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EQUILIBRIUM P-V-T RELATIONS FOR EXPANDING
LIQUID-VAPOR SYSTEMS IN A CONTAINMENT SHELL

by

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NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
c_v	Mean specific heat at constant volume (air 0.1715)	Btu/lb-°R
e	Specific stored internal energy	Btu/lb
E_{a1}	Stored energy of substance in control surface before malfunction	Btu
E_{a2}	Stored energy of substance in control surface after malfunction	Btu
g	Acceleration of gravity	ft/sec ²
h	Specific Enthalpy	Btu/lb
J	Joule's constant	778 ft-lb/Btu
p_{a1}	Initial absolute unit dry gas pressure	psia
p_{v1}	Initial absolute unit partial vapor pressure of gas	psia
p_s	Initial absolute unit saturated vapor pressure in gas	psia
p_{a2}	Final absolute unit dry gas pressure	psia
p_m	Absolute unit mixture pressure	psia
p_1	Initial absolute unit liquid, liquid-vapor, or vapor pressure	psia
p_2	Final absolute unit vapor pressure	psia
q	Transferred heat	Btu
R_a	Gas constant (air 53.34)	ft/°R
R_v	Vapor constant (H ₂ O 85.71)	ft/°R
t_{a1}	Initial temperature of gas	°F
t_{a2}	Final temperature of dry gas pressure	°F

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
t_1	Initial temperature of liquid	$^{\circ}\text{F}$
t_2	Final temperature of vapor	$^{\circ}\text{F}$
t_m	Final temperature of mixture	$^{\circ}\text{F}$
T_{a1}	Initial absolute temperature of gas	$^{\circ}\text{R}$
T_{a2}	Final absolute temperature of dry gas	$^{\circ}\text{R}$
T_2	Final absolute temperature of vapor	$^{\circ}\text{R}$
T_m	Final absolute temperature of mixture	$^{\circ}\text{R}$
u_{a1}	Initial specific internal energy of dry gas	Btu/lb
u_{a2}	Final specific internal energy of dry gas	Btu/lb
u_{f1}	Initial specific internal energy of saturated liquid	Btu/lb
u_{g1}	Initial specific internal energy of saturated vapor	Btu/lb
u_1	Initial specific internal energy of liquid, liquid-vapor or vapor	Btu/lb
u_2	Final specific internal energy of liquid, liquid-vapor, or vapor	Btu/lb
u_{f2}	Final specific internal energy of saturated liquid	Btu/lb
u_{g2}	Final specific internal energy of saturated vapor	Btu/lb
u_{fg2}	Final change of specific internal energy during vaporization	Btu/lb
u_{v1}	Initial specific internal energy of vapor in gas	Btu/lb
v_{a1}	Initial specific volume of dry gas	ft^3/lb

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
v_{f1}	Initial specific volume of saturated liquid	ft^3/lb
v_{g1}	Initial specific volume of saturated vapor	ft^3/lb
v_1	Initial specific volume of a liquid, liquid-vapor, or vapor	ft^3/lb
v_2	Final specific volume of a liquid, liquid-vapor, or vapor	ft^3/lb
v_{f2}	Final specific volume of saturated liquid	ft^3/lb
v_{g2}	Final specific volume of saturated vapor	ft^3/lb
v_{fg2}	Final change of specific volume during vaporization	ft^3/lb
V	Volume	ft^3
V_a	Volume of dry gas in container before incident, or free volume	ft^3
V_m	Volume of vapor or air in container after incident	ft^3
$\bar{V}$	Initial velocity of medium in reactor system	ft/sec
$\bar{V}_a$	Initial velocity of gas and vapor in containment shell	ft/sec
w_1	Initial weight of a liquid, liquid-vapor, or vapor	lb
w_a	Initial weight of dry gas	lb
w_s	Initial weight of saturated vapor in gas	lb
w_w	Initial weight of saturated liquid	lb
w_v	Initial weight of saturated liquid and saturated vapor	lb
w_{va}	Initial weight of vapor in gas	lb

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
X	Initial quality of vapor	
x	Final quality of vapor mixture	
Y	Constant = $\frac{p_{a2} R_v}{p_2 R_a} c_v (T_m - T_{a1})$	Btu/lb
z	Elevation above an arbitrary datum for a small mass of medium in the reactor vessel for the open system	ft
z _a	Elevation above an arbitrary datum for liquid, liquid-vapor, or vapor in reactor vessel	ft
z ₁	Elevation above an arbitrary datum for gas before a malfunction	ft
z ₂	Elevation above an arbitrary datum for a mixture of gas, liquid-vapor, or vapor following a malfunction	ft
z _{a1}	Elevation above an arbitrary datum for the medium in the containment shell for the open system for an initial selected time.	ft
z _{a2}	Elevation above an arbitrary datum for the medium in the containment shell for the open system after the initial selected time	ft
γ _a	Initial specific weight of dry gas before incident	lb/ft ³
φ	Relative humidity	
ω	Moisture content	

EQUILIBRIUM P-V-T RELATIONS FOR EXPANDING LIQUID-VAPOR SYSTEMS IN A CONTAINMENT SHELL

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ABSTRACT

From a time-independent standpoint, formulas are developed for determining a containment shell for a reactor plant should an unforeseen malfunction, where a compressed liquid, liquid-vapor, or vapor system is liberated and expands, occur. From the thermal equilibrium states, the pressure build-up inside a containment shell of known free volume is obtained, or for a specified containment shell pressure the required free volume is evolved.

For the pressure build-up inside a containment shell due to an incident on a time-dependent basis, formulas are evolved from an open-system aspect.

A table and graphs for various initial states expanding into a containment shell have been prepared, where time is not considered. Examples illustrating the usage of the developed time-independent equations are given.

I. INTRODUCTION

In a nuclear reactor plant, the release of radioactive products is possible if a mishap to the reactor vessel, primary coolant system, etc. occurs. With the removal of the constraining force, a liquid at a high temperature and pressure will dilate to a mixture of vapor and liquid. The radioactive particles, initially in the compressed liquid, would be carried along with the vapor, contaminating the surrounding region. To avoid spreading the radioactive particles over the countryside, a containment shell is provided. Here the sufficiently pressure-tight shell localizes and contains the resultant expansion. From previous tests, one can postulate that with a serious rupture of the reactor vessel, primary coolant system, etc., the available energy would be released in a short time.

The objectives of this report are to provide basic equations for the initial design, and to secure time-dependent equations for a more exact analysis of a reactor plant containment shell when a system malfunction

releases a compressed liquid, liquid-vapor, or vapor. When the initial states and amount of the medium are known, the principal items of concern are the pressure build-up in relation to the known gas volume of the containment shell, or the volume of the containment shell required to meet a specific pressure for an incident releasing the medium.

In this analysis compressed water, water-vapor, or steam is expanded into a containment shell having a medium of air; however, the equations can be made applicable to any compressed liquid, liquid-vapor, or vapor expanding into a gas.

II. MIXTURES OF VAPORS AND GASES

A. Suppositions

- (1) The mixture of the gas and liquid-vapor, or vapor is homogeneous, and a state of equilibrium exists following the incident.
- (2) The transfer of heat through the surfaces of the containment shell and to the installations within the containment shell is adiabatic.
- (3) After the initial expansion, the contribution from the reactor decay heat, primary system piping heat, pressure vessel heat, etc., is nil. (No positive or negative heat sources are considered to be present after the expansion.)
- (4) The forms of energy not considered are capillarity, chemical energy, electricity, magnetism and nuclear energy.
- (5) Potential energy and the post-incident state for kinetic energy are considered nil.
- (6) The perfect gas laws are valid, and the specific heats remain constant.
- (7) The initial states of the gas, liquid, liquid-vapor, or vapor are known.
- (8) The integrity of the containment shell is not affected by the pressure shock for a rapid rate of release.
- (9) It is assumed that the compressed liquid after an incident is the equivalent of a saturated liquid (mixture pressure is greater than saturated liquid pressure).

B. Development

The system before and some time after the malfunction reveals that no work has been performed by the surroundings and, by supposition, no heat has been added or has left the surroundings. As this is a non-flow expansion, the total internal energy, or stored energy, is conserved. This is in correlation with the Law of Conservation of Energy: The stored energy in a system isolated from its environment with respect to work and heat will remain constant regardless of the variations within the system. The stored energy includes changes in temperature and volume (internal energy), changes in motion (kinetic energy), height in a gravitational field (potential energy), etc.

The internal energy of the system is a function of two variables, such as temperature and pressure, or temperature and volume. For a perfect gas the internal energy is a function of temperature only.

The containment shell and reactor system conditions before and after a malfunction are shown schematically in Fig. 1. For basic development, the mediums for the reactor system and the containment vessel system are assumed to be flowing prior to the incident; after the incident the flow subsides and the mixture is at rest. The energy balance for this general system is:

$$\begin{aligned} w_a \left(u_{a1} + \frac{\bar{V}_a^2}{2gJ} + z_a \right) + w_{va} \left(u_{v1} + \frac{\bar{V}_a^2}{2gJ} + z_a \right) + w_l \left(u_l + \frac{\bar{V}^2}{2gJ} + z_l \right) \\ = w_a u_{a2} + (w_l + w_{va}) u_2 + (w_a + w_l + w_{va}) z_2 \quad , \end{aligned} \quad (1)$$

where the left side of the equation represents the internal energy, potential energy and kinetic energy available before the incident, and the right side represents the internal energy after the incident.

