METHOD FOR DETERMINING FILM FLOW COVERAGE

FOR THE

AP600 PASSIVE CONTAINMENT COOLING SYSTEM

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ABSTRACT

An analytical mod· has been developed to predict the stability behavior of a thin film of water flowing over heated and unheated surfaces. The surface consists of a steel shell in the shape of an elliptical dome, which extends down to form cylindrical walls. The surface of the shell is coated to resist corrosion and enhance the surface wettability. The model is compared to observed test data and is used to predict the wetting behavior of the AP600 passive containment cooling system (PCS).

Background

The AP600 PCS uses a thin film of wat·r that is applied to the outside of the containment shell. During postulated accident conditions, the film is heated by the shell as it flows radially outward from the top of the dome and then downward along the vertical sides of the shell. Heat is removed from the shell due to evaporation of the film. The effectiveness of the PCS is evaluated by the extent of water film coverage that can be achieved.

Several tests have been performed to demonstrate the operation of the AP600 PCS. These tests include water film heat transfer tests using scale models of the AP600 containment,[1,2,3] and non-heated water coverage tests using a full-scale, 1/8-section of the AP600 dome.[4] The results of these tests and analyses have indicated that:

- The evaporating water film is an effective means of removing heat following a postulated accident

- The AP600 PCS design provide· sufficient water film coverage to adequately remove heat for design basis accidents, l·miting the containment pressure and temperature below design limits

- The AP600 containment shell is coated with inorganic zinc paint, which is highly corrosion-resistant and has excellent wetting characteristics[5]

- Analyses of the AP600 containment have shown that the PCS design effectively removes heat, assuming conservatively bounding water coverage fractions.[6]

The purpose of this analysis is to develop a model that predicts the onset of flow instability in a flowing film, leading to a set of criteria that can be used to predict the ·raction of coverage for a combination of water flow rate and surface heat flux. This model will be compared to experimental results that include heated and unheated surfaces, and applied to the AP600 containment to assess the PCS water film stability and subsequent coverage.

Film Stability Model

To determine the water flow rate that will produce a stable film, a model is used that considers the momentum of the flowing film, the surface tension effects, the thermocapillary effects, and the potential energy. The model proposed by Zuber and Staub,[7] which is modified to include static pressure, is given by:

$$\frac{\rho}{15}\left[g\sin\beta\,\frac{\rho}{\mu}\right]^2\delta^4 + \rho\, g\cos\beta\,\frac{\delta}{2} = \frac{\sigma(1-\cos\theta)}{\delta} + \frac{d\sigma}{dT}\,\frac{q''}{k}\cos\theta \qquad (1)$$

where ρ is the liquid density
g is the gravitational constant
μ is the liquid viscosity
σ is the liquid surface tension
θ is the contact wetting angle between the liquid and the surface
β is the angle of inclination relative to horizontal
q'' is the surface heat flux
k is the liquid thermal conductivity
T is the liquid film temperature at which the properties are evaluated
and δ is the minimum film thickness for a stable film that is related to the minimum mass flow rate per unit perimeter, Γ_{min}, by:

$$\delta = \left[\frac{3\Gamma_{min}\mu}{g\rho^2}\right]^{1/3} \qquad (2)$$

These equations are polynomials in Γ_{min} and can be solved iteratively.

Each of the quantities in these equations are either fluid properties, such as the surface tension, viscosity, density, and thermal conductivity, or inputs specific to the application, such as the local heat flux. The only quantity that must be determined for a given problem is the contact wetting angle for the painted surface.

Determination of the Contact Wetting Angle for Coated Surface

To measure the contact wetting angle, two samples were prepared. The first is a paint sample supplied to Westinghouse by the coating vendor. This sample was painted by the vendor and was not subjected to weathering. The second sample is a 4 x 3 in.-section of a steel plate that was painted by Westinghouse and weathered for two years.

The following procedure was used to determine the contact wetting angle for both samples:

- The samples were cleaned and dried
- A drop of water was placed on the sample, which was held in a horizontal position
- An optical comparator, located at the Waltz Mill machine shop, was used to measure the angle between the sample surface and the drop at the interface
- Measurements were repeated using several drops to ensure repeatability in the results

Additional tests were conducted with the samples held at different temperatures to determine the effect of the surface temperature on the contact wetting angle. This was accomplished by heating the samples with hot water or a heat gun.

