Westinghouse Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

AW-96-927

February 15, 1996

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: T. R. QUAY

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

SUBJECT: CONSERVATISM IN MODELING OF THE PCS FILM IN THE DBA EVALUATION MODEL AND COMPARISON OF THE RANGE OF FILMS PARAMETERS IN THE PCS TEST DATA WITH AP600

Dear Mr. Quay:

The application for withholding is submitted by Westinghouse Electric Corporation ("Westinghouse") pursuant to the provisions of paragraph (b)(1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10CFR Section 2.790, Affidavit AW-96-927 accompanies this application for withholding setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-96-927 and should be addressed to the undersigned.

Very truly yours,

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja

cc: Kevin Bohrer NRC 12H5

2683A

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

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COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Nicholas J. Liparulo, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Nicholas J. Liparulo, Manager
Regulatory and Engineering Networks

Sworn to and subscribed
before me this 16 day
of February, 1996

Notary Public

Notarial Seal
Rose Marie Payne, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Nov. 4, 1996
Member, Pennsylvania Association of Notaries

2684A

(1) I am Manager, Regulatory and Engineering Networks, in the Nuclear Services Division, of the Westinghouse Electric Corporation and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Unit.

(2) I am making this Affidavit in conformance with the provisions of 10CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Unit in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) Enclosed is Letter NSD-NRC-96-4646, February 15, 1996 being transmitted by Westinghouse Electric Corporation (W) letter and Application for Withholding Proprietary Information from Public Disclosure, Brian A. McIntyre (W), to Mr. T. R. Quay, Office of NRR. The proprietary information as submitted for use by Westinghouse Electric Corporation is in response to questions concerning the AP600 plant and the associated design certification application and is expected to be applicable in other licensee submittals in response to certain NRC requirements for justification of licensing advanced nuclear power plant designs.

This information is part of that which will enable Westinghouse to:

(a) Demonstrate the design and safety of the AP600 Passive Safety Systems.

(b) Establish applicable verification testing methods.

(c) Design Advanced Nuclear Power Plants that meet NRC requirements.

(d) Establish technical and licensing approaches for the AP600 that will ultimately result in a certified design.

(e) Assist customers in obtaining NRC approval for future plants.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of meeting NRC requirements for advanced plant licenses.

(b) Westinghouse can sell support and defense of the technology to its customers in the licensing process.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar advanced nuclear power designs and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing analytical methods and receiving NRC approval for those methods.

Further the deponent sayeth not.

ENCLOSURE 2

NSD-NRC-96-4646

Conservatism in Modeling of the PCS Film in the DBA Evaluation Model and Comparison of the Range of Film Parameters in the PCS Test Data with AP600

February 15, 1996

R. P. Ofstun

Summary

The conservatism in the modeling of the evaporating film in the DBA evaluation model is examined in this report. An assumed 660 second delay in application of the PCS film in the DBA evaluation model is the sum of the maximum 53 second delay to establish the film flow plus an additional 10 minute delay to establish steady state film coverage, as measured in the Water Distribution Tests. The assumed delay conservatively neglects a minimum of 350,000 BTUs of heat removal during the 10 minute period needed to establish a steady state film coverage.

The expected AP600 shell temperature response during the 10 minute time period to establish steady state coverage is estimated. At the actual time of initiation of PCS flow rate to the shell surface (less than 60 seconds after initiation of the DBA event), the external surface temperature will have increased by less than 10°F. The dry, external shell surface temperature will have increased by less than 50°F at the time the first weir fills and begins to spill and by less than 70°F at the time the second weir fills and begins to spill. Tests run during the PCS testing program verified the ability of the water film to wet and rewet a hot surface (temperature exceeding 240°F) coated with the inorganic zinc compound to be used on the AP600 containment shell.

The range of the PCS film coverage test data parameters is tabulated and compared with the expected range for the AP600. With the exception of the maximum evaporating film temperature and maximum sidewall Re_{film} number, the test data bounds the expected range of the AP600 film parameters. It is more important to bound the lower expected film temperature with the test data, than the higher expected film temperature since the film is less stable at lower film temperatures. Also, it is more important for the tests to bound the minimum sidewall Re_{film} for evaluating the film stability model. Therefore, even though the test data does not bound the expected maximum film temperature or maximum Re_{film}, the ranges are sufficient for evaluating the Zuber-Staub film stability model.

The method used to determine the bounding margin value for the Zuber-Staub film stability model is described. The margin value obtained by this method bounds data from the unheated Water Distribution Tests and the heated baseline and Phase 2 Large Scale Tests.

The sensitivity of the Zuber-Staub film stability model to wetting angle, film temperature and heat flux is presented. The minimum stable film flow rate predicted by the Zuber-Staub model decreases with increasing film temperature and increases with wetting angle. The minimum stable film flow rate becomes less sensitive to heat flux as the assumed wetting angle increases and is relatively constant for heat flux less than 10000 BTU/hr-ft^2 at wetting angles greater than 20°.

A sample calculation for the applied PCS film flow rate input to the DBA evaluation model is provided to show how the Zuber-Staub film stability model is used to create a conservative film input flow rate for the DBA evaluation model, as described in Ref 11.

