Evaluation of Thermal Utilization of Dousing System in PHWR Nuclear Power Plant

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ABSTRACT

An effectiveness of thermal utilization of a dousing system in the 600 MW PHWR Nuclear Power Plant has been evaluated. The behavior and conditions of water droplet sprayed in a postulated accident conditions in containment configuration has been calculated. In this calculation, two pressure conditions with the consideration of obstruction area and containment wall effect has been established : one being the minimum containment pressure of 7 kPa(g) encountered for dousing shut off and the other being the containment design pressure 124 kPa(g). The results revealed that the effectiveness of the thermal utilization ranges from 93% to 97%. In the analysis on two cases without/with side wall effect in the containment building, the thermal utilization decreases with obstruction area from 89% to 85%, which satisfies the design criteria set for the containment pressure against the accident condition.

Keywords : Thermal Utilization, Dousing System, Side wall effect, Loss of Coolant Accident

1. Introduction

The 600 MW pressurized heavy water reactor (PHWR) design includes a containment system. An integral part of the system includes the dousing system. It is provided to limit the containment building peak pressure following a Loss of Coolant Accident (LOCA).

More specifically, a LOCA is characterized by a pressure build up within the containment building at a rate dependent on the severity of the accident. The energy released as steam is absorbed by the water spray, the function of dousing system, thus reducing the peak pressure in the containment building and the duration of the pressure excursion. A schematic of the dousing system is shown in

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Fig. 1. The overall design data relate to the dousing system are summarized in Table 1.

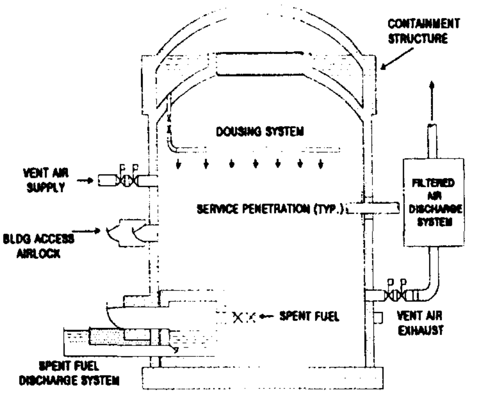

Fig. 1. Simplified Diagram of PHWR Containment Envelope

Dousing flow is automatically initiated when the containment pressure exceeds 14 kPa(g). Cooling water is then sprayed into the containment atmosphere, via a set of nozzles, to absorb heat and thus reduce the containment pressure. Dousing flow shuts off when the pressure falls to 7 kPa(g). The capacity of the cooling water absorbing the heat is a measure of the dousing system effectiveness and is reflected by its "thermal utilization".

The effectiveness of dousing systems is dependent on a number of parameters, some of which are related to droplet characteristics such as droplet size, shape, velocity and internal mixing; the remainder being associated with the containment conditions, i.e. turbulence, pressure, temperature and air/steam ratio. Most of these parameters are interdependent and are also functions of location in the containment building, and of time. Also, if there are many obstructions in the containment building, the obstructions located below the dousing spray header will negatively affect the thermal utilization of the sprayed dousing water.

The purpose of this study is to establish the thermal utilization of the 600 MW PHWR dousing system droplets under postulated minimum and maximum containment pressures and to provide a detailed assessment of the impact of the various obstructions on the thermal utilization of the dousing system.

2. Definition of Thermal Utilization

Thermal utilization (θ) is the ratio of the actual heat absorbed by a droplet, falling through an atmosphere maintained at uniform temperature and pressure, to the maximum heat that could be absorbed under the specified conditions.

Mathematically, it is defined as

$$\theta = \frac{Q_{actual}}{Q_{\max imum}} \tag{1}$$

Since Q = $C_P \triangle T$, neglecting phase change, θ can be expressed as

$$\theta = \frac{T_f - T_{wi}}{T_M - T_{wi}} \tag{2}$$

where,

T_f is the final temperature of the droplet

T_{wi} is the initial temperature of the droplet, and

T_M is the maximum temperature that could attained, (i.e. that of the atmosphere within the containment).