In Eq. (1), it has been assumed that the gas and liquid, liquid-vapor, or vapor have the same reference system. If a common reference system is not used, it can be proved that the reference terms cancel out, giving Eq. (1).

The potential energies will be considered nil since one pound of working substance must change in elevation by 778 ft to produce a British Thermal Unit. The change in elevation of the medium in the containment shell normally will be minute, as it is affected only by the addition of the reactor system volume which is usually small in comparison to the containment shell volume. Even for the change in the centroidal location of the reactor system medium, it is difficult to obtain a substantial change.

For the kinetic energy, the velocity must change from approximately 224 ft/sec to zero to attain a British Thermal Unit per pound of working substance. The velocity for the mixture after a malfunction subsides under the action of viscosity and internal heat conductivity; however,

FIG. 1
SCHEMATIC OF CONTAINMENT SHELL AND REACTOR VESSEL
CONDITIONS BEFORE AND AFTER A MALFUNCTION

before the malfunction the kinetic energy should be given consideration. Normally, the initial kinetic energy in the reactor system and containment shell is of minor importance. An investigation of several reactor vessels showed that the exit velocity of the working substance varied from about 60 ft/sec to 180 ft/sec. The velocity of the medium through the reactor vessel will be of a small magnitude in comparison to the stated exit velocities. The velocity of the reactor system medium will vary at different locations throughout the system; however, the velocity through the components such as the pressure vessel, heat exchangers, etc., will give a sufficient indication of the kinetic energy available. The kinetic energy of the medium in the containment shell will depend upon changes of the gas and the induced circulation. In this report an examination including the largest anticipated kinetic energies disclosed that they are ordinarily of minor importance. For special cases, the initial kinetic energies will be deleted.

The terms $(w_a u_{v1})$, $(w_{va} \bar{V}_a^2/2gJ)$, and $(w_{va} z_a)$, representing the internal energy, kinetic energy and potential energy of the moisture, or steam, in the air of the containment shell, are of small magnitude for many analyses. As previously stated, the potential energies will be omitted. The kinetic and internal energies will be retained in the general expression, but not for the special cases.

The perfect gas laws having been assumed, the specific internal energies for the gas are given by:

$$u_{a1} = c_v T_{a1} \quad ; \quad (2a)$$

$$u_{a2} = c_v T_{a2} \quad . \quad (2b)$$

As the mixture is assumed to reach a state of thermal equilibrium following an unforeseen event, the final temperature of the vapor and gas are the same:

$$t_m = t_{a2} = t_2 \quad (3a)$$

and

$$T_m = T_{a2} = T_2 \quad . \quad (3b)$$

Substituting Eqs. (2a), (2b), and (3b) into Eq. (1), and neglecting the potential energies, the basic general equation for the mediums initially in motion becomes:

$$\begin{aligned} w_a c_v T_{a1} + w_{va} u_{v1} + \frac{(w_a + w_{va}) \bar{V}_a^2}{2gJ} + w_1 u_1 + \frac{w_1 \bar{V}^2}{2gJ} \\ = w_a c_v T_m + (w_1 + w_{va}) u_2 \quad . \end{aligned} \quad (4)$$

Dalton's law of partial pressures states that the total pressure exerted by a mixture of gases (or vapors) is the sum of the pressures which each gas (or vapor) would exert were it to occupy the container alone at the same temperature; hence:

$$P_m = P_2 + P_{a2} \quad . \quad (5)$$

The increase in pressure of the air upon heating is computed from the equation of state of a perfect gas:

$$P_{a2} = P_{a1} \frac{T_m V_a}{T_{a1} V_m} \quad , \quad (6a)$$

where the equilibrium condition of Eq. (3b) was utilized. If the change in volume is negligible, Charles' Law is applicable: namely, for constant volume,

$$p_{a2} = p_{a1} \frac{T_m}{T_{a1}} \quad (6b)$$

Using hygrometry or psychrometry the weight of vapor in the air can be determined. Relative humidity is defined as the ratio of the actual partial pressure of the vapor in the air to the partial pressure of the vapor when the air is saturated at the same temperature. Hence, by this definition and the equation of state for perfect gas, the volume of vapor and air being the same, yields

$$\phi = \frac{p_{v1}}{p_s} = \frac{p_{v1}}{p_s} \frac{V_a / R_v T_{a1}}{V_a / R_v T_{a1}} = \frac{w_{va}}{w_s} \quad (6c)$$

and

$$w_{va} = w_s \phi = w_s \frac{p_{v1}}{p_s} = \frac{p_s V_a}{R_v T_{a1}} \phi \quad (6d)$$

Moisture content or specific humidity is defined as the ratio of the weight of water vapor to the weight of dry air in a volume of mixture. Thus, by this definition and the equations of state for perfect gases, the volume of vapor and air being equal, gives

$$\omega = \frac{w_{va}}{w_a} = \frac{p_{v1}}{p_{a1}} \frac{V_a / R_v T_{a1}}{V_a / R_a T_{a1}} = \frac{p_{v1} R_a}{p_{a1} R_v} \quad (6e)$$

and

$$w_{va} = \omega w_a = w_a \frac{p_{v1} R_a}{p_{a1} R_v} = \omega \frac{p_{a1} V_a}{R_a T_{a1}} \quad (6f)$$

In the following sections the weight of water vapor, will be retained to maintain simplicity; however, if desired the hygrometry equations can be substituted into the developed equations. When the volume is known Eqs. (6d) and (6f) are especially useful and can be used directly for air containing moisture.

1. Final State: A Mixture of Gas, Vapor and Liquid

a. Internal Energy of Vapor

By definition, the internal energy of a liquid-vapor is:

$$u_2 = u_{f2} + x u_{fg2} = (1 - x) u_{f2} + x u_{g2} \quad (7)$$

where x is the quality of the vapor. In this report X is quality before the incident and x is quality after the incident.

The basic general energy balance for this case with mediums initially in motion is:

$$w_a c_v T_{a1} + \frac{(w_a + w_{va}) \bar{V}_a^2}{2gJ} + w_{va} u_{v1} + w_1 u_1 + \frac{w_1 \bar{V}^2}{2gJ} \\ = w_a c_v T_m + (w_1 + w_{va}) (u_{f2} + x u_{fg2}) \quad . \quad (8)$$

b. Final Pressure Known; Determine Required Volume

The first development for calculating the required volume uses gas constants for the air and water vapor. The equation of state for a perfect gas gives the following equations for the air and water vapor after the incident:

$$p_{a2} V_m = w_a R_a T_m \quad (9a)$$

and

$$p_2 V_m = (w_1 + w_{va})(x)(R_v)(T_m) \quad , \quad (9b)$$

where R_a and R_v are the air and vapor constants, respectively. The volume occupied by the vapor and air is the same.

Dividing Eq. (9b) by Eq. (9a) and solving for the weight of air yields:

$$w_a = \frac{p_{a2} R_v}{p_2 R_a} (w_1 + w_{va}) (x) \quad . \quad (10)$$

Substituting Eq. (10) into Eq. (8) and solving for the quality x :

$$x = \frac{\left[\left\{ w_1 \left(u_1 + \frac{\bar{V}^2}{2gJ} \right) + w_{va} \left(u_{v1} + \frac{\bar{V}_a^2}{2gJ} \right) \right\} / (w_1 + w_{va}) \right] - u_{f2}}{u_{fg2} + \left[\frac{(p_{a2})(R_v)}{(p_2)(R_a)} \right] \left[(c_v)(T_m - T_{a1}) - \left(\frac{\bar{V}_a^2}{2gJ} \right) \right]} \quad (11)$$

where before the incident the mediums are moving.

By definition the specific volume for the liquid-vapor is:

$$v_2 = v_{f2} + x v_{fg2} = (1 - x) v_{f2} + x v_{g2} \quad . \quad (12)$$

From this definition the required volume of the air becomes:

$$V_a = (w_1 + w_{va}) [(1-x) v_{f2} + x v_{g2}] - w_1 v_1 \quad . \quad (13)$$

The volume of the vapor in the containment vessel after a malfunction is:

$$V_m = (w_1 + w_{va}) \left[x(v_{g2}) \right] \quad (14)$$

A condition frequently encountered in boilers, steam generators and reactors is for the initial states of the water and the vapor to be at saturated temperatures. For dry air ($w_{va} = 0$), with the initial states of the water and vapor at saturated temperature, and the mediums initially stagnant, or negligible, there is obtained:

$$x = \frac{(1 - X) u_{f1} + X u_{g1} - u_{f2}}{u_{fg2} + \left(\frac{p_{a2} R_v}{p_2 R_a} \right) c_v (T_m - T_{a1})} \quad (15)$$

Using w_v instead of w_1 to signify an initial condition for saturated vapor and liquid, the required dry air volume is

$$V_a = w_v \left[(1 - x) v_{f2} + x v_{g2} - (1 - X) v_{f1} - X v_{g1} \right] \quad (16)$$

As v_{f2} and v_{f1} are normally small in comparison with the terms v_{g2} and v_{g1} , an approximate expression for the air volume is

$$V_a \approx w_v (x v_{g2} - X v_{g1}) \quad (17)$$

The volume of the vapor in the plant container after the incident is

$$V_m = w_v x v_{g2} \quad (18)$$

In many instances only water at saturation temperature is in the system; hence, for dry air and with the mediums at rest, Eqs. (15), (16), (17), and (18) become:

$$x = \frac{u_{f1} - u_{f2}}{u_{fg2} + \left(\frac{p_{a2} R_v}{p_2 R_a} \right) c_v (T_m - T_{a1})} \quad ; \quad (19)$$

$$V_a = w_w [(1 - x) v_{f2} + x v_{g2} - v_{f1}] \quad ; \quad (20)$$

$$V_a \approx w_w x v_{g2} \quad ; \quad (21)$$

$$V_m = w_w x v_{g2} \quad ; \quad (22)$$

where w_w has been substituted for w_v to indicate a saturated liquid.

