidence of this effect. Sizeable experiments would be necessary to determine if this occurs in large steam generators.

The equations for the back-pressure mathematical model are presented below:

Sodium Slug

α Path:

$$\left(\frac{m}{A_1^2} \frac{d^2 V}{dt^2} \right)_\alpha + \frac{P_{og} (V_{og})^\eta}{(V_{og} - V_\alpha - V_\beta)^\eta} + P_s + \frac{\rho}{2g} \left[\frac{KN}{A_2^n} \left(\frac{dV}{dt} \right)^n \right]_\alpha$$

$$= \frac{(P_s + P_{og}) V_{ob} + P_{at} C \int_0^t (v_{w1} + v_{w2}) dt}{V_\alpha + V_\beta + V_{ob}} \quad (4)$$

β Path:

$$\left(\frac{m}{A_1^2} \frac{d^2 V}{dt^2} \right)_\beta + \frac{P_{og} (V_{og})^\eta}{(V_{og} - V_\alpha - V_\beta)^\eta} + P_s + \frac{\rho}{2g} \left[\frac{KN}{A_2^n} \left(\frac{dV}{dt} \right)^n \right]_\beta$$

$$= \frac{(P_s + P_{og}) V_{ob} + P_{at} C \int_0^t (v_{w1} + v_{w2}) dt}{V_\alpha + V_\beta + V_{ob}} \quad (5)$$

Water Tube

$$\text{End 1: } P_R - \left(\frac{m_w}{A_w} \frac{dv_w}{dt} \right)_1 - \left(K_w v_w |v_w| \right)_1$$

$$= \frac{(P_s + P_{og}) V_{ob} + P_{at} C \int_0^t (v_{w1} + v_{w2}) dt}{V_\alpha + V_\beta + V_{ob}} \quad (6)$$

$$\text{End 2: } P_R - \left(\frac{m_w}{A_w} \frac{dv_w}{dt} \right)_2 - \left(K_w v_w |v_w| \right)_2$$

$$= \frac{(P_s + P_{og}) V_{ob} + P_{at} C \int_0^t (v_{w1} + v_{w2}) dt}{V_\alpha + V_\beta + V_{ob}} \quad (7)$$

where:

- A_1 = area of liquid slug above leak, ft^2
 A_2 = effective liquid slug area for pressure drop calculation, ft^2
 A_w = cross-sectional area of the water tube at the rupture location, ft^2
 C = ratio of hydrogen generation rate to water velocity,

$$\frac{\text{ft}^3}{\text{sec}} (\text{H}_2 \text{ @ } 1800 \text{ F, Atm. Press.}) \bigg/ \frac{\text{ft}}{\text{sec}} (\text{H}_2\text{O @ } 350 \text{ F})$$

 g = acceleration of gravity, ft/sec^2
 K = pressure drop attenuation factor

$$\left(\frac{L - \frac{V}{A_2}}{L} \right) \text{ or } e^{-L}$$

 K_w = water pressure drop coefficient, $\frac{\text{lb}}{\text{ft}^2} \bigg/ \frac{\text{ft}^2}{\text{sec}^2}$
 L = length for pressure drop or exponent of e, ft
 m = mass of liquid above leak, slugs
 m_w = mass of water in the tube, slugs
 n = exponent for pressure drop expression
 N = pressure drop coefficient
 P_{at} = atmospheric pressure, lb/ft^2
 P_{og} = initial cover gas pressure, lb/ft^2
 P_R = water reservoir pressure, lb/ft^2
 P_s = static pressure from head of fluid, lb/ft^2
 V = gas bubble volume, ft^3
 v_w = water velocity at tube rupture, ft/sec
 V_{ob} = initial bubble volume, ft^3
 V_{og} = initial volume of cover gas, ft^3
 η = ratio of specific heats of cover gas
 ρ = liquid density, lb/ft^3

Subscripts:

- 1 = one end of the ruptured tube
 2 = second end of the ruptured tube
 α = alpha path for reaction relief
 β = beta path for reaction relief

The results of the runs using the back-pressure model are compared with the equivalent runs for the constant leak rate model in Figure 20. The bubble pressure for the back-pressure cases is considerably lower than that predicted by the constant leak rate model and stays constant throughout most of the period prior to penetration of the bubble into the gas space. Because the results from this model did not duplicate most of the experimental data available and the results from the unmodified model approached the data more closely, the modified model was not used extensively for analysis of the Prototype.

3. Reaction Kinetics

Since the pressure behavior of most sodium-water reaction experiments appears to be strongly influenced by the kinetics of the reaction, an attempt was made to factor this into the model. In the absence of adequate experimental definition of the important parameters, a model was postulated in which diffusion of the water through the hydrogen bubble was assumed to be the controlling mechanism. The assumptions made in deriving the expression for diffusion are as follows:

- (a) The hydrogen bubble is spherical in shape.
- (b) The water flowing into the sodium exists as vapor, at the original water temperature, in the shape of a sphere located concentrically within the hydrogen bubble.
- (c) Diffusion of water vapor takes place between the inner sphere and the sodium surface.
- (d) The reaction between the water vapor at the sodium-hydrogen interface and the sodium is instantaneous.