The overall thermal utilization (θ_o) of the dousing water considering all the obstructions

Table 1. Design Data of Dousing System [1]

Containment Temperature (°C)	
Normal	27.7° to 40.5°C
Post Accident	Not greater than 125°C
Long Term	Not greater than 55°C
Containment Pressure (kPa(g))	
Normal	-0.62 kPa(g)
Post Accident	Not greater than 124 kPa(g)
Long Term	Subatmospheric
Dousing valve Operating Pressure (kPa(g))	
Open (Initiating)	14 kPa(g)
Close (Shut off)	7 kPa(g)
Dousing Water Storage Tank (m^3)	
Total water (dousing water)	2173 m^3 (1559 m^3)
Dousing Flowrate per Header (kg/s)	1134 kg/s
Number of Downcomers	6 downcomers
Number of Dousing Spray Nozzles	281 nozzles/distribution unit
Containment Building Horizontal Plane Section Area (m^2)	1350 m^2

is calculated in the following equation :

$$\theta_o = \frac{\sum \theta_L A_L}{A_C} \tag{3}$$

where,

θ_L : local thermal utilization of droplet in the free space above each obstruction

A_L : horizontal plane section area of the obstruction

A_C : containment building horizontal plane section area

3. Analysis Methodologies

The dousing system consists of six independent spray units. There are 281 spray nozzles in each distribution unit. These nozzles are either located on top of the distribution headers or connected to small pipes radiating perpendicularly from the distribution headers. A schematic of the dousing spray header system is shown in Fig. 2.

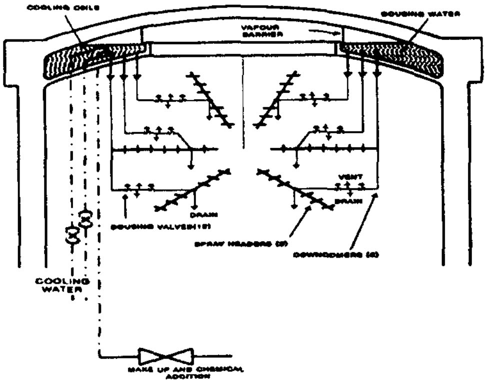

Fig. 2. PHWR Containment Dousing Spray Header System

The thermal utilization of dousing droplets is a function of two different sets of parameters. One set is defined by the nature of the LOCA, while the other depends on the design of the dousing system and of the containment building which is the same for all 600 MW PHWRs [2]. Two values of thermal utilization are estimated. One is based on the containment design pressure of 124 kPa(g), while the other is based on a minimum containment building pressure of 7 kPa(g) which is encountered during dousing.

The other evaluation of the thermal utilization is to consider the various obstructions in containment building.

4. Solution Basis

The results of the present study are based on the experimental and theoretical research investigations of E. Kulic [3]. In summary, he has simulated the heat transfer process within a droplet falling through a uniform temperature, pressure and air-steam mixture by using the following three models:

a) the "No Internal Resistance - Perfect Mixing" model,
b) the "Partial Internal Resistance - Partial Mixing" model, and
c) the "Internal Resistance and no Mixing" model.

Normally in convective heat transfer, the liquid side resistance in gas-liquid contacting is negligible. However, in combined heat and mass transfer, where the latent heat component is large, the gas side resistance may be lowered enough so that the liquid side resistance becomes significant.

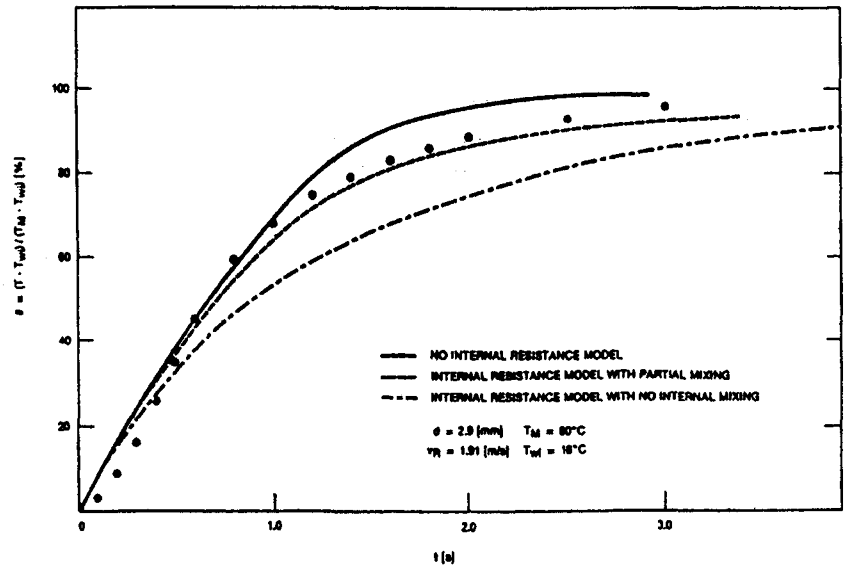

Fig. 3. Comparison of Experimental Results with Different Models

For the droplet temperature response with partial internal resistance and mixing, both sensible and latent heat transfer contributions combine to provide an apparent vapour phase heat transfer coefficient h_{app} defined as:

$$h_{app} = Q_T / (T_M - T_S) \tag{4}$$

which thus includes the effects of sensible and latent heat transfer component.