If the specific weight of dry air at the primary condition is used, the weight of air in the containment shell is given by:

$$w_a = \gamma_a V_a = \gamma_a \left[(w_1 + w_{va})(v_{f2} + xv_{fg2}) - w_1 v_1 \right] \quad (23)$$

The second treatment for computing the required volume is obtained by using Eq. (23) in Eq. (8); hence the quality x for the mediums initially in motion is:

$$x = \frac{w_1 \left(u_1 + \frac{\bar{v}_1^2}{2gJ} \right) + w_{va} \left(u_{v1} + \frac{\bar{v}_a^2}{2gJ} \right) - (w_1 + w_{va})u_{f2} - \gamma_a \left[c_v(T_m - T_{a1}) - \frac{\bar{v}_a^2}{2gJ} \right] \left[(w_1 + w_{va})v_{f2} - w_1 v_1 \right]}{(w_1 + w_{va}) \left[u_{fg2} + \gamma_a (v_{g2} - v_{f2}) \left\{ c_v(T_m - T_{a1}) - \frac{\bar{v}_a^2}{2gJ} \right\} \right]} \quad (24)$$

For the conditions having the initial states of the water and the vapor at saturation temperature, dry air in the containment shell, and a stagnant medium, Eq. (24) yields:

$$x = \frac{(1 - X)u_{f1} + Xu_{g1} - u_{f2} - c_v \gamma_a v_{f2} (T_m - T_{a1}) + c_v \gamma_a [(1 - X)v_{f1} + Xv_{g1}] (T_m - T_{a1})}{u_{fg2} + c_v \gamma_a (v_{g2} - v_{f2}) (T_m - T_{a1})} \quad (25)$$

Under most conditions it is possible to disregard the terms including v_{f1} and v_{f2} , as the specific volume of the initial and final state of the saturated water, the mean specific heat at constant volume, and the specific weight of the air are all of small magnitude. Therefore, Eq. (25) becomes:

$$x \approx \frac{(1 - X)u_{f1} + Xu_{g1} - u_{f2} + c_v \gamma_a Xv_{g1} (T_m - T_{a1})}{u_{fg2} + c_v \gamma_a v_{g2} (T_m - T_{a1})} \quad (26)$$

For a system having only saturated water, dry air and mediums at rest, Eqs. (25) and (26) simplify to:

$$x = \frac{u_{f1} - u_{f2} - \gamma_a c_v (T_m - T_{a1})(v_{f2} - v_{f1})}{u_{fg2} + c_v \gamma_a (v_{g2} - v_{f2})(T_m - T_{a1})} \quad (27)$$

and

$$x \approx \frac{u_{f1} - u_{f2}}{u_{fg2} + c_v \gamma_a v_{g2} (T_m - T_{a1})} \quad (28)$$

The volume is obtained from a previously developed appropriate volume formula. If desired, the formulas for x can be substituted into the volume expressions and the volume obtained directly.

The required volume is determined by a trial and error method. The method employed is outlined by the following steps, where steam tables are prerequisite:

- (1) Select the total pressure of the mixture, p_m .
- (2) Estimate the partial pressure of the vapor, p_2 , or the temperature of the mixture, T_m .
- (3) Calculate the partial pressure of the air p_{a2} by Charles' Law as an estimate (Eq. (6b)).
- (4) Check. The selected total pressure of the mixture, p_m , must equal the sum of the partial pressures of the vapor, p_2 , and air, p_{a2} (Eq. (5)).
- (5) If Step (4) provides fairly reasonable values, determine the post-expansion value for the quality, the vapor volume, the initial air volume, and the air pressure by applicable equations.
- (6a) If the summation of the air pressure obtained by Step (5) and the vapor pressure are equal to the selected total pressure of the mixture, iterate using the latest computed air pressure, and recalculate the quality, vapor volume, air volume and air pressure. Continue iteration if air pressure obtained in Steps (5) and (6) do not agree.
- (6b) If the summation of the air pressure from Step (5) and the vapor pressure are not equal to the selected total pressure, repeat Steps (2), (3), (4), and (5) as needed.

An illustrative example of this procedure is given in the appendix.

c. Volume Known; Determine Final Pressure of Mixture

The flashing problem will now be considered where the volume is given and the final pressure of the mixture is essential. The initial specific weight of the air is assumed known; thus, by Eqs. (8) and (23) and solving for x , the general case for the mediums in motion becomes:

$$x = \frac{w_1 \left(u_1 + \frac{\bar{V}^2}{2gJ} \right) - (w_1 + w_{va}) u_{f2} - V_a \gamma_a c_v (T_m - T_{a1}) + w_{va} u_{v1} + \frac{(V_a \gamma_a + w_{va}) \bar{V}_a^2}{2gJ}}{(w_1 + w_{va}) u_{fg2}} \quad (29)$$

For the case of saturated vapor and water expanding into a containment shell of dry air, the quality with the mediums stagnant is

$$x = \frac{(1-X) u_{f1} + X u_{g1} - u_{f2} - \frac{V_a}{w_v} \gamma_a c_v (T_m - T_{a1})}{u_{fg2}} \quad (30)$$

and for saturated water

$$x = \frac{u_{f1} - u_{f2} - \frac{V_a}{w_w} \gamma_a c_v (T_m - T_{a1})}{u_{fg2}} \quad (31)$$

The blowoff can be analyzed for a given volume by using gas constants as done for the pressure. The weight of the dry air initially in the vessel is

$$w_a = \gamma_a V_a = \frac{P_{a1}}{R_a T_{a1}} V_a \quad (32)$$

where γ_a is obtained from the equation of state for a perfect gas. For the general case of mediums initially in motion, Eqs. (32) and (8) yield

$$x = \frac{w_1(u_1 + \frac{\bar{V}^2}{2gJ}) - (w_1 + w_{va})u_{f2} - V_a \frac{P_{a1}}{R_a T_{a1}} c_v (T_m - T_{a1}) + w_{va} u_{v1} + \frac{(V_a \frac{P_{a1}}{R_a T_{a1}} + w_{va}) \bar{V}_a^2}{2gJ}}{(w_1 + w_{va})u_{fg2}} \quad (33)$$

For the case of saturated vapor and water expanding into a vessel of dry and stagnant mediums,

$$x = \frac{(1-X)u_{f1} + X u_{g1} - u_{f2} - \frac{V_a P_{a1}}{w_v R_a T_{a1}} c_v (T_m - T_{a1})}{u_{fg2}} \quad (34)$$

and

$$x = \frac{u_{f1} - u_{f2} - \frac{V_a P_{a1}}{w_v R_a T_{a1}} c_v (T_m - T_{a1})}{u_{fg2}} \quad (35)$$

for saturated liquid.

Equations (32) to (35) are especially useful where the initial air temperature and pressure of the containment vessel are not atmospheric.

As in the previous analysis, a solution is obtained by a trial and error method with the aid of steam tables:

- (1) Estimate the partial pressure of the vapor, p_2 , or the temperature of the mixture, T_m .
- (2) Compute the quality x by the appropriate formula, depending upon the case being investigated.
- (3) Check the actual volume against a computed volume depending upon the initial state and accuracy required. Note: The approximate formulas for the volume can be used for the saturated liquid or saturated liquid-vapor at least until the trial and error solution is fairly well established.
- (4) Iterate Steps (1), (2), and (3) until the correct values are obtained.
- (5) Compute the total pressure of the mixture with Eq. (5), (6a), or (6b).