Introduction

A large portion of the energy released to containment following a postulated accident in the AP600 is removed by evaporation of an applied water film from the outer containment shell surface. Several questions have been raised on the level of conservatism in the DBA modeling assumptions related to the coverage and stability of the evaporating film. The purpose of this report is to address questions related to:

1. The conservatism in the DBA evaluation model assumed time delay for application of the PCS film;

2. A comparison of the range of film coverage parameters for the PCS tests with the range expected for AP600

3. The method used to determine a conservative, bounding margin value (R_{ref}) for the Zuber-Staub film stability model;

4. The method used to determine a conservative, bounding minimum applied PCS flow rate for the DBA evaluation model.

Conservatism in the Assumed Time Delay for Application of the PCS Film in the DBA Evaluation Model

The Water Distribution Tests were used to test the ability of various weir designs to cover a large fraction of the containment shell with water and to estimate the time to establish steady state film coverage on the AP600. A full scale test section representing a 1/8 sector of the containment dome was built. Based on a review of the video tapes for the phase 3 (improved weir design) water distribution tests, the time to fill and begin to spill over the first weir with a flow rate of 27.5 gpm (equivalent to 220 gpm flow rate on AP600) was estimated to be about 2.5 minutes, the time to fill and begin to spill over the second weir was estimated to be about 5 minutes, and the total time to establish steady state coverage of the dome and sidewall was estimated to be about 10 minutes.

The maximum time for water to begin flowing onto the shell surface, following a postulated event that actuates the PCS, is 53 seconds and is based on a maximum 20 second valve stroke time plus 30 seconds to fill the pipes and 3 seconds to fill the bucket. Therefore, for the DBA evaluation model, steady state film coverage is conservatively assumed to occur at 11 minutes after event initiation. The 11 minute coverage delay time assumed in the DBA model is conservative in that it neglects energy removal from the shell while steady state film coverage is being developed. An assessment of the amount of conservatism in the predicted energy removal is provided in the calculations that follow.

Wall Temperature and Heat Removal Calculations

The time for the dry outer shell to reach a given temperature can be tabulated as a function of the internal energy transfer coefficient using the properties of the [ ]^{a,c} steel shell and Figure 4-8 from Kreith (Ref. 1). The initial shell temperature will be assumed to be 120°F and the time for the outer shell to reach the boiling point for water (212°F) will be calculated with the following input:

T = 212°F
T_i = 120°F
T_∞ = 250°F
ζ = $(T - T_\infty)/(T_i - T_\infty)$ = 0.292

k_s = 25 BTU/hr-ft-F
L = [ ]^{a,c} ft
α = 0.49 ft^2/hr

Assume the internal energy transfer coefficient (condensation in air) is much larger than the external heat transfer coefficient (forced convection) such that the dry outer shell surface can be considered adiabatic (insulated) over the time period of interest. This assumption should lead to a minimum value for the time to reach 212°F. The results of the calculation are tabulated below.

U (BTU/hr-ft^2-F)	1/Bi	$\alpha t/L^2$	t (seconds)
5	34.3	43	5792
10	17.1	22	2963
50	3.43	5	673
100	1.71	2.6	350

Based on previous calculations assuming perfect mixing inside containment, the average internal energy transfer coefficient is expected to be around 60 BTU/hr-ft^2-F. The transient value in steam rich regions (if the containment stratifies quickly) could be higher, and a 25-50% increase is not unreasonable. Therefore, the time for the dry outer containment shell temperature to reach the boiling point following a LOCA event is estimated to be between 400 and 600 seconds.

A WGOTHIC AP600 model was run for comparison with the hand calculations. The calculated temperatures at the top of the dome, before application of the PCS film, are shown in Figure 1.

The WGOTHIC calculation of the time for the shell surface temperature on top of the dome to reach 212°F (about 450 seconds) agrees reasonably well with the estimate above. The heatup rate is about 0.2°F/sec and falls between the 50 and 100 BTU/hr-ft^2-F internal energy transfer coefficient values assumed in the hand calculation. During the 10 minute transient time after the initial blowdown, the containment temperature (and therefore the maximum possible internal shell temperature) is limited to about 260°F by condensation on the heat sinks inside containment.

Assuming the maximum delay in application of water to the dome (53 seconds), the outer shell temperature will have increased by less than 10°F at the time water is first applied at the top of the dome. Using a nominal 33 second application delay time and the weir fill times determined in the phase 3 Water Distribution Tests with the 220 gpm PCS flow rate (based on the single failure criteria), the temperature of the dry portion of the outer shell will have increased by less than 50°F at the time the first weir begins to spill (about 183 seconds) and less than 70°F at the time the second weir begins to spill (about 333 seconds). Therefore, the sidewall temperature will be less than 200°F at the time the water film begins to advance down the vertical surface.