The results of the tests are summarized in Table 1. It should be noted that the low temperature data should be discounted due to condensation on the sample surface. Also, at high temperatures, the wetting angles started out higher than at lower temperatures. It was observed, however, that the drops quickly flattened out, reducing the angle.

It can be concluded from these tests that the contact wetting angle between the painted surface and water ranges from 20 to 28 degrees for weathered surfaces, and 30 to 53 degrees for unweathered surfaces. Since the AP600 containment should be well weathered prior to operation, the contact wetting angle should be taken as 20 to 28 degrees.

Table 1
SUMMARY OF TEST RESULTS TO DETERMINE CONTACT WETTING ANGLE

Description of Test		Contact Angle Weathered Sample	Contact Angle Unweathered Sample
1. Room Temperature, T=80°F		24°	30°
2. Heated, T=110°F		23°	33°
3. Heated, T=180°F	t=0 sec.	28°	53°
	t=15 sec.	23°	44°
	t=30 sec.	20°	35°
	t=60 sec.	20°	28°

Liquid Film Flow over an Elliptical Dome

The AP600 PCS operates by applying the water at the center of the elliptical dome. The water flows radially outward where it encounters weirs that collect the water and reapply it in an even film. A simplified model of the film that accounts for the change in flow area due to the dome geometry and the change in the liquid flow due to evaporation is useful to determine the average radial flow per unit perimeter, Γ.

The dome surface is approximated by an oblate spheroid. The surface area is given by:

$$A_{dome} = \pi a^2 + \frac{1}{2}\frac{\pi b^2}{\varepsilon}\ln\left[\frac{1+\varepsilon}{1-\varepsilon}\right] \tag{3}$$

where a is the major semiaxis
b is the minor semiaxis
and ε is the eccentricity of the revolving ellipse given by:

$$\varepsilon = \frac{\sqrt{a^2+b^2}}{a} \tag{4}$$

Given an initial mass flow rate of water onto the top of the dome, the flow at any subsequent radius is given by:

$$\dot{m}_i = \dot{m}_{i-1} - \frac{q''_i \Delta A_i}{h_{fg}} \tag{5}$$

where h_{fg} is the latent heat of vaporization
q''_i is the heat flux at the location
and ΔA_i is the differential area given by:

$$\Delta A_i = \pi(x_i + x_{i-1})\sqrt{(x_i - x_{i-1})^2 + (y_{i-1} - y_i)^2} \tag{6}$$

where:

$$x_i = r_i \cos\alpha \tag{7}$$

$$y_i = r_i \sin\alpha \tag{8}$$

$$r_i = \frac{ab}{\sqrt{a^2(\sin\alpha)^2 + b^2(\cos\alpha)^2}} \tag{9}$$

where α is the angle between the vector normal to the surface and horizontal.

This approach results in a conic approximation to the elliptical surface. Using angular increments of 6 degrees, the error is less than 1 percent.

Finally, the mass flow per unit perimeter is given by:

$$\Gamma_i = \frac{\dot{m}_i}{2\pi r_i} \tag{10}$$

Thus, for an initial mass flow rate, the mass flow per unit perimeter can be calculated at each radius along the dome for a given heat flux distribution.

A useful quantity is the ratio of the mass flow per unit perimeter to the minimum stable value as calculated in Equation 2.

$$R = \frac{\Gamma}{\Gamma_{min}} \tag{11}$$

As discussed in Reference 7, the film is expected to split, causing a dry patch to form when this ratio is less than unity. However, this work was done for a smooth, vertical surface, and it is expected that this ratio or stability margin should be somewhat greater than unity to account for surface inconsistencies and/or flow maldistributions under non-laboratory conditions.