2. Final State: A Mixture of Gas and Vapor

a. Final Pressure Known; Determine Required Volume

The first development makes use of the gas constants; hence, the use of the perfect gas equation of state yields the following equations for the final gas and vapor state:

$$p_{a2} V_m = w_a R_a T_m \quad (36a)$$

and

$$p_2 V_m = (w_1 + w_{va}) (R_v) (T_m) \quad (36b)$$

Dividing Eq. (36a) by Eq. (36b) and solving for the weight of air yields

$$w_a = \frac{p_{a2} R_v}{p_2 R_a} (w_1 + w_{va}) \quad (37)$$

Substituting Eq. (37) into Eq. (4) and rearranging terms, with the known quantities on the left side and the unknowns on the right gives

$$u_1 + \frac{\bar{V}^2}{2gJ} = \left(1 + \frac{w_{va}}{w_1}\right) u_2 + c_v \left(1 + \frac{w_{va}}{w_1}\right) \frac{R_v p_{a2}}{R_a p_2} (T_m - T_{a1}) - \frac{w_{va}}{w_1} u_{v1} - \left[\left(1 + \frac{w_{va}}{w_1}\right) \frac{p_{a2} R_v}{p_2 R_a} + \frac{w_{va}}{w_1} \right] \frac{\bar{V}_a^2}{2gJ} \quad (38)$$

The final steam volume of the steam is

$$V_m = (w_1 + w_{va}) v_2 \quad , \quad (39)$$

and the initial volume of the air is

$$V_a = (w_1 + w_{va}) v_2 - w_1 v_1 \quad . \quad (40)$$

If only dry air is present and the mediums at rest, Eqs. (38), (39) and (40) reduce to

$$u_1 = u_2 + c_v \frac{R_v p_{a2}}{R_a p_2} (T_m - T_{a1}) \quad ; \quad (41)$$

$$V_m = w_1 v_2 \quad ; \quad (42)$$

$$V_a = w_1 (v_2 - v_1) \quad . \quad (43)$$

Using a trial and error method, and with the aid of steam tables:

- (1) Estimate the final temperature and pressure of steam.
- (2) Calculate the final steam volume, initial air volume, and final air pressure.
- (3) Check the computed final mixture pressure against design and equality of energy balance.
- (4) Iterate Steps (1), (2), and (3) until the correct values are obtained.

The second evolvment utilizes the specific weight of dry air at the initial condition. From Eq. (23) and (40) the weight of dry air is

$$w_a = \gamma_a V_a = \gamma_a [(w_1 + w_{va}) v_2 - w_1 v_1] \quad . \quad (44)$$

Substituting Eq. (44) into Eq. (4) and rearranging the known quantities on the left side and the unknowns on the right side,

$$(45)$$

For stagnant mediums and dry air, Eq. (45) becomes:

$$u_1 - \gamma_a v_1 c_v T_{a1} = u_2 + \gamma_a c_v [v_2 (T_m - T_{a1}) - v_1 T_m] \quad . \quad (46)$$

The volume is obtained in a manner analogous to the gas constant method.

b. Volume Known; Determine Final Pressure of Mixture.

For the case of a known initial air volume, Eqs. (44) and (4) give

$$w_1 \left(u_1 + \frac{\bar{V}^2}{2gJ} \right) + \gamma_a V_a \left(c_v T_{a1} + \frac{\bar{V}_a^2}{2gJ} \right) + w_{va} \left(u_{v1} + \frac{\bar{V}_a^2}{2gJ} \right) = (w_1 + w_{va}) u_2 + \gamma_a V_a c_v T_m \quad (47)$$

For dry air and with the fluids at rest

$$w_1 u_1 + \gamma_a V_a c_v T_{a1} = w_1 u_2 + \gamma_a V_a c_v T_m \quad (48)$$

For an initial known air volume, Eqs. (32) and (4) yield

$$w_1 \left(u_1 + \frac{\bar{V}^2}{2gJ} \right) + \frac{p_{a1} V_a}{R_a T_{a1}} \left(c_v T_{a1} + \frac{\bar{V}_a^2}{2gJ} \right) + w_{va} \left(u_{v1} + \frac{\bar{V}_a^2}{2gJ} \right) = (w_1 + w_{va}) u_2 + \frac{p_{a1} V_a}{R_a T_{a1}} c_v T_m \quad (49)$$

For stagnant mediums and dry air Eq. (47) reduces to

$$w_1 u_1 + \frac{p_{a1} V_a}{R_a T_{a1}} c_v T_{a1} = w_1 u_2 + \frac{p_{a1} V_a}{R_a T_{a1}} c_v T_m \quad (50)$$

Using a trial and error method:

- (1) Estimate final temperature and pressure of the steam.
- (2) Calculate the final steam volume and the final air pressure.
- (3) Check the computed initial air volume against the actual volume and equality of energy balance.
- (4) Iterate Steps (1), (2) and (3) until the correct values are obtained.

C. Working Data

Table I lists the computed values for various initial states of water at saturation temperature, and the mixture values after expansion to different total absolute pressures, for a containment shell having dry air initially at a pressure of 14.7 psia and temperatures of 60° F and 100° F. Figures 2 to 11 are graphs for various initial states from saturation to a

TABLE I

EXPANSION OF ONE POUND SATURATED WATER INTO A CONTAINER SHELL OF DRY AIR INITIALLY AT 14.7 psia

INITIAL STATE					FINAL STATES												
SATURATED WATER				AIR	MIXTURE			AIR	WATER VAPOR								
P ₁	V _{f1}	t ₁	u _{f1}	V _a	P _m	V _m	t _m	P _{a2}	P ₂	V _{f2}	V _{fg2}	V _{g2}	u _{f2}	u _{fg2}	u _{g2}	Y	X
psia	ft ³ /lb	°F	Btu/lb	ft ³	psia	ft ³	°F	psia	psia	ft ³ /lb	ft ³ /lb	ft ³ /lb	Btu/lb	Btu/lb	Btu/lb		
INITIAL DRY AIR TEMPERATURE 60°F																	
500	0.0197	467.01	447.6	0.634	140.44	0.639	339.99	22.44	118.00	0.01787	3.770	3.788	310.73	796.7	1107.4	14.68	0.1687
				1.093	100.69	1.099	311.16	21.69	79.00	0.01756	5.519	5.537	280.86	821.0	1101.9	19.00	0.1985
				1.927	70.88	1.933	281.01	20.88	50.00	0.01727	8.498	8.515	249.93	845.4	1095.3	25.43	0.2270
				3.473	50.04	3.480	250.33	20.04	30.00	0.01701	13.729	13.746	218.73	869.1	1087.8	35.04	0.2531
				5.142	40.49	5.149	230.57	19.49	21.00	0.01685	19.175	19.192	198.73	883.9	1082.6	43.63	0.2683
				9.307	30.70	9.316	201.96	18.70	12.00	0.01665	32.38	32.40	169.92	904.8	1074.7	60.95	0.2875
				37.36	20.00	37.37	141.48	17.00	3.00	0.01630	118.69	118.71	109.36	947.3	1056.7	127.23	0.3148
1000	0.0216	544.61	538.4	1.054	140.43	1.063	339.99	22.43	118.00	0.01787	3.770	3.788	310.73	796.7	1107.4	14.67	0.2806
				1.688	100.68	1.698	311.16	21.68	79.00	0.01756	5.519	5.537	280.86	821.0	1101.9	19.00	0.3066
				2.811	70.87	2.821	281.01	20.87	50.00	0.01727	8.498	8.515	249.93	845.4	1095.3	25.43	0.3313
				4.850	50.04	4.860	250.33	20.04	30.00	0.01701	13.729	13.746	218.73	869.1	1087.8	35.03	0.3536
				7.017	40.49	7.028	230.57	19.49	21.00	0.01685	19.175	19.192	198.73	883.9	1082.6	43.63	0.3662
				12.3	30.69	12.36	201.96	18.69	12.00	0.01665	32.38	32.40	169.92	904.8	1074.7	60.94	0.3816
				47.39	20.00	47.40	141.48	17.00	3.00	0.01630	118.69	118.71	109.36	947.3	1056.7	127.23	0.3993
2000	0.0257	635.82	662.2	1.625	140.40	1.641	339.99	22.40	118.00	0.01787	3.770	3.788	310.73	796.7	1107.4	14.65	0.4332
				2.497	100.66	2.514	311.16	21.66	79.00	0.01756	5.519	5.537	280.86	821.0	1101.9	18.96	0.4540
				4.015	70.86	4.031	281.01	20.86	50.00	0.01727	8.498	8.515	249.93	845.4	1095.3	25.41	0.4734
				6.725	50.03	6.742	250.33	20.03	30.00	0.01701	13.729	13.746	218.73	869.1	1087.8	35.02	0.4905
				9.573	40.49	9.590	230.57	19.49	21.00	0.01685	19.175	19.192	198.73	883.9	1082.6	43.62	0.4997
				16.50	30.69	16.52	201.96	18.69	12.00	0.01665	32.38	32.40	169.92	904.8	1074.7	60.93	0.5098
				61.06	20.00	61.08	141.48	17.00	3.00	0.01630	118.69	118.71	109.36	947.3	1056.7	127.22	0.5145
3000	0.0346	695.36	783.4	2.180	140.34	2.207	339.99	22.34	118.00	0.01787	3.770	3.788	310.73	796.7	1107.4	14.61	0.5826
				3.285	100.62	3.313	311.16	21.62	79.00	0.01756	5.519	5.537	280.86	821.0	1101.9	18.94	0.5983
				5.189	70.84	5.217	281.01	20.84	50.00	0.01727	8.498	8.515	249.93	845.4	1095.3	25.38	0.6126
				8.557	50.02	8.585	250.33	20.02	30.00	0.01701	13.729	13.746	218.73	869.1	1087.8	35.00	0.6246
				12.07	40.48	12.10	230.57	19.48	21.00	0.01685	19.175	19.192	198.73	883.9	1082.6	43.59	0.6304
				20.55	30.69	20.58	201.96	18.69	12.00	0.01665	32.38	32.40	169.92	904.8	1074.7	60.91	0.6353
				74.44	20.00	74.47	141.48	17.00	3.00	0.01630	118.69	118.71	109.36	947.3	1056.7	127.21	0.6273
INITIAL DRY AIR TEMPERATURE 100°F																	
500	0.0197	467.01	447.6	0.629	139.86	0.634	340.62	20.86	119.00	0.01788	3.740	3.758	311.39	796.1	1107.5	11.62	0.1686
				1.081	100.16	1.087	312.03	20.16	80.00	0.01757	5.454	5.472	281.76	820.3	1102.1	14.72	0.1986
				1.895	70.42	1.901	282.26	19.42	51.00	0.01728	8.342	8.359	251.21	844.3	1095.5	19.13	0.2275
				3.381	49.60	3.388	252.22	18.66	31.00	0.01702	13.313	13.330	220.63	867.7	1088.3	25.25	0.2542
				4.954	40.17	4.962	233.07	18.17	22.00	0.01687	18.358	18.375	201.26	882.0	1083.3	30.28	0.2700
				8.734	30.46	8.743	205.88	17.46	13.00	0.01667	30.04	30.06	173.87	901.9	1075.8	39.19	0.2909
				29.66	20.09	29.67	152.97	16.09	4.00	0.01636	90.61	90.63	120.85	939.3	1060.2	58.70	0.3274
1000	0.0216	544.61	538.4	1.047	139.84	1.056	340.62	20.84	119.00	0.01788	3.740	3.758	311.39	796.1	1107.5	11.61	0.2811
				1.672	100.15	1.682	312.03	20.15	80.00	0.01757	5.454	5.472	281.76	820.3	1102.1	14.72	0.3074
				2.770	70.41	2.780	282.26	19.41	51.00	0.01728	8.342	8.359	251.21	844.3	1095.5	19.12	0.3326
				4.733	49.65	4.744	252.22	18.65	31.00	0.01702	13.313	13.330	220.63	867.7	1088.3	25.24	0.3559
				6.780	40.16	6.791	233.07	18.16	22.00	0.01687	18.358	18.375	201.26	882.0	1083.3	30.28	0.3696
				11.63	30.46	11.64	205.88	17.46	13.00	0.01667	30.04	30.06	173.87	901.9	1075.8	39.19	0.3874
				37.90	20.08	37.92	152.97	16.08	4.00	0.01636	90.61	90.63	120.85	939.3	1060.2	58.70	0.4184
2000	0.0257	635.82	662.2	1.617	139.82	1.632	340.62	20.82	119.00	0.01788	3.740	3.758	311.39	796.1	1107.5	11.60	0.4343
				2.477	100.13	2.493	312.03	20.13	80.00	0.01757	5.454	5.472	281.76	820.3	1102.1	14.70	0.4556
				3.963	70.40	3.979	282.26	19.40	51.00	0.01728	8.342	8.359	251.21	844.3	1095.5	19.11	0.4760
				6.575	49.65	6.592	252.22	18.65	31.00	0.01702	13.313	13.330	220.63	867.7	1088.3	25.23	0.4945
				9.267	40.16	9.284	233.07	18.16	22.00	0.01687	18.358	18.375	201.26	882.0	1083.3	30.27	0.5053
				15.58	30.46	15.60	205.88	17.46	13.00	0.01667	30.04	30.06	173.87	901.9	1075.8	39.18	0.5189
				49.14	20.08	49.16	152.97	16.08	4.00	0.01636	90.61	90.63	120.85	939.3	1060.2	58.70	0.5424
3000	0.0346	695.36	783.4	2.169	139.76	2.196	340.62	20.76	119.00	0.01788	3.740	3.758	311.39	796.1	1107.5	11.57	0.5844
				3.260	100.09	3.287	312.03	20.09	80.00	0.01757	5.454	5.472	281.76	820.3	1102.1	14.68	0.6008
				5.125	70.38	5.152	282.26	19.38	51.00	0.01728	8.342	8.359	251.21	844.3	1095.5	19.09	0.6164
				8.373	49.63	8.402	252.22	18.63	31.00	0.01702	13.313	13.330	220.63	867.7	1088.3	25.21	0.6303
				11.70	40.15	11.73	233.07	18.15	22.00	0.01687	18.358	18.375	201.26	882.0	1083.3	30.25	0.6381
				19.44	30.45	19.47	205.88	17.45	13.00	0.01667	30.04	30.06	173.87	901.9	1075.8	39.17	0.6477
				60.14	20.08	60.17	152.97	16.08	4.00	0.01636	90.61	90.63	120.85	939.3	1060.2	58.69	0.6639