E. Kulic's. experimental results showed that the Partial Internal Resistance with Partial Mixing model can represent the experimental results best as shown in Fig. 3. In this analysis, however, the actual experimental data will be used to derive the thermal utilization for the two postulated conditions.

4.1 Theoretical Analysis of Pertinent Parameters

Under the assumption of constant containment conditions, the thermal utilization of a single droplet is affected primarily by the following parameters:

a) droplet size,
b) droplet velocity,
c) droplet exposure time in the containment atmosphere, and
d) the steam volumetric fraction (Xs) of the containment atmosphere.

4.2 Droplet Size, Velocity and Exposure Time

Fig. 4 shows the effect of the droplet size on its thermal utilization. There are a number of different ways to define the average droplet size of a particular spray. The Sauter Mean

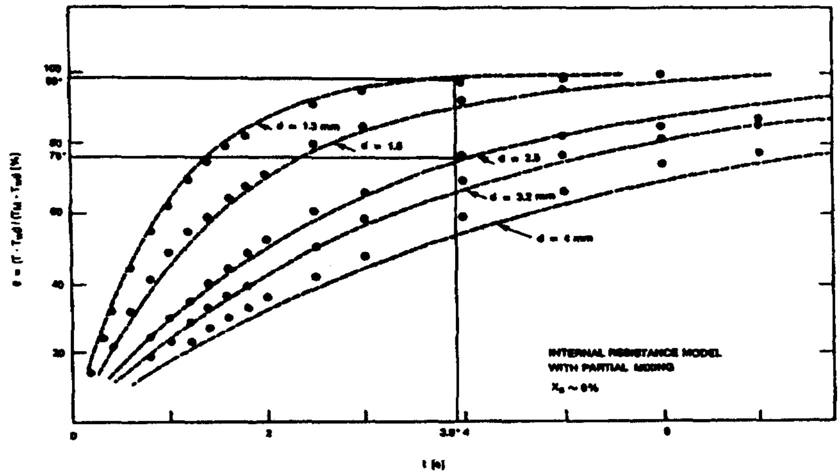

Fig. 4. Comparison of Experimental Results with Predictions Using Internal Resistance Model with Partial Mixing for Different Droplet Sizes at Steam Volumetric Fraction (Xs)~6%

Diameter is defined as the diameter for which a spherical droplet would have the same volume to surface area ratio as the entire spray. As the droplet size decrease, the thermal utilization curve increase drastically. The composite SMD of 1.1 ㎜ is representative of the entire droplet distribution.

The effect of droplet velocity is indicated in Fig. 5. Higher velocities tend to accelerate the temperature response of a particular size droplet under constant steam conditions. A typical dousing system droplet will undergo projectile motion and it will eventually reach its terminal velocity (V_T) which is a function of its size alone. This velocity is given by Best's equation [4] as:

$$V_T = 943\ [1-(\exp(-d/1.77)^{1.147}]\ \text{cm/s} \qquad (5)$$

where, the droplet diameter, d is in ㎜.

Upon substitution for the mean droplet diameter, equation (5) yields the terminal velocity (V_T) of 4.8 m/s.

As shown in Fig. 3, 4 and 5, the longer a droplet is exposed to the air-steam mixture the more heat it absorbs, as reflected by its higher thermal utilization.

In the 600 MW PHWR containment, the spray headers are located at an elevation of 40.2 m from the base of the containment building. With the exception of the boilers, most massive obstructions are located at levels below the 25 m level while there is enough empty space below the 25 m level to make up for the volume of the boilers. Thus, an estimated effective elevation of the header is 15 m [5]. A schematic is shown in Fig. 6.