The expression derived for the diffusion rate, when factored into the mathematical model, resulted in equations too complex to be solved by the computer techniques originally used. Further analytical effort coupled with large-scale sodium-water reaction experiments will be necessary to define and predict the effect of reaction kinetics on the bubble pressure.

4. Shock Waves

The possibility exists that shock waves could be formed during bubble formation; however, this is a function of the kinetics of the reaction. If shock waves are formed, the liner and vessel wall would experience a somewhat different pressure-time history and the bubble pressure would be modified. In order to predict quantitatively the characteristics of the shock wave(s) from a reaction, a knowledge of the chemical and physical behavior of the reaction is necessary. Since this information is not known, only a qualitative discussion can be given. The primary shock wave emitted by the

FIG. 20 EFFECT OF THE LEAK RATE VARIATION WITH BACK PRESSURE ON HYDROGEN BUBBLE PRESSURE

bubble travels at a velocity up to several times the speed of sound in the quiescent sodium, depending on the pressure at the shock front. Initially, the bubble will probably be spherical; therefore, it will be assumed that the wave is spherical. After the wave leaves the bubble, the bubble pressure is decreased considerably. The maximum pressure and specific impulse of the wave, as it radiates away from the bubble, decreases in proportion to the inverse of the radius of the wave. The passage of the spherical wave through the sodium initiates an outward velocity or "afterflow" which causes pulsations in the gas bubble volume and pressure.

When the wave reaches a rigid structure, a reflection occurs which, for weak shocks and incidence of the wave normal to the surface, results in a pressure at the structure double that in the shock wave. For strong shock waves, the resulting pressure can be greater than twice the amplitude of the wave; e.g., a wave with a peak pressure of 735,000 psi reflecting from a rigid structure in water results in a pressure at the structure of about four times the wave pressure. If the response time of the structure is small or of the same order of magnitude as the duration of the wave, the pressure of the wave should be applied to the structure as a static pressure for purposes of analysis. If the response time is large compared to the duration of the wave, however, the impulse of the wave should be used for the analysis.

VI. DISCUSSION OF RESULTS

A. ANALYSIS

The simultaneous severance of all 25 boiler downcomer tubes in the boiler downcomer annulus, Case XVI, is considered to be the maximum accident that can occur from a sodium-water reaction in the Prototype Steam Generator. The results for this case are presented in Figures 11 through 18. In this instance, it was assumed that (1) the center pipe collapsed in a manner that rendered it unavailable as a reaction relief path, and (2) that the two boiler downcomer boxes collapsed outwardly. Although the bubble volume shown in Figure 11 is quite small at the initiation of the reaction, the liner of the Prototype, because of its proximity, will be subjected to a pressure approaching that of the full bubble pressure at the same point. The pressure on the liner further away from the reaction will be lower by a factor of the ratio of the distance between the bubble and the point in question to the length of the path from the reaction to the free surface. As the bubble becomes large enough to contact the surface of the liner, the liner will be subject to the bubble pressure at this point and the pressure distribution elsewhere will change according to the ratio given above. There is the possibility that shock waves could be formed during the reaction. Although a quantitative evaluation of this was impossible because of a lack of reaction kinetic data, the formation of shock waves from a reaction would greatly change the pressure and behavior of the bubble.

Although most of the assumptions and techniques used in the analysis were conservative, several uncertainties were not resolved. As discussed in Section IV-A, reaction kinetics were neglected by assuming that all the water leaking into the sodium reacted instantaneously as it left the tube. This results in the maximum integrated mechanical energy release at any time; however, it does not necessarily give the maximum rate at which the energy could be released. Also, a bubble temperature of 1800 F was used for the analysis. As noted in Section IV-A, this temperature may be low. However, the effect of a higher temperature on the bubble pressure is not gross i.e., an increase in bubble pressure of 25% if the maximum adiabatic temperature of 3050 F is used.

Conservative assumptions in the analysis were that (1) the leak rate was constant and not a function of the back pressure, (2) the reaction was according to the equation $2\text{Na} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{O} + \text{H}_2$, (3) the sodium remained as a solid slug with no penetration, and (4) the sodium was limited to two flow paths for reaction relief. The greatest conservatism lies in the accident postulated for the analysis. The steam generator operating mode giving the greatest leak rate was chosen. The length of time during which the steam

generator will be in this mode is short in relation to the full-power operating time of the unit. A complete and simultaneous shear of all 25 tubes in the boiler section was used as the accident. This would be an extremely unlikely occurrence and is used to indicate what the maximum accident would be. A more realistic accident would be one in which the tubes started leaking through holes caused by wastage from an initial leak. For such a case, the leak rate would build up over a period of time with the possibility that the leak may be detected and isolation achieved before all the tubes are affected. Also, the leak rate from a small hole in a tube is much less than the total leak rate from both ends of a severed tube.