After splitting, it is proposed that the coverage of the film can be reduced by an amount equal to the ratio, R; that is, the film contracts to the stability limit based on uniform thickness. Thus, the fraction of the surface area covered by the water film, ϕ, is given by:

$$\phi_{i+1} = \frac{\phi_i R_i}{R_{ref}} \tag{12}$$

where R_i is the local value of the stability margin

ϕ_i is the local value of the film coverage fraction

ϕ_{i+1} is the value of the film coverage fraction at the next point down the wall

and R_{ref} is the reference value of the stability margin that is used to determine the onset of instability and accounts for the surface inconsistencies and/or flow maldistribution

The value of ϕ is defined as unity before the onset of instability. As the film thins due to geometric spreading or evaporation, the value of R can approach R_{ref}. At this point, the flow is assumed to split, and the coverage fraction, ϕ is reduced according to Equation 12. As the film splits, the water redistributes, increasing flow uniformly in the remaining wet areas. These areas remain stable until the flow thins, causing additional splitting. In this way, coverage fractions for unstable flows will decrease asymptotically until the film reaches the bottom of the surface.

This model can be correlated to water coverage fractions observed in the heated and unheated AP600 PCS tests. Specifically, the model will be applied to determine the value of R_{ref} that best predicts the observed coverage fractions from these tests. This correlation will then be used to estimate the coverage fractions for the AP600 containment under postulated accident conditions.

Analysis Method for Predicting Film Flow and Stability

A computer program was written to solve the equations for film flow over a dome, to determine the minimum flow per unit perimeter to ensure the stability of the film, and to determine the coverage fraction should the film become unstable. The program considers a typical containment geometry, including a dome section and a cylindrical wall section. Given the surface geometry, initial conditions, heat flux distribution, contact wetting angle, and water flow rate, Equations 1 through 12 are solved to determine the value of Γ, Γ_{min}, R, and ϕ at each radial position down the dome. If R is greater than R_{ref}, the average flow per unit perimeter exceeds the minimum value, and the flow is expected to be stable. If R is less than R_{ref}, the average flow per unit perimeter is less than the minimum value, causing the flow to split and the coverage fraction to be reduced accordingly.

Variations in the surface of the shell will cause local flow distributions that vary around the circumference. These local variations cannot be predicted using these simple models, but the observed coverage can be predicted using the local stability model and comparing it to various tests. The model can then be used with confidence to estimate the coverage for the AP600 PCS under postulated accident conditions.

Existing data from both heated and unheated tests will be evaluated using the local stability model. The heated tests include the AP600 large-scale containment tests, which include a scale model of the dome; while the unheated tests include the AP600 water distribution tests, which utilize a full-scale, 1/8-sector of the AP600 dome. Key parameters from these tests are summarized in Table 2.

The large-scale baseline tests[3] utilized a series of nozzles to apply the film in a ring near the top of the dome. It is likely that local variations in the film flow around the circumference were significant. Observations of the tests showed that for the high heat flux/low flow tests, dry stripes were found to occur, indicating film-stability-based coverage fractions.

The unheated water distribution tests were run with a wide range of water flow rates. The film was found to remain intact at moderate to high flow rates, and steady dry stripes formed at lower flow rates. These tests included maximum weld and surface deviations, thus, providing base cold coverage fractions, accounting for full-scale geometry effects.

The stability model was used to predict the results of thirteen large-scale tests. Three different values of the reference value of the stability margin, R_{ref}, were used, and the results are shown in Figure 1. The reference value of the stability margin that best predicts the data was found to be:

[ ]$^{(a,c)}$ (13)

In all, the stability model was applied to the large-scale tests and four water distribution tests. These results are summarized in Table 3, and are shown graphically in Figure 2. As shown in Figure 2, the unheated AP600 water distribution tests are predicted by the model that was developed using the heated large-scale test data.

It is also expected that this model, which relies on local film stability, is applicable to any size structure with similar geometric shape, such as the prototypical AP600 containment.

Table 2
KEY PARAMETERS—AP600 LARGE-SCALE AND WATER DISTRIBUTION TESTS

a,c

Parameter		Large-Scale Tests[3]	AP600 Water Distribution[4]
Dome Major Axis (a)			
Dome Minor Axis (b)			
Vertical Wall Beneath Dome			
Water Flow Rate			
Initial Water Temperature			
Contact Wetting Angle			
Peak Heat Flux			
Heat Flux Distribution	β=0° (Top)		
(See Note B)	β=24°		
	β=48°		
	β=72°		
	β=90°		
	Vertical		

-A: Note that the AP600 water distribution tests modeled the dome and 20-ft. section of vertical wall. The actual AP600 containment has a vertical wall section that is 83 ft. high.

