DYNAMIC LOADINGS OF SODIUM-WATER REACTIONS IN LMFBR AND FUSION POWER DESIGNS

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SUMMARY

In liquid metal fast breeder reactor and lithium cooled fusion reactor, a sodium loop is being proposed to transfer heat from the primary coolant loop to the steam turbine cycle. Although by careful design and quality assurance programs, the probability for steam generator tube failure can be minimized, failure will still occur. The direct contact of sodium and water would cause a chemical reaction where hydrogen and sodium compounds are produced. This paper presents an evaluation of the potential hazards as a result of such a reaction.

The sodium-water reaction is explosive in nature with highly corrosive chemical by-products. Depending on the magnitude of the reaction, a blast wave of strength up to 2300 atmospheres can be generated. The time and the propagation of this high pressure pulse rely on the dynamical behavior of the reaction zone. The extent of the reaction zone is also important in examining wastage effects on structural materials. The wastage can cause the enlargement of the failure area, can induce other steam generator tubes failures, and can affect areas downstream of the failure point. Both the pressure force and the wastage effects can cause structural damage to the sodium piping system.

An analytical method is developed to investigate the extent of the reaction zone and the propagation of the pressure wave in the sodium system. In the calculation, the chemical reaction is assumed to be instantaneous, governed by the equation

$$2\mathrm{Na}(l) + \mathrm{H_2O}(l) \rightarrow \mathrm{Na_2O}(l) + \mathrm{H_2}(g) + 31.4\ \mathrm{K\ cal/gm.\ mole} \qquad (1)$$

Both the temperature and pressure rise in the reaction zone can be established from the energy balance and the equation of state for the gaseous product. As a consequence of the energy released, the chemical products suddenly expand with a high velocity. The expansion also generates a shock wave in both the water and the sodium systems. Results indicate that the reaction zone can expand in a rate of 1500 ft/sec and a shock wave with initial strength of 2300 atmospheres propagates with a speed of 8000 ft/sec into the sodium system. The propagating characteristics of the shock wave are obtained by solving the basic fluid equations. The shock wave decays rapidly, in the neighborhood of milliseconds, as soon as the reaction zone stops to expand. The decrease in the reaction zone pressure allows more water to react with the sodium and a second pulse is generated.

It is observed that although the magnitude of the pressure pulse generated from the sodium-water reaction is large, its duration is short. The results of the analysis would be useful for evaluating the structural response of the steam generator and for designing safeguard systems to mitigate the consequence of the sodium-water reactor in future electric power systems.

1. Introduction

In both Tokamak fusion and Liquid Metal Fast Breeder Reactors, an intermediate sodium sodium loop is being proposed to transfer heat from the primary coolant loop to the steam turbine cycle [1, 2]. Although by careful design and quality assurance programs, the probability for steam generator tube failure can be minimized, failure will still occur. The direct contact of sodium and water would cause a chemical reaction in which hydrogen gas and sodium compounds are produced. This paper presents an evaluation of the potential hazards as a result of such a reaction.

Although the designs of the steam generators may vary from vendor to vendor, they share some generic characteristics. The pressure of the steam side is usually higher than the sodium pressure. A single steam or water tube failure can be initiated by excessive thermal loadings, hydraulic vibrations or corrosions. Because of the pressure difference, water will be blown into the sodium medium where chemical reaction takes place. The reaction is exothermic in nature with highly corrosive chemical by-products. Depending on the extent of the sodium-water interaction, the exothermic nature of the reaction can be explosive with the generation of a blast wave. The time and propagation of this high pressure pulse rely on the dynamical behavior of the reaction zone. The determination of the loads imposed on components and structures in the neighborhood of the failure area is a rather complex problem. It involves the calculation of chemical kinetics in the reaction zone, the dynamics of the shock wave, and the damping effects of the structural components. The corrosive by-products in the reaction zone can cause long-term wastage effects on structural materials. The wastage can cause the enlargement of the failure area, can induce other steam generator tube failures and can affect areas downstream from the failure point. Hence, it is possible that the neighboring tubes can be failed in short time intervals by blast wave effects and in long time intervals by wastage effects. The sequential events for the sodium-water interaction are summarized in Figure 1.