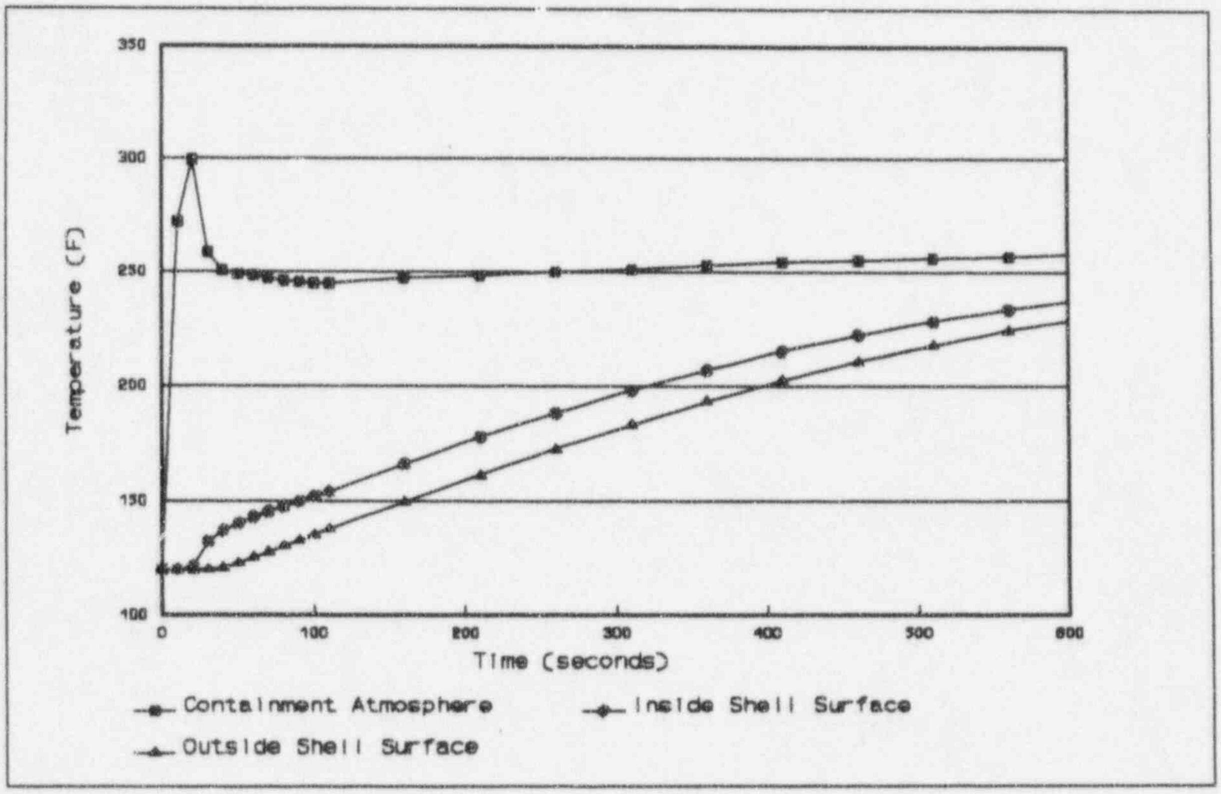

Figure 1 - Shell Temperatures at the Top of the Dome (without PCS Film Flow)

The WGOTHIC code predicts the average energy transfer coefficient for the internal shell surface at the top of the dome to be about 67 BTU/hr-ft^2-F over the first 3 minutes. It continues to decrease after that as the shell temperature increases. The code calculated internal energy transfer coefficient is only about 10% higher than the 60 BTU/hr-ft^2-F assumed in the hand calculations.

The bulk of the internal energy transfer for the dome surface is by condensation mass transfer as shown in Figure 2. Therefore, the heat flux to the steel shell is limited by the condensation rate.

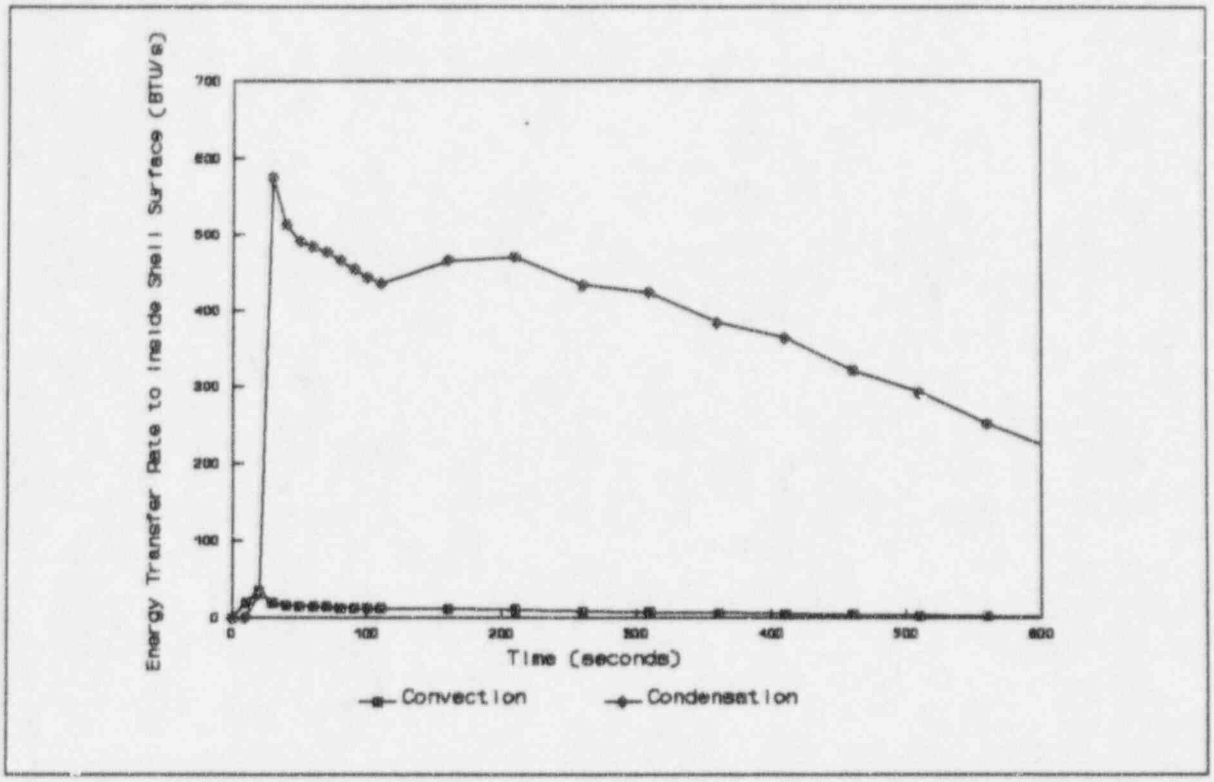

Figure 2 - Comparison of Internal Condensation and Convective Energy Transfer at the Top of The Dome

The temperatures of both the wet and dry portions of the shell will continue to increase during the time required to establish steady state water coverage (10 minutes). Based on the shell temperature predictions shown above, the outer shell surface temperature for the dry regions of the dome and sidewall will not exceed 240°F before steady state water coverage is established. Tests run during the PCS testing program verified the ability of the water film to wet and rewet a hot, dry surface (temperature exceeding 240°F) coated with the inorganic zinc compound to be used on the AP600 containment shell. Therefore, water coverage is not adversely affected by application of the film to a hot, dry shell surface.