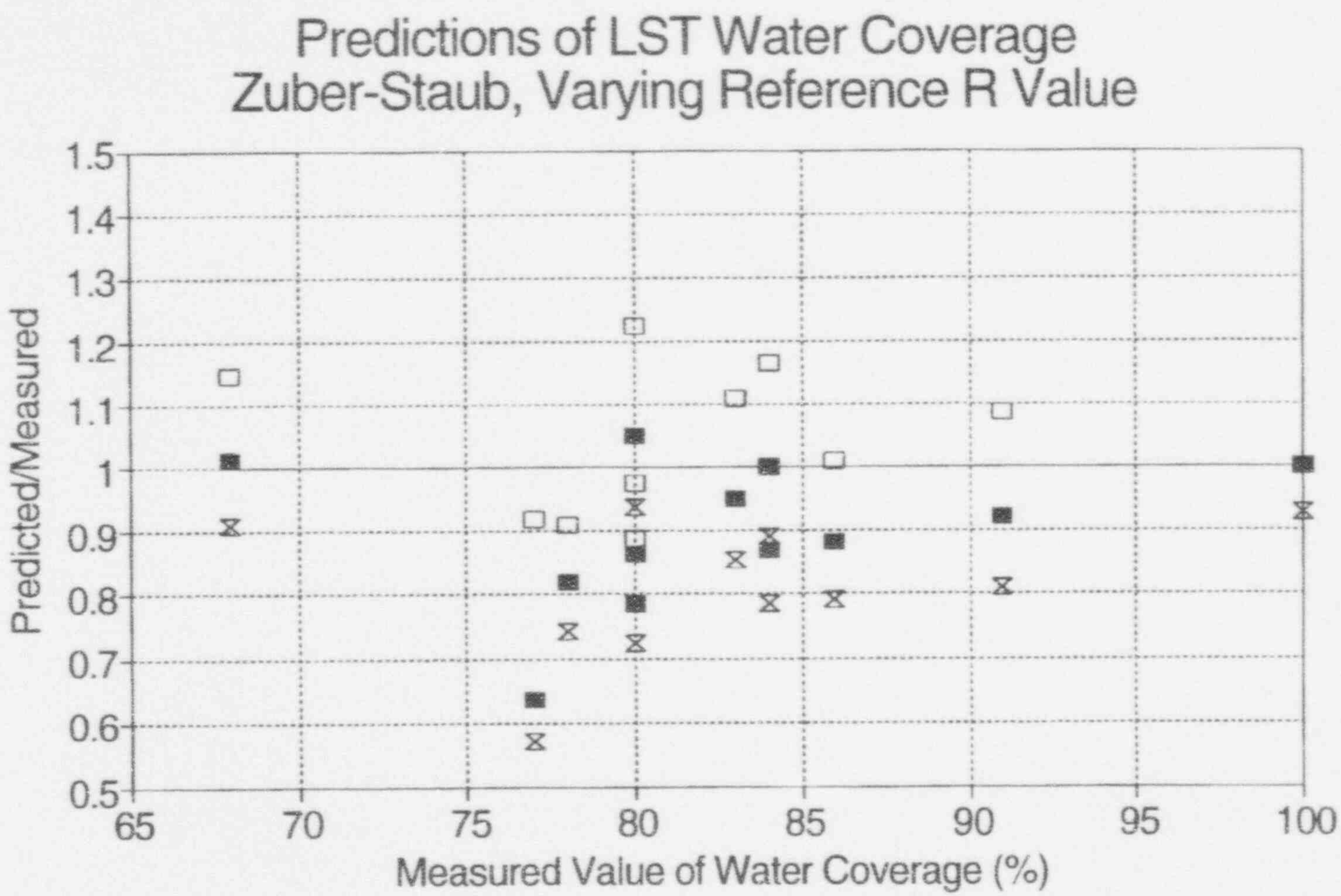
-B: Note that the heat flux profile is due to subcooled water added at the top of the dome.