Because of its potential hazards, the problem of sodium-water interaction has drawn considerable attention. Petukhov et al. [3] calculated the temperature, temperature gradient, and concentration of reaction products in a sodium-steam reaction zone. They reported a temperature peak of 1,500° C shortly after the chemical reaction. No attempt was made to measure the pressure pulse magnitude. The TRANSWRAP code [4], which was developed by Atomic International, utilized a continuous-water-fed mixing model for the reaction zone. The propagation of the pressure pulse was handled by the method of characteristics. Details of the calculational method in the code are not available. It was reported that the code predicts a pressure pulse of 4×10^6 N/m^2 in the sodium system of a LMFBR [4].

The present work represents a first step towards putting the shock wave propagation, which is responsible for the dynamical loadings on the structural components, on a quantitative basis. Use is made of the wave theory to analyse the extent of the reaction zone and the decay of the pressure pulse in the sodium system. A one-dimensional model is assumed and the analysis attempts to be as simple and generic as possible so that the results can be applied to future steam generator and safeguard system designs.

2. Analysis

2.1 Reaction Zone

The leakage of water or steam into sodium can lead to the following chemical reactions:

$$Na + H_2O \rightleftarrows NaOH + \tfrac{1}{2}H_2$$

$$2Na + NaOH \rightleftarrows Na_2O + NaH \qquad (1)$$

$$NaH \rightleftarrows Na + \tfrac{1}{2}H_2$$

For rapid interaction, the above set of equations can be represented by a single equation

$$2Na(\ell) + H_2O(\ell) \rightleftarrows Na_2O(\ell) + H_2 \qquad (2)$$

This reaction is exothermic with 31.4 kcal/g-mol of Na_2O produced. The boiling point of Na_2O at 1 atmosphere is 2,223° K, hence it is expected that Na_2O will be in a liquid state. For an instantaneous reaction between a stoichiometric mixture of sodium and water, both the temperature and pressure rise can be established from

(a) the energy equation

$$\tfrac{1}{2}(P + P_o)(\nu + \nu_o) = -q + (u - u_o) \qquad (3)$$

and

(b) the equation of state for the hydrogen gas

$$P\nu_{H_2} = RT \qquad (4)$$

where

P = pressure

T = temperature

ν = specific volume per g-mol

q = heat of reaction per g-mol

u = specific internal energy per g-mol

R = universal gas constant

The subscript 0 represents the initial state of the reactants.

If the process is assumed to be isochoric, then the initial temperature and pressure in the reaction zone are estimated to be 1,276° K and 2,300 atm respectively. These two parameters are independent of the extent of the chemical reaction.

2.2 Propagation of the Shock Waves

As a consequence of the high pressure generated in the reaction zone, the gas tries to expand with a high velocity. The initial pressure $P_1(0)$ in the sodium must equal the initial pressure in the gas region. This pressure is not necessarily the same as the adiabatic pressure calculated in the previous section. The equalization of pressure is achieved by the generation of an outgoing compression wave in the sodium and a rarefaction wave in the gas products as shown in Figure 2. Basically, the flow fields in these two regions are governed by the following conservation equations:

$$\text{Mass:} \qquad \frac{\partial \rho_i}{\partial t} + u_i \frac{\partial \rho_i}{\partial x} + \rho_i \frac{\partial u_i}{\partial x} = 0 \qquad (5)$$

Momentum: $$\rho_i \frac{\partial u_i}{\partial t} + \rho_i u_i \frac{\partial u_i}{\partial x} + \frac{\partial P_i}{\partial x} = 0 \qquad (6)$$

Entropy: $$\frac{\partial S_i}{\partial t} + u_i \frac{\partial S_i}{\partial x} = 0 \qquad (7)$$