In an attempt to quantify the amount of energy removal neglected during the development of steady state film coverage, the WGOTHIC base case described above was extended out to 1800 seconds to compare the shell temperature and heat removal results to a second case in which the assumed water coverage delay time (for the top of the dome) was reduced to a more realistic value. For the base case, the water film was applied at 660 seconds and for the second case, the water film was applied at 60 seconds. In both cases, the input water coverage fractions for the 3 portions of the dome (PCS bucket down to the first weir, between the first and second weirs, and from the second weir down to the springline) were set to 25%, 70% and 90% to match the measured values from the phase 3 Water Distribution Tests.

Note, the WGOTHIC code assumes steady state water coverage develops instantaneously at the time the film is applied, i.e, the time required to fill the weirs and develop steady state coverage is bounded by the assumed 660 second time delay in application of the film. Although the second case, with a more realistic estimate of the film application delay time for the top of the dome, will give a more accurate estimate of the heat removal from the top portion of the dome, it will overestimate heat removal from the rest of the dome and sidewall since the code does not model the time required to fill the weirs and establish the steady state water coverage. Therefore, only the heat removal from the top of the dome will be compared to give a minimum value for the heat removal neglected.

The transient inner and outer shell temperatures of the wet portion on the top of dome down to the first weir for both assumed PCS delay times are shown in Figure 3. The wet outer shell temperature increases to only about 165°F in the more accurate, 60 second delay case. It is also interesting to note that about 5 minutes after water is applied in the 660 second delay case, the wet shell temperatures decrease to about the same values as the 60 second water coverage delay case and that the difference in the coverage delay time doesn't seem to have much impact on the containment temperature.

The transient inner and outer shell temperatures for the wet and dry areas at the top of the dome for the 60 second delay case are shown in Figure 4. WGOTHIC models 1-D conduction (through the shell) so conduction between the wet and dry areas is neglected. If azimuthal conduction were modeled, the temperature of the dry area would be lower and the temperature of the wet area would be higher. More water would be evaporated at the higher elevations so the amount predicted to reach the lower elevations (or runoff the shell) over time would be lower. Therefore, the use of a 1-D conduction model in the evaluation model results in a higher predicted runoff flow rate and reduces the amount of evaporative heat removal from the shell.

Figures 5 and 6 compare the transient and integrated energy removal rate from the top of the dome as a function of time. There is very little difference in the energy removal rates for the first 300 seconds (due to the relatively long time constant of the shell), but the earlier application of the water film does significantly increase heat removal after 300 seconds. The heat removal rate for the 660 second delay case increases rapidly after the liquid film is applied and matches the heat removal rate of the 60 second delay case about 5 minutes later. Approximately 350,000 BTUs more energy is released from the top portion of the dome due to the earlier application of water on the dome. The energy release from the lower portions of the dome and sidewalls (if calculated with the proper weir fill delay times) would cause this difference to increase significantly. Therefore, the assumed 10 minute water coverage delay time conservatively neglects the energy removal from containment during the initial water coverage transient.