Table 3
ANALYTICAL PREDICTIONS OF AP600 PCS TEST RESULTS

Test	Description	Predicted Coverage	Measured Coverage
Large-Scale Tests (Heated)			
R9L	Pressure = 10 psig		
R10L	Pressure = 30 psig		
R8L	Pressure = 43 psig		
R17AL	Pressure = 10 psig		
R34L	Pressure = 31 psig		
R27L	Pressure = 40 psig		
R24L	Pressure = 30 psig		
R23L	Pressure = 30 psig		
R26L	Pressure = 30 psig		
R21L	Pressure = 31 psig		
R22L	Pressure = 31 psig		
R28AL	Pressure = 40 psig		
R28L	Pressure = 40 psig		
AP600 Water Distribution Tests (Unheated)			
WDT14	Flow = 55 GPM		
WDT10	Flow = 100 GPM		
WDT9	Flow = 220 GPM		
WDT11	Flow = 280 GPM		

(a,c)

(a,c)


Predictions of LST Water Coverage
Zuber-Staub, Varying Reference R Value
Predicted/Measured
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
65
70
75
80
85
90
95
100
Measured Value of Water Coverage (%)

[ ]$^{(a,c)}$

Figure 1

(a,c)

Figure 2

Prediction of Water Coverage for the AP600 Under Postulated Accident Conditions

The film stability model developed from the AP600 containment tests was used to predict the coverage of the AP600 containment during a postulated accident. The AP600 passive containment cooling system (PCS) is initiated when the pressure inside the containment reaches a set value. At that time, water is applied at the top of the dome of the steel containment shell. The water flows radially outward and encounters a series of weirs, which distribute the flow over the majority of the dome and the vertical wall. The maximum water flow is reached early in the transient when the maximum energy due to the reactor cooling system blowdown is released inside containment. The water flow is reduced later in the transient as the reactor decay heat level decreases. The average wall heat flux, as calculated by the WGOTHIC containment analysis code, and the corresponding cooling water flow rates are shown in Figure 3.[8] The initial value of flow and heat flux is indicative of the blowdown phase of the transient, while subsequent times represent the reactor decay heat level. The WGOTHIC model that generated these heat flux values divides the water flow path into seven discrete areas; three on the dome and four on the vertical wall. The model assumes a water coverage fraction of 40 percent for the dome and 70 percent for the vertical wall.

The local stability model was used to analyze several flow/heat flux pairs from Figure 3. The results of these analyses are summarized in Table 4. These results indicate that the coverage fraction input into the WGOTHIC model should be higher in the dome region and lower in the vertical wall region.

Table 4
PREDICTION OF AP600 PCS WATER COVERAGE—DESIGN BASIS ACCIDENT

(a,c)

Time	Flow	q''	Dome (%)			Cylinder (%)				
Hr	lbm/s	Btu / s-ft²	Top	Mid	Bot	Top	Mid Top	Mid Bot	Bot	Exit
0.183	30.4	.990								
2.167	29.7	.728								
5.167	28.7	.473								
5.667	15.7	.473								
9.167	15.3	.393								
15.17	14.7	.331								
21.17	14.1	.301								
26.17	11.8	.288								