Equation of State: $$\rho_i = f(P_i,\ S_i) \qquad (8)$$

where

ρ = density
u = velocity
P = pressure
S = entropy
x = space co-ordinate
t = time co-ordinate

and subscript

$i = 1$ for sodium
$i = 2$ for reactant gas

For an isentropic process, the equation of state for the hydrogen gas is

$$P_2/\rho_2{}^{\gamma} = \text{constant} \qquad (8a)$$

where $\gamma = 1.2$, and the equation of state for the liquid sodium is

$$P_1 + W = W(\rho_1/\rho_{10})^m \qquad (8b)$$

where

$W = 4{,}082$ atm
ρ_{10} = density of the sodium at low pressure ($P \simeq 0$)

These equations together with the appropriate boundary conditions can be solved to give the pressure and the velocity transients. The boundary conditions at the interfacial (or contact) surface between the gas and the sodium are

$$P_1(x_c) = P_2(x_c) \qquad (9)$$

$$u_1(x_c) = u_2(x_c) \qquad (10)$$

where x_c is the location of the contact surface.

At the shock front, a balance of mass and momentum would yield the following conditions:

$$\rho_1(x_s)[u_1(x_s) - u_s] = \rho_{10}(u_{10} - u_s) = m \qquad (11)$$

$$P_1(x_s) + m[u_1(x_s) - u_s] = P_{10} + m[u_{10}(x_s) - u_s] \qquad (12)$$

where the subscript 10 represents the steady state of the sodium medium which is ahead of the shock front, and u_s is the shock front speed.

Mathematically, the governing equations are first-order non-linear partial differential equations with moving boundaries. One numerical approach would be the finite difference method while another approach would be the wave tracing [5]. The exact numerical solutions of these equations are not attempted at this stage. Rather an approximated scheme is adopted for the solutions. If the rarefaction wave propagation phenomenon is neglected in the gas region, then the expansion of the reaction zone is given by

$$P_2(t)x_c^{\gamma}(t) = P_{20}x_{20}^{\gamma} \qquad (13)$$

where

x_{20} = the initial reaction zone co-ordinate, value depending on the amount of water interacting with the sodium

γ = specific heat ration for hydrogen gas, equal to 1.2

P_{20} = initial reaction zone pressure = 2,300 atm

In addition, if the time for the propagation of the pressure and the velocity change in the sodium region can be neglected, then by combining equations (11) and (12) the velocity behind the shock is given by

$$\tilde{u}_1(x_s) = \left[\frac{[(\tilde{P}_1(x_s) + 1)^{1/m} - 1]\tilde{P}_1(x_s)}{(\tilde{P}_1(x_s) + 1)^{1/m}m}\right]^{\frac{1}{2}} \qquad (14)$$

where

$\tilde{u}_1(x_s) = u_1(x_s)/C_o$

$\tilde{P}_1(x_s) = P_1(x_s)/W$

C_o = sonic velocity in sodium = 1,800 m/s

On differentiating equation (12),

$$\frac{d\tilde{P}_1(x_c)}{d\tilde{t}} = -\gamma\tilde{P}_o^{-1/\gamma}\tilde{P}_1(x_c)^{\frac{1+\gamma}{\gamma}}\tilde{u}_1(x_c) \qquad (15)$$

Equations (13) and (14) provide the necessary equations for solving the two unknowns $\tilde{P}_1(x_c)$ and $\tilde{u}_1(x_c)$. The shock speed is given by

$$u_s = \frac{P_1(x_c) - P_{10}}{\rho_{10}u_1(x_s)} \qquad (16)$$

the location of the contact surface is given by

$$x_c = \int_0^t u_1(x_c)\,dt \qquad (17)$$

and the location of the shock front is given by

$$x_s = \int_0^t u_1(x_s)\,dt \qquad (18)$$

In the above set of equations (i.e. from (13) to (18)) the only unknown parameter is x_{20}, which depends on the size of the initial reaction zone. It can only be determined from experimental data. If the parameters x_{20}, c_o, W, W/c_o^2, and x_{20}/c_o are chosen as the referenced length, speed, pressure, density, and time, respectively, then the pressure and the velocity, the contact and the shock front propagation can be expressed in terms of ξ which is equal to $(tc_o)/x_{20}$.