FIG. 2
EXPANSION OF ONE POUND OF SATURATED WATER INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 3
EXPANSION OF ONE POUND OF LIQUID-VAPOR (WATER) INITIALLY AT 500 psia
INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 4
EXPANSION OF ONE POUND OF LIQUID-VAPOR (WATER) INITIALLY AT 1000 psia
INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 5
EXPANSION OF ONE POUND OF LIQUID-VAPOR (WATER) INITIALLY AT 2000 psia
INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 80°F

FIG. 6
EXPANSION OF ONE POUND OF LIQUID-VAPOR (WATER) INITIALLY AT 3000 psia
INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 7
EXPANSION OF ONE POUND OF WET MIXTURE (QUALITY = 10%) INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 8

EXPANSION OF ONE POUND OF WET MIXTURE (QUALITY = 20%) INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 9
EXPANSION OF ONE POUND OF WET MIXTURE (QUALITY = 30%) INTO A CONTAINMENT VESSEL OF DRY AIR INITIALLY AT 14.7 psia AND 80°F

FIG. 10
EXPANSION OF ONE POUND OF WET MIXTURE (QUALITY = 40%) INTO A CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

FIG. 11
EXPANSION OF ONE POUND OF WET MIXTURE (QUALITY = 50%) INTO A
CONTAINMENT SHELL OF DRY AIR INITIALLY AT 14.7 psia AND 60°F

quality of 50% expanding into a containment shell having an initial temperature of 60°F and pressure of 14.7 psia. In both the tabulated results and the graphic representations it has been assumed that the change in velocity of the medium, or mediums, is nil.

III. THE OPEN SYSTEM

A. Suppositions

- (1) The working substance is homogeneous in composition, state and velocity at the breach at any instance.
- (2) The forms of energy considered are flow work ($w p v/J$), internal energy ($w u$), kinetic energy ($w V^2/2gJ$), potential energy (wz), and transferred heat (q).
- (3) The forms of energy not considered are capillarity, chemical energy, electricity, magnetism and nuclear energy.

B. Method of Analysis

An open system can be defined as a system where the working substance crosses its containment boundaries in the process of a change of state. For many thermodynamic processes, the movement of the thermal working substance cannot be treated as a steady flow process; hence the First Law of Thermodynamics for changes of state is applicable. The breaching of a reactor pressure vessel and consequent admission of the reactor working substance into the containment shell is an unsteady flow process from the onset of the rupture until the motion has subsided.

The method of analysis is to define the boundary or control surface through which the working substance flows at any instant as a prerequisite to the application of the First Law for changes of state and quantity. As shown in Fig. 12, the stationary boundaries of the system are the inner surfaces of the containment shell and the outer surfaces of the reactor vessel which contains an infinitesimal element of weight dw . In the event of a vessel rupture, the small element will penetrate the boundary at the breach and join the mass inside the system. In this analysis the boundary at the breach is assumed to remain fixed.

The environment exerts a pressure against the element during its passage through the boundary; hence the work performed by the surroundings on the compound system consisting of the system and element is given by

$$pv \, dw$$

where p denotes the pressure, and v the specific volume of the element crossing the boundary.

For simplicity, let E_{a1} and E_{a2} signify the stored energy of the substance in the containment shell before the malfunction and after the malfunction, respectively; dq the heat transferred to the compound system during the process; and e the specific internal energy of the infinitesimal element. From the Law of Conservation of Energy, an energy balance of the compound system is made at any instant, namely, the rate of increase within the containment shell must equal the net rate of the inflow of the energies and flow work:

$$- dq = E_{a1} - (E_{a2} + e dw) - \left(\frac{Pv}{J}\right) dw \quad . \quad (51)$$

The negative sign $(-dq)$ denotes that heat is leaving the compound system. If a heat source is present it is possible to have the over-all heat transfer positive. The heat transfer term includes the heat through the surfaces of the containment shell, to the internal equipment, decay heat of reactor, etc.

Considering the stored energies to be comprised of only internal energy, kinetic energy and potential energy, it is possible to write

$$-dq = w_a \left(u_{a1} + \frac{\bar{V}_{a1}^2}{2gJ} + z_{a1} \right) - w_a \left(u_{a2} + \frac{\bar{V}_{a2}^2}{2gJ} + z_{a2} \right) - \left(u + \frac{pv}{J} + \frac{\bar{V}^2}{2gJ} + z \right) dw, \quad (52)$$

or, recalling the definition of enthalpy and neglecting the potential energies,

$$-dq = w_a \left(u_{a1} + \frac{\bar{V}_{a1}^2}{2gJ} \right) - w_a \left(u_{a2} + \frac{\bar{V}_{a2}^2}{2gJ} + z_{a2} \right) - \left(h + \frac{\bar{V}^2}{2gJ} \right) dw \quad (53)$$

For a finite mass transferred across the boundary, Eq. (53) can be utilized by summing up the dq and $(h + \bar{V}^2/2gJ) dw$ terms; thus,

$$- \int dq = w_a \left(u_{a1} + \frac{\bar{V}_{a1}^2}{2gJ} \right) - w_a \left(u_{a2} + \frac{\bar{V}_{a2}^2}{2gJ} \right) - \int \left(h + \frac{\bar{V}^2}{2gJ} \right) dw \quad (54)$$

The components dq and $(h + \bar{V}^2/2gJ)$ are normally functions of time because of the unsteady flow; hence, this equation may not always be easy to solve.