B. DESIGN

Any steam generator design must be a compromise between heat transfer efficiency, reliability, economics, and safety considerations. The Prototype, being no exception, is not ideally designed to withstand a sodium-water reaction as discussed in the following paragraphs.

The high pressures predicted by the analysis are transient effects produced by the sudden buildup of gas under a large liquid head. Therefore, to minimize these transient pressures, the head above any potential reaction area should be as small as possible, and the area of the path available to the free surface should be large. In addition, the frictional resistance between a potential reaction region and the surface should be minimized. The greatest head of sodium above a potential reaction area in the Prototype is 23 feet; this results in a large mass of sodium that must be accelerated during a reaction. Also, the steam generator is divided vertically by shrouds and tube supports into regions of relatively small cross-sectional area. The presence of tube supports, convection baffles, and tubes creates a tortuous path through which the sodium must move for reactions in many regions. B&W has found that some of the small area-high pressure drop regions will fail, allowing relief of the reaction into other sections of the unit; the boiler and superheater downcomer boxes are an example.

B&W has found that the one, large unrestricted path for reaction relief, the center pipe, will probably collapse inwardly from reactions in the steam generator. The collapse could be in such a way as to render the center section unavailable as a relief path. This leaves the path through the boiler and superheater sections of the unit as the only relief channel of any significance. This path, although of relatively large area, contains significant frictional resistance to flow.

VII. RECOMMENDATIONS

A. ANALYSIS

The analysis of the Prototype was severely hampered by the lack of sodium-water reaction test data applicable to the unit. Although various devices have been used in small-scale tests to simulate the inertial effects of a large head of sodium, no tests have been conducted where large amounts of sodium are available for reaction. Also, the effects of the tubes, tube supports, etc. on the reaction have not been experimentally demonstrated. Verification of the mathematical model used in the analysis, therefore, has been impossible. Large-scale sodium-water reaction experiments are necessary to prove the conservatism of the analysis of the Prototype. One possibility for such a test program would be to use the Prototype itself for a reaction vessel subsequent to performance testing in SCTI.

Further sodium-water reaction experiments are also necessary for determination of the reaction kinetics and temperatures generated. The existing mathematical model could be greatly improved if more information on these characteristics of a reaction could be obtained. In order to shed light on the analysis in these areas, data from the AEC's Small Leak Program conducted by APDA and experiments being conducted elsewhere will be studied when they are available.

B. DESIGN

During the course of the analysis, several recommendations were made to B&W. As a result of these, the tube supports and convection baffles in the downcomer and riser regions have been changed by B&W to provide more uniform spacing. B&W also explored the recommendation to reduce the volume of sodium in the center pipe which would reduce the inertial effects of reactions near the bottom of the unit; however, it was determined that the center pipe would probably collapse during a reaction, possibly eliminating this area as a reaction relief path. It was also recommended that communication between the boiler downcomer boxes and the annulus around the superheater region be established. B&W found that the downcomer boxes ruptured as a result of an internal reaction and provided communication for relief of the reaction. Further recommendations were that communication be provided between the boiler downcomer annulus and the region between the boiler and superheater sections, and that the possibility of internal pieces of the unit penetrating the vessel wall from movement induced by the reaction be investigated.

As a result of the analyses presented in this report, the following recommendations are suggested:

1. Alternatives should be explored which will assure that the center pipe area will remain available for relief throughout the duration of a reaction:
 - (a) The pipe could be reinforced to prevent it collapsing from the pressure differential created by a reaction.
 - (b) The pipe could be designed to rupture locally and not deform to block the reaction relief.
 - (c) The pipe could be designed to collapse completely throughout its whole length providing a large open area for reaction relief.
2. Provision should be made to pressurize the center pipe with gas, if this is consistent with any design change resulting from recommendation 1.
3. If the center pipe is pressurized, a rupture disk should also be provided in the gas space outside the center pipe.
4. Ways to provide communication between the boiler downcomer annulus and the region between the superheater and boiler sections during a reaction in the annulus should be explored.
5. In the stress analysis of the shell, to be conducted by B&W, consideration should be given to the following:
 - (a) The possibility of fragments of various internal structures accelerated by the reaction pressure effects penetrating the shell wall.
 - (b) The local force on the wall exerted by the supports between the liner and the wall.
 - (c) The possibility of the movement of both tube bundles from the reaction pressures causing failure of the shell.
 - (d) The effect of the sodium moving at a high velocity impinging on the upper head of the steam generator causing it to fail.
6. The mode of failure of the boiler downcomer boxes during a reaction in the boiler downcomer annulus or boxes should be determined to be certain that it will not impede the relief of the reaction significantly or rupture the shell.

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