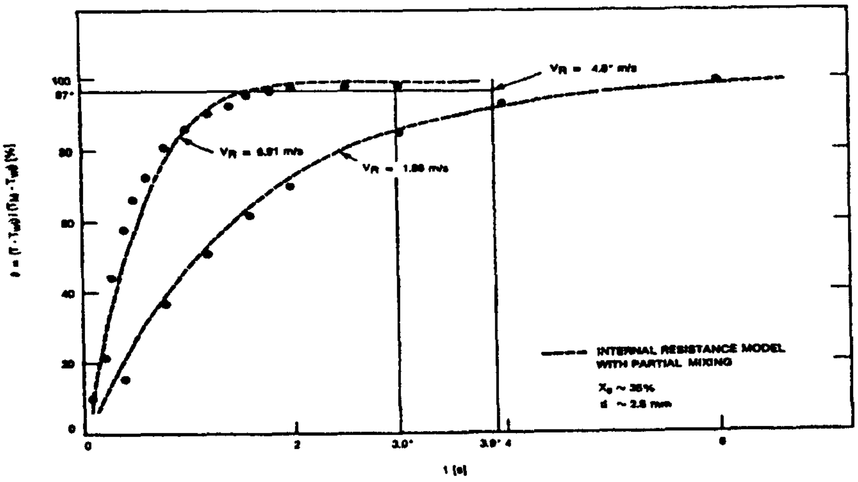

Fig. 5. Comparison of Experimental Results with Predictions Using Internal Resistance Model with Partial Mixing for Different Velocities of the Air/Steam Mixture and d ~2.8 mm and Steam Volumetric Fraction (Xs) ~ 35%

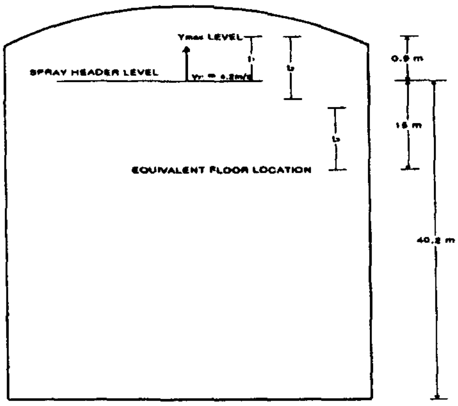

Fig. 6. **A Schematic Representation of the Effective Spray Header Elevation (Not to Scale)**

The nozzles are directed perpendicularly upwards. The mean velocity of the droplets in the vicinity of the nozzle is found to be 4.2 m/s.

The flight time of the droplet is the summation of the following times:

a) the time taken to reach a maximum height, t_1,

b) the time taken to reach its terminal velocity, t_2, and

c) the time taken to travel the remaining distance at its terminal velocity, t_3.

The total flight time is given by equation (6).

$$t = t_1 + t_2 + t_3 \qquad (6)$$

Then, the time taken to reach for each height are calculated from the following equation.

$$v_y^2 = v_{yi}^2 - 2gy \qquad (7)$$

On the assumption that the droplet undergoes projectile motion, the flight time of the 1.1 ㎜ diameter droplet has been calculated to be 3.9 s.

4.3 Steam Volumetric Fraction

The steam volumetric fraction X_s, in a mixture composed of dry air and saturated steam at a particular temperature and pressure, is defined as the volume ratio of the steam to that of the mixture.

Mathematically,

$$X_s = \frac{V_s}{V_M} \qquad (8)$$

Assuming that the steam is of 100% quality and neglecting the volume of the condensed water, the containment pressure P_M is the sum of the partial pressures of dry air and saturated steam. Mathematically,

$$P_M = P_A + P_S \qquad (9)$$

If we assume that the saturated steam approximates an ideal gas, the containment atmosphere can be treated as a mixture of two ideal gases. As such, its steam volumetric fraction is 0.47 which is given by equation (10).

$$X_s = \frac{P_S}{P_M} \qquad (10)$$

As shown if Fig. 7, the steam volumetric fraction, X_s, is a significant factor in thermal utilization calculations. Different accident conditions result in different steam fractions. Based on saturated conditions, at a maximum and a minimum containment pressure of 124 and 7 kPa(g), the corresponding steam volumetric fractions are found to be 47% and 3.4% respectively.