In Eq. (52) through (54) the subscripts a , a_1 and a_2 refer to the substance in the containment shell and not necessarily a dry gas as stated in the nomenclature.

The size of the gap must be known to establish the velocity of jet stream from the reactor pressure vessel. Nozzle formulas can be employed, but it must be kept in mind that the flow is not steady. A technique of solution is to take an energy balance for a finite time increment of the system and assume that the initial values of temperature, rates of heat transfer, discharge velocity, etc., remain constant.

IV. DISCUSSION

The method of analysis for mixtures of vapors and gases has been developed from a general theorem known as the Gibbs-Dalton Law. Three basic rules for mixture properties are generally presented as deductions from the general theorem. One of the rules was stated in the method of

analysis, namely, Dalton's Law of Partial Pressures, and the second was implied by the First Law of Thermodynamics or Law of Conservation of Energy. From the First Law, the second rule deduced is: the internal energy of a mixture of gases (or vapors) is the sum of the internal energies which each gas (or vapor) would have were it to occupy the container at the temperature of the mixture. The third basic rule that may be deduced is: The total entropy of a mixture of gases (or vapors) is the sum of the entropies which each gas (or vapor) would have were it to occupy the container alone at the temperature of the mixture. These rules cannot be derived solely from the First and Second Laws of Thermodynamics; hence, they do not hold for all systems comprising mixtures of vapors and gases. From experiments, the rules hold at low pressures to a high degree of precision and apply to real gases over a greater pressure range than do the perfect gas relations.

In this analysis the equation of state for a perfect gas and the Gibbs-Dalton Law have been assumed valid. It must be remembered that these relations are only applicable for a specific range. For a mixture at low pressure relative to the critical pressure, the Gibbs-Dalton Law usually gives the properties of the mixture to an accuracy approximately equal to that of the data of the constituents. At higher pressures the law becomes very unreliable.

To obtain greater reliability, the pressure, volume and temperature relations of a substance or substances are frequently stated in an equation form which is called an equation of state. Well-known equations of state are the van der Waals equation and the Beattie-Bridgman equation. For a mixture requiring a good representation over a range of conditions, the Beattie-Bridgman equation generally yields satisfactory results.

Other methods meriting mention for improving the results where the idealized equations are in considerable error are the Law of Corresponding States and Gilliland's Method. However, the Law of Corresponding States loses all validity at low pressure.

Heat sources and heat sinks were deliberately omitted for the mixtures of vapors and gases in an endeavor to emphasize the open system. It is frequently customary to add a heat source or a heat sink to the mixtures of vapors and gases to obtain a better account of the event and to provide a conservative design. For computational purposes, it is a simple matter to insert heat sinks and sources into the mixtures of vapors and gases equations. For example they may be added to the right side of Eq. (4): positive if a heat source, and negative if a heat sink. The heat sinks and sources are dependent upon the reactor design; hence, no values are related. The mixtures of vapors and gases in this analysis are based on two states: before an incident, and after an incident. The open system contains processes, namely, heat transfer, pressures, temperatures, etc., which vary

with time. If a heat source of any magnitude is present after the malfunction, an increase in the size of the containment shell would be necessary. A reduction in the containment shell size can be obtained if the heat sink present is capable of handling the heat transfer.

The plots of pressure versus containment volume for the mixtures of vapors and gases indicate that a containment shell capable of withstanding only low pressures must have a tremendous volume to prevent a rupture. To avoid using a large containment shell, an arbitrary containment volume of 5 ft³ per lb. of saturated water can be used. This results in a containment shell pressure range from 33 psia to 72 psia, for initial system pressures from 200 psia to 3000 psia.

A comparison of the required containment volumes for the mixtures of vapors and gases for the different initial dry air temperatures of 60° F and 100° F reveals that the lower temperature necessitates a larger free volume than the higher temperature. The difference between the free volumes for the initial dry air temperatures considered is small for the higher final mixture pressures, but becomes pronounced for the lower final mixture pressures.

Independent calculations using the gas constants or the specific weight of air were performed to determine the quality (x) of mixtures of gases and vapors resulting from water initially at 1000 psia and saturation temperature. The quality by the two methods was found to be exact for the first three digits. The maximum variations was less than 0.2%, and the gas constant method yielded the lower value.

For the heat transfer from an air-water-vapor mixture, or an air-vapor mixture to the containment shell surfaces and internal installations to be nil, a very rapid expansion would be required. In the case of instantaneous expansion, the rapidity of the air temperature reaching the mixture equilibrium temperature should be given consideration. Analyses have been made where the air was neglected for the mixtures of vapors and gases.

The moisture content in the free air volume of the containment shell can be established by standard psychrometric or hygrometric methods. In the Appendix, Example No. 2 shows that the presence of moisture in the air reflects an increase in containment volume, while in Example No. 4 the presence of moisture in the air requires a smaller free volume. In both problems the mixtures of vapors and gases analysis was utilized and the change in free volumes was small.

A comparison between the data in Table I and References 4 and 10 shows that, for the extreme case, the internal energy of compressed water is approximately 0.2 Btu greater than for saturated water. Therefore, for all practical purposes, the thermodynamic properties of a compressed liquid can be considered equivalent to the properties of a saturated liquid at identical temperatures.

For the open system, the mixing process of the vapor and air being extremely complex, the rate at which the mixture would reach equilibrium cannot be computed with precision; therefore, a supposition of instantaneous homogeneous - complete mixing and thermal equilibrium throughout the system can be employed.

APPENDIX

ILLUSTRATIVE EXAMPLESExample No. 1

A reactor pressure vessel operating at 1000 psia contains a mixture of 68 lb of saturated water and 32 lb of saturated steam. The containment shell is designed to withstand an air-water-vapor pressure of 35 psig. The air in the containment shell is initially dry at 14.7 psia and 60° F. The flow of mediums is negligible.

Problems

1. Determine the partial pressures of the air and water vapor, the quality of the vapor, and the volume of the shell following an incident.
Note: Use $R_a = 53.34 \text{ ft}^2/\text{°R}$, $R_v = 85.71 \text{ ft}^2/\text{°R}$, and $c_v = 0.1715 \text{ Btu}/(\text{lb})(\text{°R})$.

2. Check the final quality (x), by assuming dry air has a specific weight of $0.07636 \text{ lb}/\text{ft}^3$ (from Ref. 1, p. 290).

3. Check the final quality (x), using the volume computed in Problem No. 1.

SolutionsProblem No. 1

From the steam tables:

$$u_{f1} = 538.4 \qquad v_{f1} = 0.0216$$

$$u_{g1} = 1109.4 \qquad v_{g1} = 0.4456$$

Estimate the vapor pressure (p_2) to be 30 psia and, using the steam tables, the air-water-vapor temperature (t_m) would be 250.33° F. Calculate the increase in air pressure, using Eq. (6b) as a first approximation:

$$p_{a2} = (14.7) \left(\frac{460 + 250.33}{460 + 60} \right) = 20.08 \text{ psia.}$$

Check the design pressure against the total pressure:

$$P_m \text{ (1st est.)} = 30 + 20.08 = 50.08 \text{ psia}$$

$$P_m \text{ (design)} = 35 + 14.7 = 49.7 \text{ psia.}$$

As the air volume increases after the incident, the actual pressure will be lower; therefore, the first estimate is close and it is advisable to continue the investigation. From the steam tables there is obtained:

$$u_{f2} = 218.73 \quad v_{f2} = 0.01701$$

$$u_{fg2} = 869.1 \quad v_{g2} = 13.746$$

Use Eq. (15) as a first approximation for quality:

$$x = \frac{(1 - 0.32)(538.4) + (0.32)(1109.4) - 218.73}{869.1 + \left[\frac{(20.08)(85.71)}{(30)(53.34)} \right] (0.1715)(710.33 - 520)} = 0.55561$$

Use Eqs. (16), (18), and (6a) to estimate the volume and new pressure:

$$V_a = 100 [(1 - 0.55561)(0.01701) + (0.55561)(13.746) - (1 - 0.32)(0.0216) - (0.32)(0.4456)] = 748.77 \text{ ft}^3$$

$$V_m = (100)(0.55561)(13.746) = 763.74 \text{ ft}^3$$

$$p_{a2} \text{ (1st est.)} = (14.7) \left[\frac{(710.33)(748.77)}{(520)(763.74)} \right] = 19.69 \text{ psia}$$

Iterate:

$$x = \frac{(1 - 0.32)(538.4) + (0.32)(1109.4) - 218.73}{869.1 + \left[\frac{(19.69)(85.71)}{(30)(53.34)} \right] (0.1715)(710.33 - 520)} = 0.55603$$

$$V_a = (100) [(1 - 0.55603)(0.01701) + (0.55603)(13.746) - (1 - 0.32)(0.0216) - (0.32)(0.4456)] = 749.35 \text{ ft}^3$$

$$V_m = (100)(0.55603)(13.746) = 764.32 \text{ ft}^3$$

$$p_{a2} \text{ (2nd est.)} = (14.7) \left[\frac{(710.33)(749.35)}{(520)(764.32)} \right] = 19.69 \text{ psia}$$