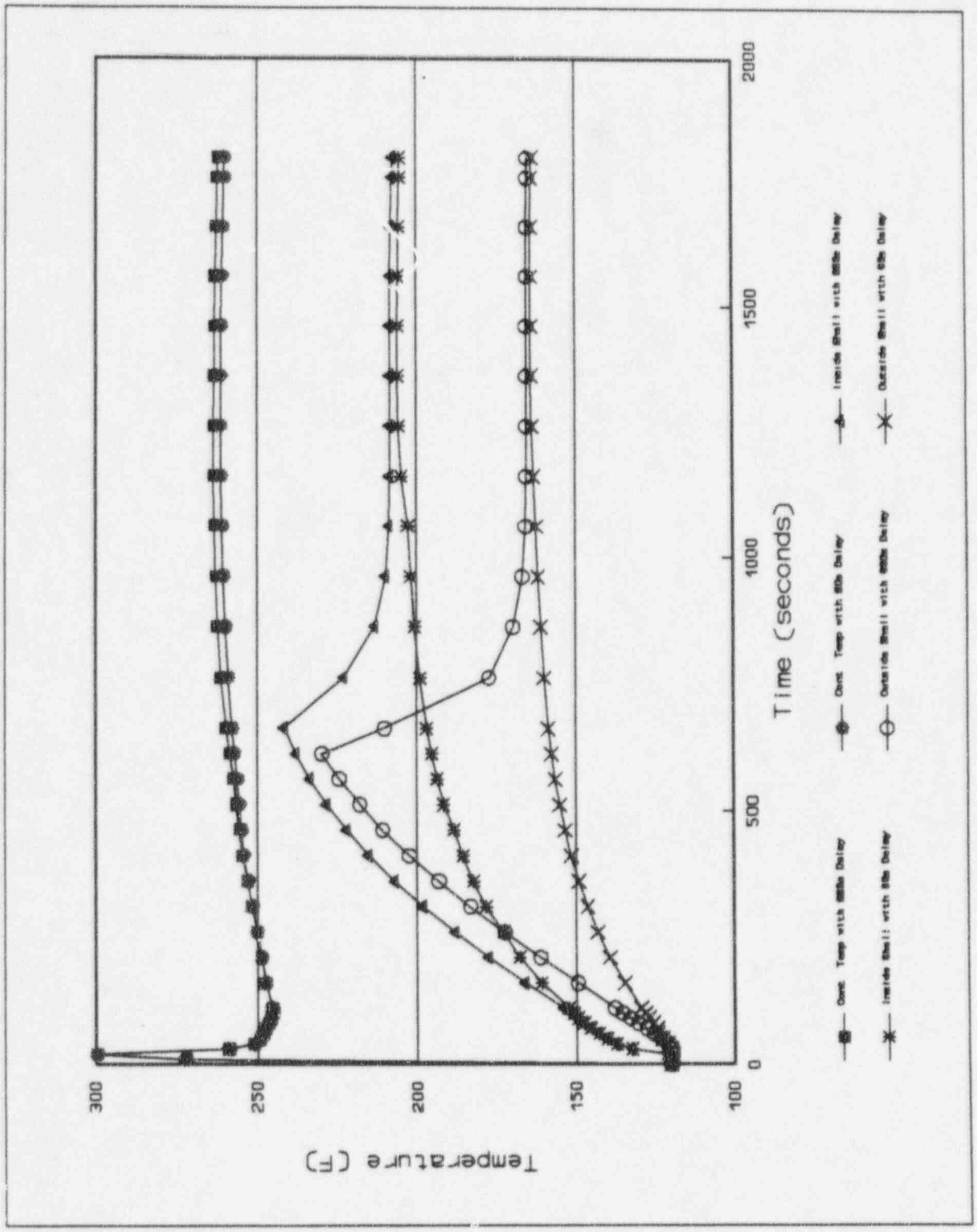

Figure 3 - Comparison of Wet Shell Temperatures at Top of Dome
(with PCS Film Applied at 60 and 660 Seconds)

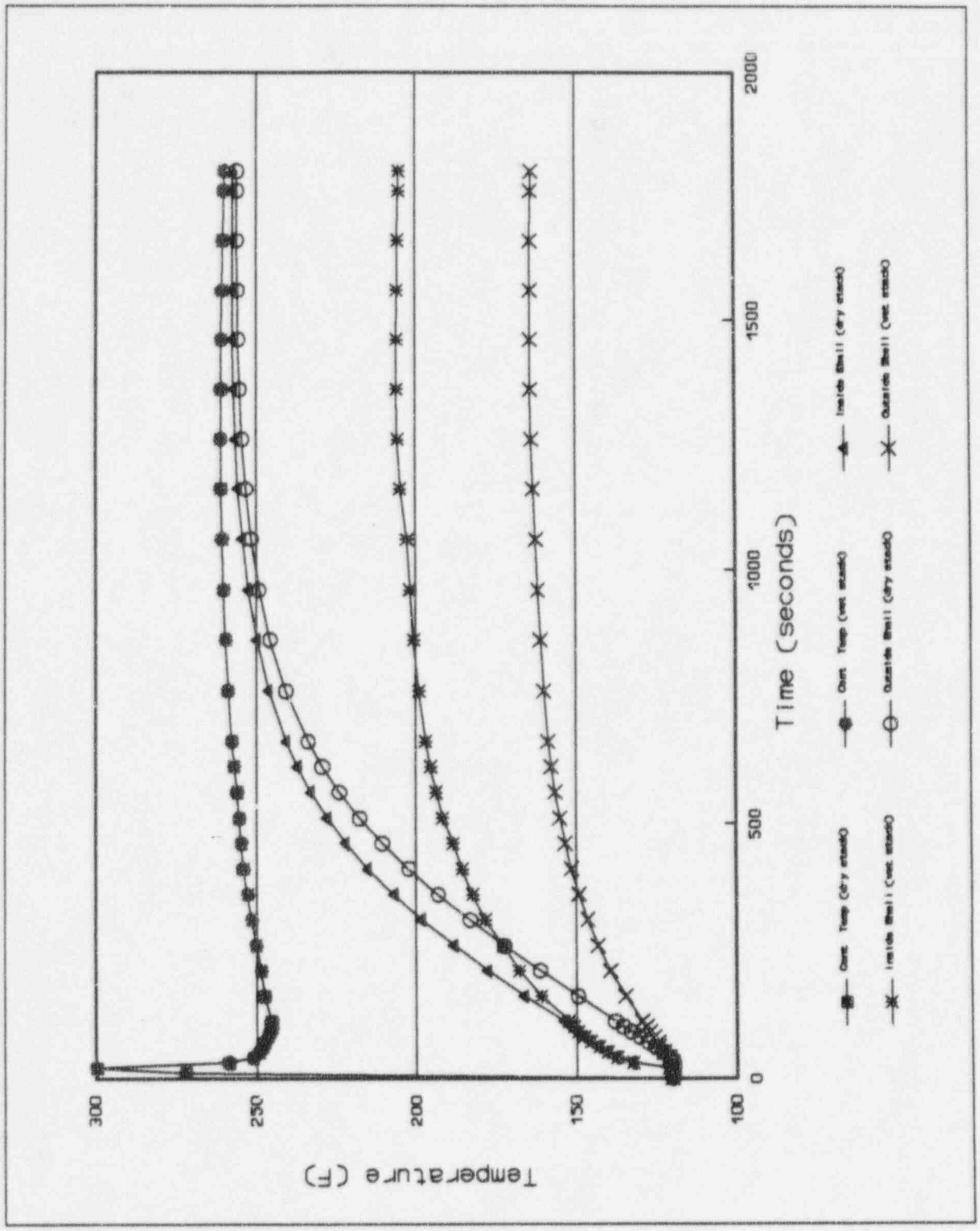

Figure 4 - Comparison of Wet and Dry Shell Temperatures at Top of Dome (with PCS Film Applied at 60 seconds)