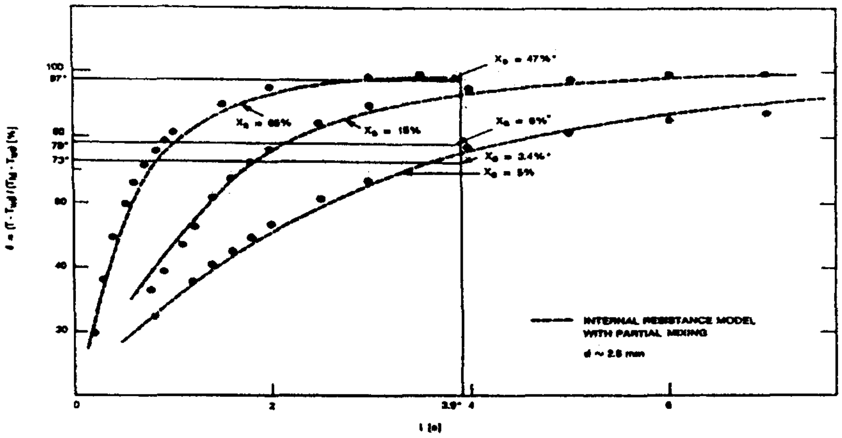

Fig. 7. Comparison of Experimental Results with Predictions using Internal Resistance Model with Partial Mixing for Different Steam Concentrations d ~ 2.5 mm

5. Results and Discussion

5.1 Effect of Velocity Variation on Thermal Utilization

Consider Fig. 5 for V_R = 6.91 m/s. As the relative velocity of the droplet increases, the thermal utilization curve remains relatively horizontal indicating no significant change in thermal utilization after 2 seconds of flight time. The relative or terminal velocity of 4.8 m/s considered in the present analysis is high enough to give a relatively fast response as shown in Fig. 5. Thus, whether the total flight time t = 3.9 s or the flight time t_3 = 3.0 s, during which the droplet travels at its terminal velocity, is used will have no appreciable effect.

5.2 Effect of Obstruction on Thermal Utilization

The local thermal utilization in the free space above a given obstruction can be estimated as the sum of the thermal utilizations for the varying velocity portion and the constant velocity portion of the water droplet on to the obstruction.

The calculation of the thermal utilization for the varying velocity portion is done by step by step integration. For each step period of 0.1 sec of the droplet flight, an average velocity in absolute value is calculated for the step period using equation (7).

The calculated local thermal utilization and overall thermal utilization with the obstructions by elevation in containment building was shown in Fig. 8 and Table 2.

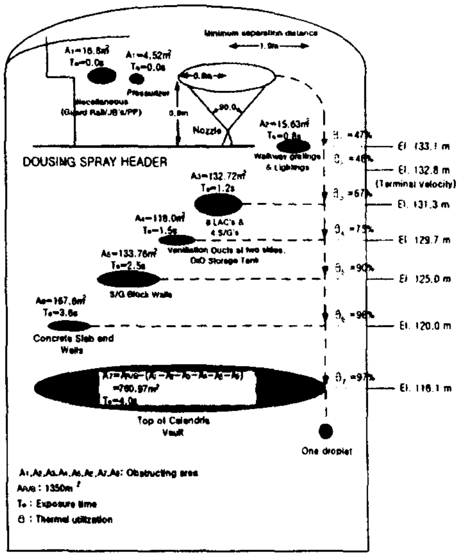

Fig. 8. Thermal Utilization, Obstructing Area and Exposure Time with Elevation

5.3 Estimate of the Vertical Side Walls Effect

The thermal utilization is calculated based on the assumption that the droplets fall in the vertical direction. If we assume that the droplet trajectory will be more like oblique because of some air movement in the containment building affecting the droplet trajectory, the obstructions of vertical side wall need to be taken into account. Although it is difficult to define the droplet trajectory taking into account the air movement, in the worst case scenario this change in trajectory may have the same effect as increasing the obstruction projected area, because now some vertical side walls will now contribute to the obstruction of the droplets fall.

In Table 3, thermal utilization is given with respect to side walls effects.