As p_{a2} (1st est.) and p_{a2} (2nd est.) are in accord, make a final check for agreement between design and calculated total pressure:

$$p_m \text{ (design)} = 49.7 \text{ psia}$$

$$p_m \text{ (calculated)} = 30 + 19.69 = 49.7 \text{ psia}$$

Problem No. 2

Given $p_2 = 30$ and $\gamma_a = 0.07636$, use Eq. (25) to check the quality (x) of Problem No. 1:

$$x = \frac{(1-0.32)(538.4) + (0.32)(1109.4) - 218.73 - (0.1715)(0.07636)(0.01701)(710.33 - 520) + (0.1715)(0.07636)[(1-0.32)(0.0216) + (0.32)(0.4456)](710.33 - 520)}{869.1 + (0.1715)(0.07636)(13.746 - 0.01701)(710.33 - 520)}$$

$$= 0.55655$$

Problem No. 3

Given $V_a = 749.35$ (from Problem No. 1) and $p_2 = 30$, use Eq. (30) to check the quality (x) of Problem No. 1:

$$x = \frac{(1-0.32)(538.4) + (0.32)(1109.4) - 218.73 - (1/100)(749.35)(0.07636)(0.1715)(710.33 - 520)}{(869.1)}$$

$$= 0.55656$$

Example No. 2

Problem

Calculate the required volume, quality, and pressure if, instead of dry air, the initial condition in the shell is saturated air at 60° F and the other states are the same as in Example No. 1.

Data

Weight of saturated vapor	= 0.0008278 lb/ft ³ (Ref. 1, p. 290)
Pressure of saturated vapor	= 0.2561 psi. (Ref. 1, p. 290)
Pressure of dry air	= 14.700 - 0.256 = 14.444 psi
Specific enthalpy of vapor	= 1086.2 Btu/lb (Ref. 1, p. 290)
Specific volume of vapor	= 1/0.0008278 = 1208 ft ³ /lb
Specific internal energy of vapor	= 1086.2 - (144)(0.2561)(1208)/(778)
	= 1028.9 Btu/lb

Solutions

Use computed volume and pressure of Example No. 1 for initial approximations:

$$w_{va} \text{ (1st est.)} = (749.35)(0.0008278) = 0.6203 \text{ lb.}$$

From Eq. (11):

$$x \text{ (1st est.)} = \frac{[\{(68)(538.4) + (32)(1109.4) + (0.6203)(1028.9)\} / (100 + 0.6203)] - 218.73}{869.1 + \left[\frac{(19.69)(85.71)}{(30)(53.34)} \right] (0.1715)(710.33 - 520)} = 0.55813$$

From Eq. (13):

$$V_a \text{ (1st est.)} = (100.6203) [(0.01701)(1 - 0.55813) + (0.55813)(13.746)] \\ - (100) [(0.68)(0.0216) + (0.32)(0.4456)] = 756.99 \text{ ft}^3$$

From Eq. (14):

$$V_m \text{ (1st est.)} = (100.6203)(0.55813)(13.746) = 771.96 \text{ ft}^3$$

From Eq. (6a):

$$p_{a2} \text{ (1st est.)} = (14.444) \left[\frac{(710.33)(756.99)}{(520)(771.96)} \right] = 19.348 \text{ psia}$$

Iterate:

Estimate weight of vapor:

$$w_{va} \text{ (2nd est.)} = (756.99)(0.0008278) = 0.6266 \text{ lb}$$

$$x \text{ (2nd est.)} = \frac{[\{(68)(538.4) + (32)(1109.4) + (0.6266)(1028.9)\} / (100 + 0.6266)] - 218.73}{869.1 + \left[\frac{(19.348)(85.71)}{(30)(53.34)} \right] (0.1715)(710.33 - 520)} \\ = 0.55853$$

$$V_a \text{ (2nd est.)} = (100.6266) [(0.1701)(1 - 0.55853) + (0.55853)(13.746)] \\ - (100) [(0.68)(0.0216) + (0.32)(0.4456)] = 757.59 \text{ ft}^3$$

$$V_m \text{ (2nd est.)} = (100.6266)(0.55853)(13.746) = 772.57 \text{ ft}^3$$

$$p_{a2} \text{ (2nd est.)} = 14.444 \left[\frac{(710.33)(757.59)}{(520)(772.57)} \right] = 19.348 \text{ psia}$$

As the total pressure is shy of the design pressure, the final pressure of the liquid-vapor must be increased. Estimate the final pressure to be 30.3 psia. From the steam tables obtain by linear interpolation:

$$uf_2 = 219.30$$

$$v_{g2} = 13.621$$

$$uf_{g2} = 868.7$$

$$t_m = 250.90^\circ \text{ F}$$

$$vf_2 = 0.01701$$

Then:

$$x \text{ (3rd est.)} = \frac{[(68)(538.4) + (32)(1109.4) + (0.6266)(1028.9)] / (100 + 0.6266) - 219.30}{868.7 + \left[\frac{(19.348)(85.71)}{(30.3)(53.34)} \right] (0.1715)(710.90 - 520)} = 0.55829$$

$$V_a \text{ (3rd est.)} = (100.6266) [(1 - 0.55829)(0.01701) + (0.55829)(13.621)] \\ - (100) [(0.68)(0.0216) + (0.32)(0.4456)] = 750.24 \text{ ft}^3$$

$$V_m \text{ (3rd est.)} = (100.6266)(0.55829)(13.621) = 765.21 \text{ ft}^3$$

$$p_{a2} \text{ (3rd est.)} = (14.444) \left[\frac{(710.90)(750.24)}{(520)(765.21)} \right] = 19.360 \text{ psia}$$

Estimate weight of vapor:

$$w_{va} = (750.24)(0.0008278) = 0.6210$$

Then:

$$x \text{ (4th est.)} = \frac{[(68)(538.4) + (32)(1109.4) + (0.6210)(1028.9)] / (100 + 0.6210) - 219.30}{868.7 + \left[\frac{(19.360)(85.71)}{(30.3)(53.34)} \right] (0.1715)(710.90 - 520)} = 0.55826$$

$$V_a \text{ (4th est.)} = (100.6210) [(1 - 0.55826)(0.01701) + (0.55826)(13.621)] \\ - (100) [(0.68)(0.0216) + (0.32)(0.4456)] = 750.15 \text{ ft}^3$$

$$V_m \text{ (4th est.)} = (100.6210)(0.55826)(13.621) = 765.13 \text{ ft}^3$$

$$p_{a2} \text{ (4th est.)} = (14.444) \left[\frac{(710.90)(750.15)}{(520)(765.13)} \right] = 19.360 \text{ psia}$$

Example No. 3

It is postulated that a superheater in a reactor plant will rupture if the steam reaches a pressure of 1000 psia and temperature of 800° F. To limit the steam expansion in the event of a malfunction, the reactor plant is enclosed in a containment shell designed for 35 psig. The medium in the containment shell is dry air at 14.7 psia and 60° F.

Problems

1. Calculate the partial pressures of the air and steam, the mixture temperature, and the volume of the container for the expansion of 1 lb of steam. Use $c_v = 0.1715 \text{ Btu}/(\text{lb})(^\circ\text{R})$, $R_v = 85.71 \text{ ft}/^\circ\text{R}$, $R_a = 53.34 \text{ ft}/^\circ\text{R}$.
2. Check results of Problem No. 1 by assuming dry air has a specific weight of $0.07636 \text{ lb}/\text{ft}$ (Ref. 1, p. 288).
3. Check results using the volume computed in Problem No. 1

Solutions

Problem 1:

From the steam tables obtain $v_1 = 0.6878$, $h_1 = 1389.2$, and by computation:

$$\begin{aligned} u_1 &= h_1 - \frac{P_1 v_1}{J} \\ &= 1389.2 - \frac{(1000)(144)(0.6878)}{778} \\ &= 1261.9 \end{aligned}$$

Iterate:

Estimate the steam pressure at 24 psia and the mixture temperature at 440°F .

Then:

$$\begin{aligned} v_2 &= 22.18 \text{ ft}^3/\text{lb} \\ h_2 &= 1257.7 \text{ Btu}/\text{lb} \\ u_2 &= 1257.7 - \frac{(24)(144)(22.18)}{778} = 1159.2 \text{ Btu}/\text{lb} \end{aligned}$$

From Eqs. (42) and (43):

$$\begin{aligned} V_m \text{ (1st est.)} &= (1)(22.18) = 22.18 \text{ ft}^3 \\ V_a &= (1)(22.18 - 0.6878) = 21.49 \text{ ft}^3 \end{aligned}$$

From Eq. (6a):

$$p_{a2} \text{ (1st est.)} = (14.7) \left[\frac{(900)(21.49)}{(520)(22.18)} \right] = 24.65 \text{ psia}$$

Use Eq. (41) to check the heat balance:

$$1261.9 = 1159.2 + (0.1715) \left[\frac{(85.71)(24.65)}{(53.34)(24.00)} \right] (900-520) = 1266.8$$

Continue to iterate:

Estimate the steam pressure at 25 psia, and the mixture temperature at 440° F.