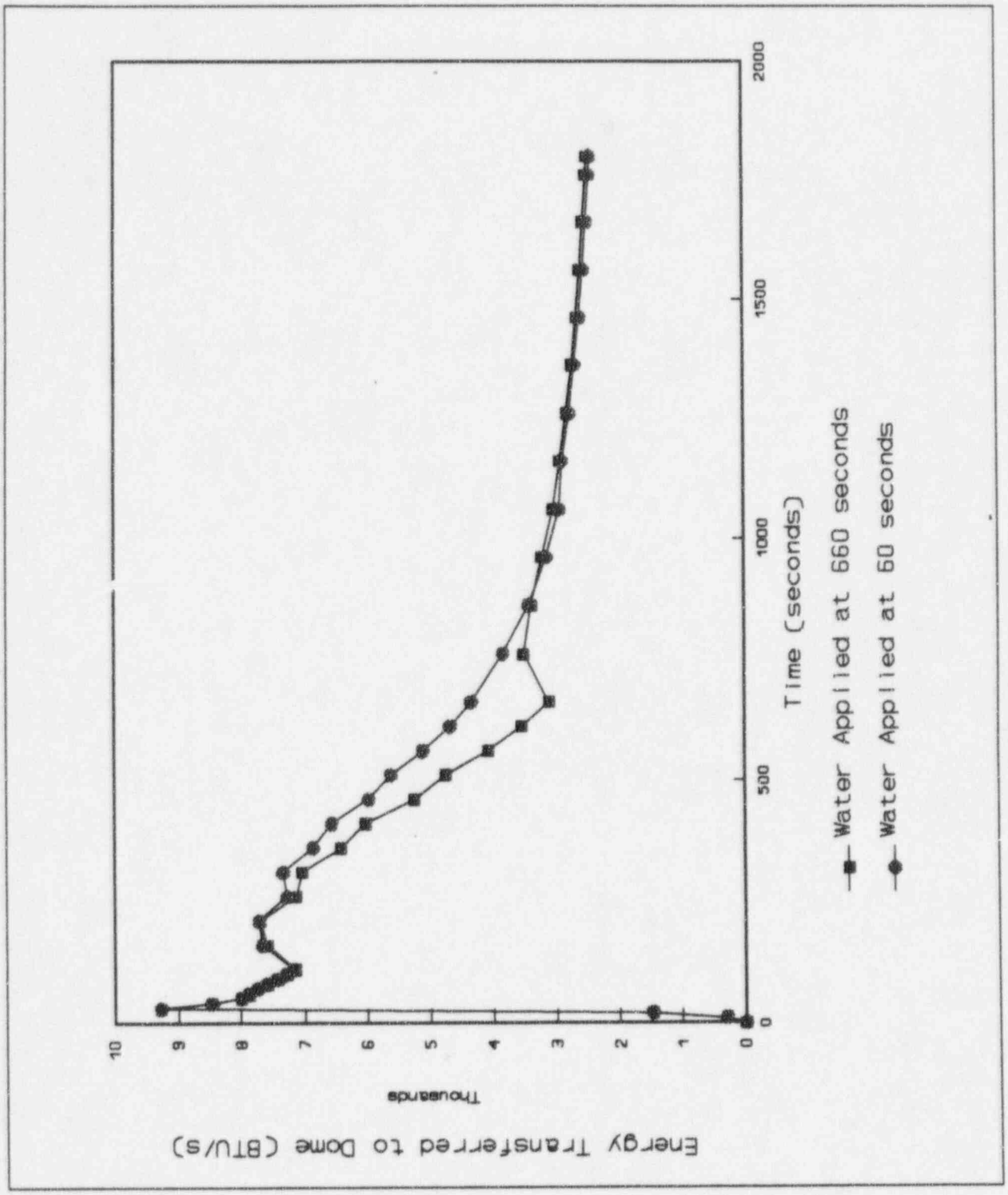

Figure 5 - Comparison of Energy Transferred at the Top of Dome (with PCS Film Applied at 60 and 660 Seconds)