Table 2. Thermal Utilization based on The System Configuration

No	Obstruction Description	Elevation	Obstruction Area (A_i)	Droplet Flight Time (T_f) & Flight Distance (L_l)	Local Thermal Utilization (θ_L)	$\frac{\theta_L A_L}{A_C}$
1	Pressurizer Guard Rail/Junction Box	134.0 m	4.52 ㎡ 16.8 ㎡	T_f : 0.0 s L_f : 0.0 m	0.0 %	0.00 %
2	6 walkways in greatings (10%)	133.1 m	15.63 ㎡	T_f : 0.8 s L_f : 1.8 m	47 %	0.54 %
3	8 Local Air Coolers & 4 Steam Generators (S/G)	131.3 m	132.72 ㎡	T_f : 1.2 s L_f : 3.6 m	67 %	6.59 %
4	Ventilation Ducts D_2O Storage Tank	129.7 m	118.00 ㎡	T_f : 1.5 s L_f : 5.2 m	75 %	6.56 %
5	S/G Concrete Block Wall	125.0 m	133.76 ㎡	T_f : 2.5 s L_f : 9.9 m	90 %	8.92 %
6	Concrete Slabs	120.0 m	167.60 ㎡	T_f : 3.6 s L_f : 14.9 m	96 %	11.92 %
7	Calandria Vault	118.1 m	760.97 ㎡	T_f : 4.0 s L_f : 16.8 m	97 %	54.68 %
Total			1350 ㎡			89.21 %

Table 3. Side-wall Effect

Obstruction Area Increase due to Side Walls Effects	Total Thermal Utilization
0 %	89.21 %
10 %	88.64 %
20 %	88.07 %
30 %	87.50 %
40 %	86.93 %
50 %	86.36 %
60 %	85.78 %
70 %	85.21 %

Based on engineering judgement, the side wall effects should not affect the obstructions area by more than 10 %, as the bulk of the air/steam movement will be vertical and the D_2O jet from the LOCA break will not directly discharge to the free space above the top of the Calandria because of buoyancy effect among other things. From Table 3, the thermal utilization is still more than 85 % when the obstruction area is increased by an unrealistic value of 70 % due to side walls effects.

5.4 Consideration of Number of Nozzles Affected

If thermal utilization is calculated by considering the number of nozzles affected by the obstructions as opposed to the obstruction area, we find that the result is less conservative than that obtained in Table 2 by considering obstruction area.

When nozzles are only affected partially, an equivalent number of fully affected nozzles is calculated by dividing the assumed area of the affected nozzles by the average area density of nozzles, which is 0.8 ㎡/nozzle (=1350 ㎡/1686 nozzles).

5.5 Impact on Reactor Building Peak Pressure

The peak pressure after a LOCA depends on the rate of energy absorption by the dousing spray. The energy absorbed by the spray during a time step is calculated using the following equation :

$$E = WC_p\,\theta(T_n - T_i)\,\Delta t \qquad (11)$$

where,

Δt : the time step, s
C_p : the specific heat of water, J/kg ℃
W : the dousing flow rate, kg/s
T_n : the temperature of containment building atmosphere (steam-air mixture), ℃
T_i : the dousing water initial temperature, ℃
θ : the thermal utilization, and

E : the energy removed by dousing water from containment building atmosphere, kW

The rate of energy absorbed by the spray is affected directly by dousing flow rate and thermal utilization. The design value of dousing flow rate per header is 1134 kg/s. However, the input for peak pressure analysis is 1021 kg/s (90% of design flow rate). This large margin easily offsets a reduction of up to approximated 10 % in thermal utilization, from 95% to 85%. It should be noted that the thermal utilization of 85% was calculated from unrealistic high side walls effects.

6. Conclusion

The thermal utilization of the 600 MW PHWR containment has been estimated for two different conditions.

Under the assumption that the pressure of the containment is raised to its nominal design pressure of 124 kPa(g), a corresponding thermal utilization of 97% has been estimated. At a pressure of 7 kPa(g), it is estimated that the dousing system provides for a minimum of 93% thermal utilization. Thus, one can conclude that for accident conditions which cause pressures between 7 and 124 kPa(g), the thermal utilization will lie between 93% and 97%, increasing along with containment pressure.

Based on considering of the obstructions such as system configuration, side wall effect, nozzle interference and peak pressure in the reactor building, it is concluded that the current PHWR design for the Dousing System satisfies the system safety, functional and performance requirements. As described above, the current dousing system design provides enough margin for reducing containment peak pressure during a LOCA even with reduced thermal utilization from 95% to 85%.

Nomenclature

Symbols

C_P - specific heat at constant pressure
d - droplet diameter
E - energy
P - pressure
Q - heat
T - temperature
t - exposure time
V - volume
v - velocity
W - flowrate
X - volumetric fraction
Δ - difference of
θ - thermal utilization

Subscripts

A - air
D - droplet
C - containment building
e - exposure
f - final
i - initial
M - mixture
o - dry air - saturated steam equilibrium condition
R - relative
S - steam
T - terminal
v - vapour
w - water
y - y direction

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