3. Results and Discussion

In the event of a sodium-water interaction, the adiabatic temperature and pressure in the reaction zone are found to be 1,276° K and 2,300 atm respectively. The initial size of the reaction zone, x_{20}, depends on the extent of the water-sodium interaction. For instance, in the case of a cross section dimension in the sodium channel of 1.6 cm x 5.08 cm, a value of 1 mm for x_{20} is equivalent to a mixture of 0.0018 g-mol of water and 0.0032 g-mol of sodium.

The decay of the pressure in the reaction zone is shown in Figure 3 where the non-dimensional pressure is plotted versus the non-dimensional time ξ. For the case of x_{20} = 1 mm, the pressure will decay to 100 atm in 1 ms (ξ = 1,800). At the same time, both the gas expansion rate $(u(x_c))$ and the shock wave speed are reduced (Figure 4). The propagation of the shock front and the contact surface are shown in Figure 5. All of these results are presented in the non-dimensional form for general application. For example, in the event of a chemical reaction between a mixture of 0.0018 g-mol of water and 0.0032 g-mol of sodium in a rectangular channel of 1.6 cm x 5.08 cm, then x_{20} is calculated to be 1 mm. The pressure behind the shock would decrease from its initial value of 2,300 atm to 100 atm in 1 ms. At that time, the gas will expand by a factor of 138, i.e. x_c = 14 cm. The shock wave would have propagated for a distance of 186 cm.

4. Conclusions

It should be pointed out that the analysis presented here is based on the assumption of a homogenous atom-to-atom mixture and that the reaction is instantaneous. In the actual system, the reaction rate is finite and the reaction takes place only at the contact surface between the water and the sodium. These two effects will reduce the initial pressure rise in the reaction zone and hence the consequences of the accident. In view of the lack of an appropriate theory to predict the surface reaction phenomenon, the present approach for the reaction zone represents a very conservative estimate. However, the methodology developed for the propagation and decay of the shock front can still be applied with a better reaction zone model.

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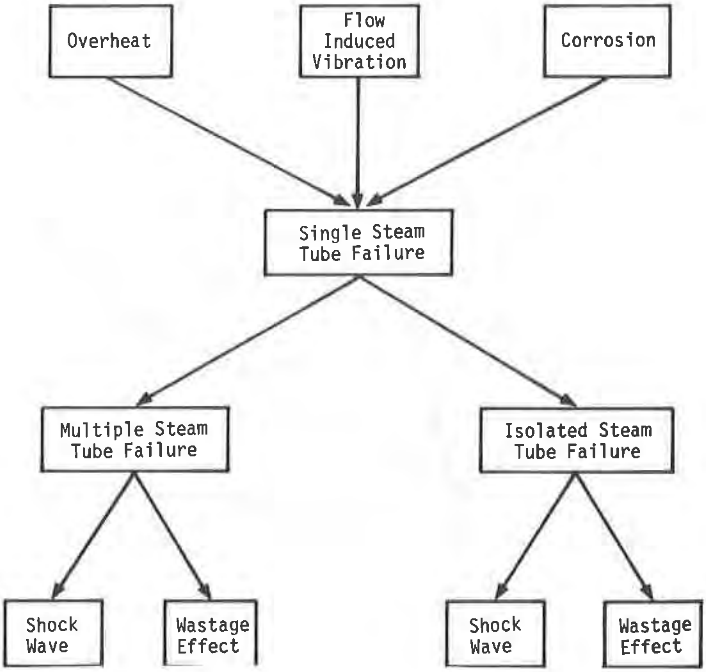

Fig. 1 Event Sequence of Steam Generation Tube Failure in Future Power Designs.