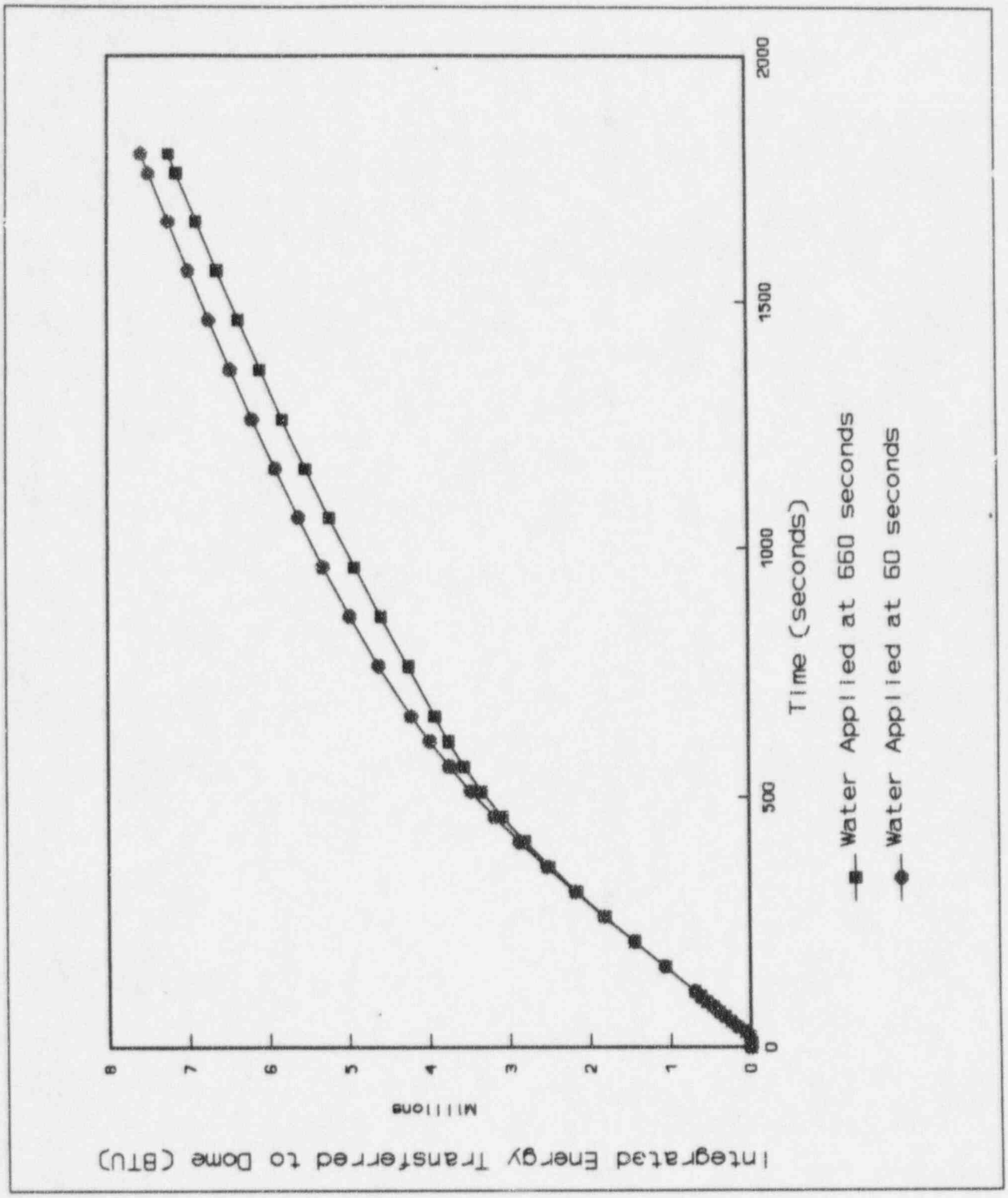

Figure 6 - Difference in the Integrated Energy Transferred to the Top of the Dome (with PCS Film Applied at 60 and 660 Seconds)

Summary of the PCS Wetting Tests

Observations and/or measurements of film coverage on the prototypical inorganic-zinc coated surface were made in several PCS tests. This section provides a description of each test and a summary of results. Table 1 presents a summary of the ranges of the test parameters that characterize the film coverage for all the PCS wetting tests.

Water Film Formation Tests

The Water Film Formation Tests (Ref. 3) were performed to show the wettability of the selected exterior coating for the AP600 containment shell and to characterize general requirements for forming a water film over a large surface area. An 8-ft. long, 4-ft. wide steel plate was placed on a pivoting frame to simulate the various angles on the containment dome and sidewall. The steel plate was painted with the selected inorganic zinc coating. A stream of water was applied to the center top edge of the plate. Various film spreading mechanisms were investigated, but no source of heat was modeled.

With a flow rate of 1 gpm from a 1/2-inch diameter tube pointed vertical to the surface, the water spread to form an initial 1-ft. wide stripe of film. The initial width appeared to be independent of the plate angle. The initial film thickness was not uniform near the point of application; it was thinnest just below the application point and thicker on both sides. The film continued to spread (more slowly as the surface became more vertical) and a very thin, wet region was created at the edges as the film traveled downward.

Water Distribution Tests

The Water Distribution Tests were used to determine the water coverage fraction and estimate the time to establish steady state film coverage on the AP600. A full scale test section representing a 1/8 sector of the containment dome was built. There was no source of heat to simulate energy removal by evaporation for these tests. Various weir distribution systems were tested before the design was frozen and tested in the phase 3 Water Distribution Tests (Ref. 4).

The water coverage fraction for the 27.5 gpm flow rate (equivalent to 220 gpm on the AP600) was estimated to be 25% from the top of the dome down to the first weir, and 70% between the first and second weirs, based on a review of the video tapes for the phase 3 water distribution tests (with the improved weir design). The entire vessel was wet at the bottom of the dome, but only the width of the visibly flowing water stripes were measured. A 90%, flowing water coverage fraction was measured at the springline (below the second weir). The phase 3 test data is summarized in Table 2.