Then:

$$v_2 = 21.29 \text{ ft}^3/\text{lb}$$

$$h_2 = 1257.6 \text{ Btu/lb}$$

$$u_2 = 1257.6 - \frac{(25)(144)(21.29)}{778} = 1159.1 \text{ Btu/lb}$$

and

$$V_m \text{ (2nd est.)} = 21.29 \text{ ft}^3$$

$$V_a \text{ (2nd est.)} = (1)(21.29 - 0.6878) = 20.60 \text{ ft}^3$$

$$p_{a2} = (14.7) \left[\frac{(900)(20.60)}{(520)(21.29)} \right] = 24.62 \text{ psia}$$

$$p_m = 25 + 24.62 = 49.62 \text{ psia}$$

$$\begin{aligned} 1261.9 &= 1159.1 + (0.1715) \left[\frac{(85.71)(24.62)}{(53.34)(25)} \right] (900-520) \\ &= 1262.2 \end{aligned}$$

If greater accuracy is necessary, the iteration is continued.

Problem No. 2

Use Eq. (46) to check the results of Problem No. 1. Assume dry air has a specific weight of 0.07636 lb/ft.

$$1261.9 - (0.07636)(0.6878)(0.1715)(520) = 1159.1 + (0.07636)(0.1715)[(21.29)(900-520) - (0.6878)(900)]$$

$$1257.2 = 1256.9$$

Problem No. 3

Use Eq. (48) and the computed volume to check the results of Problem No. 1.

$$1261.9 + (0.07636)(20.60)(0.1715)(520) = 1159.1 + (0.07636)(20.60)(0.1715)(900)$$

$$1402.2 = 1401.9$$

Example No. 4Problem

Compare the volume requirements per pound of coolant for a containment shell with dry air, and with saturated air initially at 14.7 psia and 100° F. The coolant in the reactor pressure vessel is assumed to be 1000 psia (saturated). The design pressure for the containment shell is 25.46 psig; mediums stagnant.

Solutions

From the steam tables obtain:

$$\begin{aligned} u_{f1} &= 538.4 \text{ Btu/lb} & t_1 &= 544.61^\circ \text{ F} \\ v_{f1} &= 0.0216 \text{ ft}^3/\text{lb} \end{aligned}$$

Dry Air

Estimate the vapor pressure (p_2) at 22 psia. The air-water-vapor temperature (t_m) from the steam tables is 233.07° F.

Use Eq. (6b) to calculate the increase in air pressure:

$$p_{a2} = (14.7) \left(\frac{460 + 233.07}{460 + 100} \right) = 18.193 \text{ psia}$$

Check the total partial pressures against the design pressure.

$$p_m \text{ (design)} = 14.7 + 25.46 = 40.16 \text{ psia}$$

$$p_m \text{ (1st est.)} = 18.19 + 22 = 40.19 \text{ psia}$$

The actual pressure will be lower because of the increase in air volume; therefore the estimate is close.

From the steam tables obtain:

$$u_{f2} = 201.26 \quad v_{f2} = 0.01687$$

$$u_{fg2} = 882.0 \quad v_{g2} = 18.375$$

From Eq. (19):

$$x \text{ (1st est.)} = \frac{538.4 - 201.26}{882 + \left[\frac{(18.193)(85.71)}{(22)(53.34)} \right] (0.1715)(693.07 - 560)} = 0.36954$$

From Eq. (22):

$$V_m \text{ (1st est.)} = (0.36954)(18.375) = 6.7903 \text{ ft}^3$$

From Eq. (20)

$$V_a \text{ (1st est.)} = (1 - 0.36954)(0.01687) + (0.36954)(18.375) - 0.0216 = 6.7793 \text{ ft}^3$$

From Eq. (6a):

$$p_{a2} \text{ (1st est.)} = (14.7) \left[\frac{(693.07)(6.7793)}{(560)(6.7903)} \right] = 18.164 \text{ psia}$$

Iterate:

$$x \text{ (2nd est.)} = \frac{538.4 - 201.26}{882 + \left[\frac{(18.164)(85.71)}{(22)(53.34)} \right] (0.1715)(693.07 - 560)} = 0.36956$$

$$V_m \text{ (2nd est.)} = (0.36956)(18.375) = 6.7907 \text{ ft}^3$$

$$V_a \text{ (2nd est.)} = (1 - 0.36956)(0.01687) + (0.36956)(18.375) - 0.0216 = 6.7797 \text{ ft}^3$$

$$p_{a2} \text{ (2nd est.)} = (14.7) \left[\frac{(693.07)(6.7797)}{(560)(6.7907)} \right] = 18.164 \text{ psia}$$

As p_{a2} (1st est.) and p_{a2} (2nd est.) are in agreement, make a final check on the design and calculated total partial pressures.

$$p_m \text{ (design)} = 40.16 \text{ psia}$$

$$p_m \text{ (calc.)} = 18.16 + 22 = 40.16 \text{ psia}$$

Saturated Air

From Reference 1, page 290, and by calculation:

$$\begin{aligned}
 \text{Weight of saturated vapor} &= 0.002851 \text{ lb/ft} \\
 \text{Specific volume of vapor} &= (1/0.002851) = 350.8 \text{ ft}^3 \text{ per lb.} \\
 \text{Pressure of saturated vapor} &= 0.9487 \text{ psi} \\
 \text{Pressure of dry air } (14.7 - 0.949) &= 13.751 \text{ psi} \\
 \text{Specific enthalpy of vapor} &= 1104.2 \text{ Btu/lb} \\
 \text{Specific internal energy of vapor} &= 1104.2 - \left[\frac{(144)(0.9487)(350.8)}{778} \right] \\
 &= 1042.6 \text{ Btu/lb}
 \end{aligned}$$

Estimate the post-incident pressure of the liquid-vapor at 23 psia since the partial pressure of dry air for the mixture is ~1 psi below the pressure which would exist if only dry air were present before the incident. From the steam tables obtain:

$$\begin{aligned}
 u_{f2} &= 203.71 & v_{g2} &= 17.627 \\
 u_{fg2} &= 880.2 & t_m &= 235.49^\circ \text{ F} \\
 v_{f2} &= 0.01689
 \end{aligned}$$

Use the computed volume for dry air to estimate the weight of the vapor:

$$w_{va} \text{ (1st est.)} = (6.7797)(0.002851) = 0.019329 \text{ lb}$$

and the air pressure:

$$p_{a2} \text{ (1st est.)} = (13.751) \left[\frac{(695.49)(6.7797)}{(560)(6.7907)} \right] = 17.050 \text{ psia}$$

From Eq. (11), neglecting the kinetic energy:

$$x \text{ (1st est.)} = \frac{[\{ 538.4 + (0.01933)(1042.6) \} / 1.01933] - 203.71}{880.2 + \left[\frac{(17.050)(85.71)}{(23)(53.34)} \right] (0.1715)(695.49 - 560)} = 0.37918$$

From Eq. (14):

$$V_m \text{ (1st est.)} = (1.01933)(0.37918)(17.627) = 6.8130 \text{ ft}^3$$

From Eq. (13):

$$\begin{aligned}
 V_a \text{ (1st est.)} &= (1.01933) [(1 - 0.37918)(0.01689) + (0.37918)(17.627)] - 0.0216 \\
 &= 6.8021 \text{ ft}^3
 \end{aligned}$$

From Eq. (6a):

$$p_{a2} \text{ (2nd est.)} = (13.751) \left[\frac{(695.49)(6.8021)}{(560)(6.8130)} \right] = 17.051 \text{ psia}$$

The calculated total pressure is less than the containment design pressure:

$$p_m = 17.05 + 23 = 40.05 \text{ psia}$$

therefore, estimate the liquid-vapor pressure at 23.1 psia, and by linear interpolation obtain:

$$\begin{aligned} u_{f2} &= 203.95 & v_{g2} &= 17.558 \\ u_{fg2} &= 880.0 & t_m &= 235.72 \\ v_{f2} &= 0.01689 \end{aligned}$$

Use the computed values to estimate the weight of the vapor, and the air pressure:

$$w_{va} \text{ (2nd est.)} = (6.8021)(0.002851) = 0.01939 \text{ lb}$$

$$p_{a2} \text{ (3rd est.)} = (13.751) \left[\frac{(695.72)(6.8021)}{(560)(6.8130)} \right] = 17.056 \text{ psia}$$

Then:

$$x \text{ (2nd est.)} = \frac{[\{ 538.4 + (0.01939)(1042.6) \} / 1.01939] - 203.95}{880 + \left[\frac{(17.056)(85.71)}{(23.1)(53.34)} \right] (0.1715)(695.72 - 560)} = 0.37906$$

$$V_m \text{ (2nd est.)} = (1.01939)(0.37906)(17.558) = 6.7846 \text{ ft}^3$$

$$\begin{aligned} V_a \text{ (2nd est.)} &= (1.01939) [(1 - 0.37906)(0.01689) + (0.37906)(17.558)] - 0.0216 \\ &= 6.7737 \text{ ft}^3 \end{aligned}$$

and

$$p_{a2} \text{ (4th est.)} = (13.751) \left[\frac{(695.72)(6.7737)}{(560)(6.7846)} \right] = 17.056 \text{ psia}$$

A comparison of the V_a values for dry air and for saturated air shows that the required volume is smaller for the saturated conditions.

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