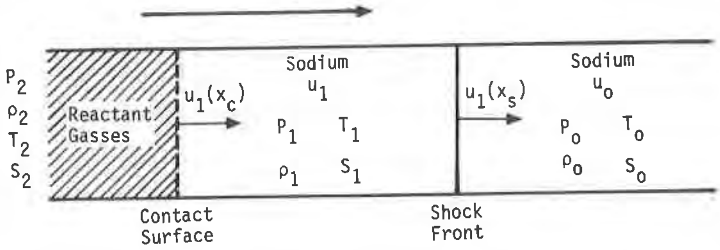

Fig. 2a Physical Model of the Propagation of Shock Front into the Sodium System due to Sodium-Water Interaction.

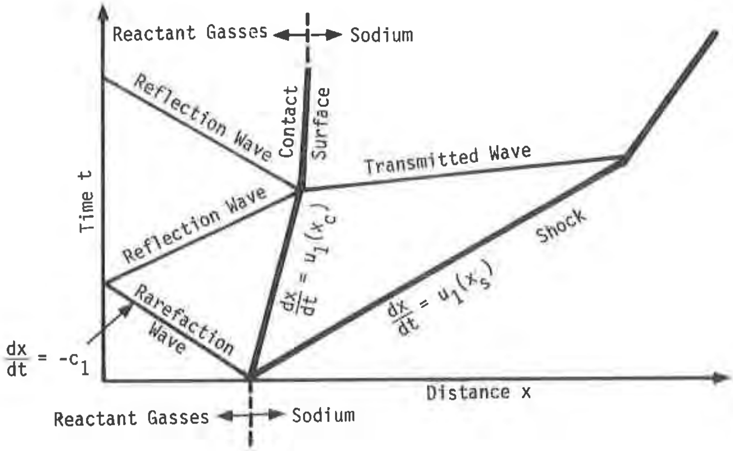

Fig. 2b Wave Propagation in the x-t Diagram.

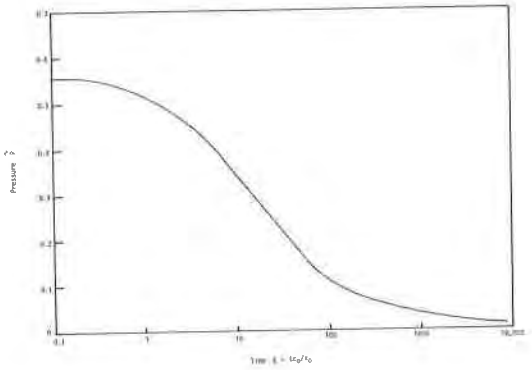

Fig. 3 Decay of the Shock Pressure as a Function of Time.

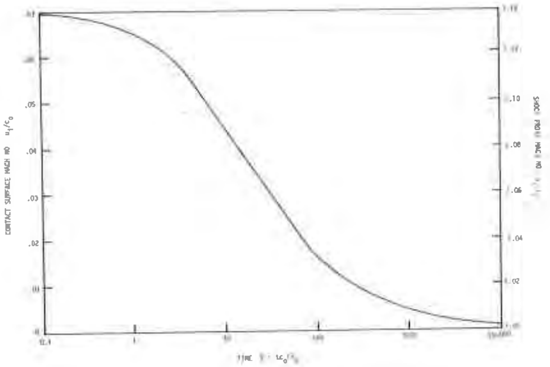

Fig. 4 Propagation Speed of Shock Front and Contact Surface in Liquid Sodium.

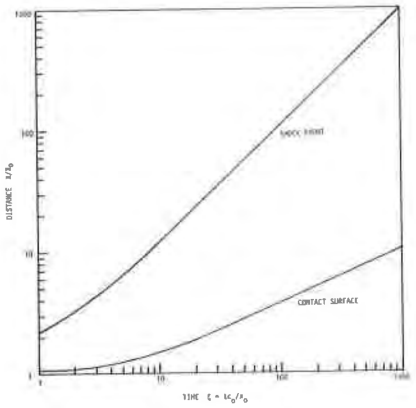

Fig. 5 Propagation of Shock Front and Contact Surface in Liquid Sodium.