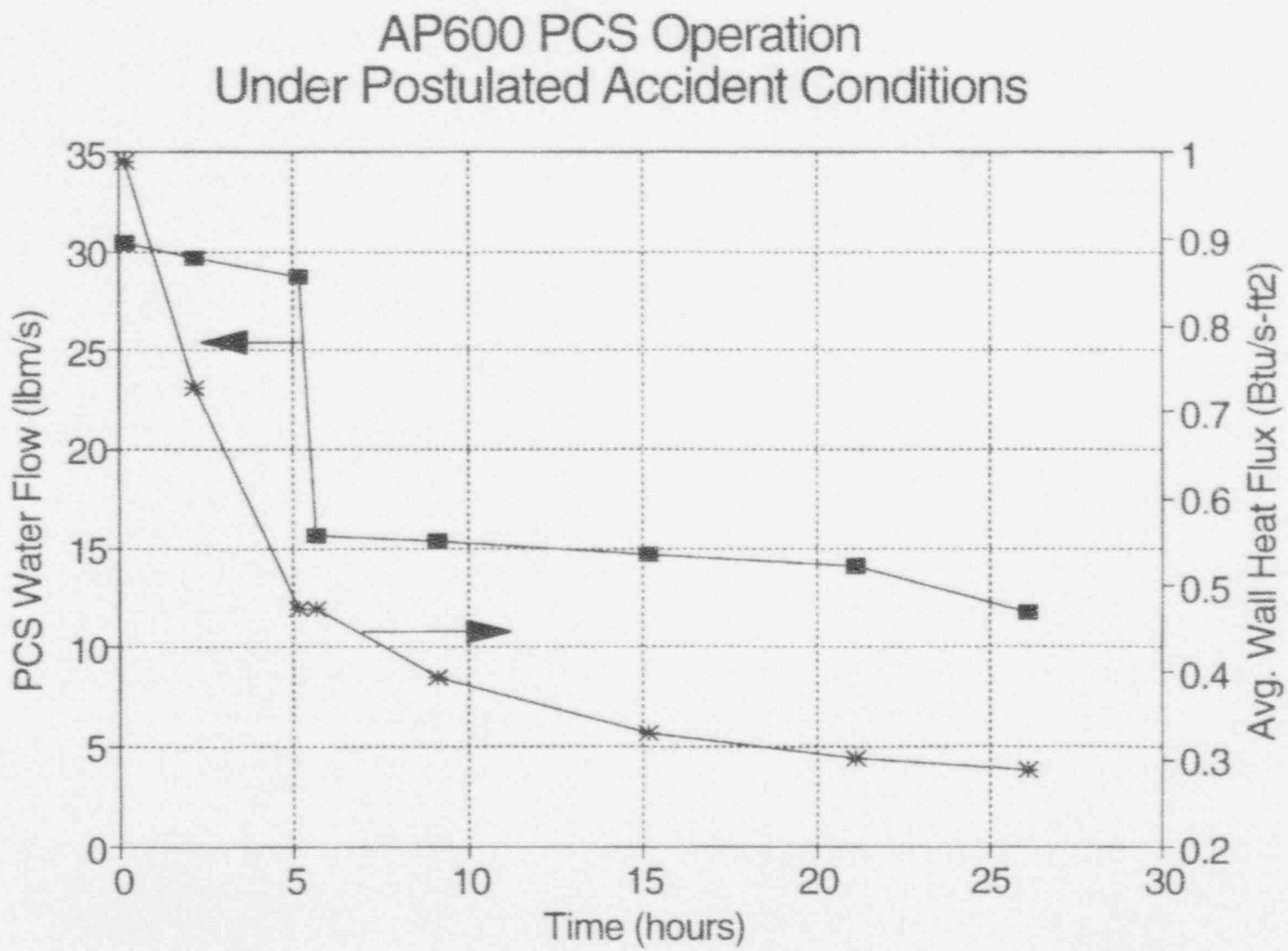

AP600 PCS Operation
Under Postulated Accident Conditions
PCS Water Flow (lbm/s)
Avg. Wall Heat Flux (Btu/s-ft2)
Time (hours)
0
5
10
15
20
25
30
35
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 3

CONCLUSIONS

The following conclusions can be drawn from this analysis:

- A set of criteria have been developed to determine the stability of water films on a coated surface for both heated and unheated conditions.

- In order to apply these criteria, the contact wetting angle between the water and the coated surface was experimentally measured. This angle was measured to be approximately 20 degrees for a wide range of surface temperatures.

- These criteria have been applied to several AP600 water flow tests to develop a method for calculating the film coverage for a coated steel containment structure, given a heat flux at the wall and an initial water flow rate.

- This method has been shown to predict the behavior of the large-scale heated tests and the AP600 water distribution tests. These tests cover a wide range of geometries, water flow rates, and wall heat flux values.

- The method relies on local film stability and is applicable to any size structure with a similar geometric shape to the prototypical AP600 containment.

- This method has been applied to the AP600 containment to predict coverage values during postulated accident conditions. These values are somewhat different than what is currently used in the AP600 WGOTHIC analysis.

Based on these conclusions, it is recommended that the WGOTHIC AP600 model should be revised to reflect the coverage values shown in Table 4. An evaluation should be made to determine the sensitivity of the containment pressure to these coverage values.

Based on sensitivity studies that have been performed with WGOTHIC for the AP600,[8] it is expected that these recommended coverage values will not significantly affect the containment pressure response.

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