Table 1 - Test Film Coverage Parameter Ranges

Large Scale Test Data Ranges

a,b,c

Parameter	Min.	Max.	Units
Avg. Wet Surface Temperature			F
Applied Film Temperature			F
Runoff Film Temperature			F
Peak Dome Heat Flux			$BTU/hr\text{-}ft^2$
Peak Heat Flux at Bottom			$BTU/hr\text{-}ft^2$
Applied Film Flow rate			lbm/hr
Top Sidewall Film Flow rate			lbm/hr-ft
Bottom Sidewall Film Flow rate			lbm/hr-ft
Exit Film Reynolds Number			

STC Wet Flat Plate Test Data Ranges

a,b,c

Parameter	Min.	Max.	Units
Wet Surface Temperature			F
Applied Film Temperature			F
Runoff Film Temperature			
Average Heat Flux			$BTU/hr\text{-}ft^2$
Applied Film Flow rate			lbm/hr
Top Plate Film Flow rate			lbm/hr-ft
Exit Film Flow rate			lbm/hr-ft
Exit Film Reynolds Number			

Small Scale Test Data Ranges

a,b,c

Parameter	Min.	Max.	Units
Avg. Wet Surface Temperature			F
Applied Film Temperature			F
Runoff Film Temperature			F
Average Heat Flux			$BTU/hr\text{-}ft^2$
Applied Film Flow rate			lbm/hr
Top Sidewall Film Flow rate			lbm/hr-ft
Bottom Sidewall Film Flow rate			lbm/hr-ft
Exit Film Reynolds Number			

Phase 3 Water Distribution Test Data Ranges

a,b,c

Parameter	Min.	Max.	Units
Applied Film Flow rate			lbm/hr
Top Sidewall Film Flow rate			lbm/hr-ft
Top Sidewall Reynolds Number			

Table 2 - Summary of the Water Distribution Tests

Water Distribution Tests (Cold)

Test	Coverage	Tf-in (F)	Tf-out (F)	Flow-GPM	Measured Exit lbm/hr	Avg. Gamma	Qflux
13							
9							
10							
11							
12							
14							

a,b,c

At the 220 gpm equivalent flow rate for the modeled 1/8 sector of the dome, there are [ ]^{a,c} flow streams (with an average flow rate of about [ ]^{a,c} gpm per stream) from the first weir and [ ]^{a,c} streams (with an average flow rate of about [ ]^{a,c} gpm per stream) from the second weir. Closeups of the flow from the weir show how the water spreads radially outward from the point of application on the dome before merging with the streams on either side and flowing downward. The width of the stripes of water film increases as they fall between the first and second weirs.

Assuming each stream from the first weir spreads out about 1-ft (based on the Water Film Formation Tests), the water coverage and film Re number just below the first weir (at the [ ]^{a,c} radius) can be estimated for the scaled 220 gpm PCS flow rate as follows:

Fractional Coverage = [ ]^{a,c} = 0.92
Γ = [ ]^{a,c} = 0.2 lbm/ft-s
$Re = 4*\Gamma/\mu = 4*0.2/.458E\text{-}03 = 1810$

If the stripes of film did not spread at all (i.e. the thickness and width remained constant), the coverage fraction just above the second weir (at the [ ]^{a,c} radius) would be half this value, 0.46. This is much less than the observed value of approximately 0.7 because the film stripes were observed to spread significantly between the first and second weirs on the inclined (but not vertical) surface of the dome.

After passing through the second weir, the water coverage and film Re number are estimated similarly as follows (assuming the spread is only 0.5 ft per stream at the lower flow rate):

Fractional Coverage = [ ]^{a,c} = 0.92
Γ = 0.1 lbm/ft-s
$Re = 4*\Gamma/\mu = 905$

If the stripes of film did not spread at all, the coverage at the springline (65-ft. radius) would be:

Fractional Coverage = [ ]^{a,c} = 0.70

This is less than the measured value of 0.9, so the film stripes also spread on the nearly vertical surface between the second weir and the vertical sidewall. The film Re number at the springline is estimated as follows:

Γ = [ ]^{a,c} = 0.0827 lbm/ft-s
$Re = 4*\Gamma/\mu = 722$

Figure 7 presents the measured sidewall coverage as a function of the applied water flow rate for all of the Phase 3 Water Distribution Tests. The coverage decreases as the applied flow rate decreases. The flow rate was not adjusted to account for the water lost at sampling points upstream of the springline. This correction would shift the data points slightly to the left.

a,c

Figure 7 - Phase 3 Water Distribution Test Coverage as a Function of Sidewall Flow Rate

STC Wet Flat Plate Tests

The primary purpose of the STC wet flat plate tests was to generate evaporation heat and mass transfer data with representative temperatures, heat flux, air velocity and film flow rates to bound the expected conditions on the AP600 containment shell. A secondary purpose was to observe the film hydrodynamics including possible formation of dry patches due to surface tension instabilities.

Tests were performed in 2 orientations; vertical and 15 degrees from horizontal with various combinations of air velocity, film flow rate and heat flux. A wavy laminar water film was formed easily on the hot coated steel surface, even in the vertical orientation. Once formed, the film showed no instability or tendency to form rivulets. This was true at all tested water flow rates. A description of the test section and results from the various tests are given in Ref. 5. The test data is summarized in Table 3.

Two of the heated flat plate tests were run with very low film flow rates at relatively high heat flux and the film did dryout before reaching the end of the test section. The observations are given in Ref. 5 (pages 36-37). "The upper part was 80% wetted and fingers of water film extended down four feet to within two feet of the end of the heated plate. The bottom of the fingers slowly moved up and down. The dry patch between fingers was between one quarter of an inch and one and one half inches wide. These tests showed that the end point of water films on the containment would still be stable film evaporation, even with very thin films and high heat fluxes."

Small-Scale Integral Tests

The small-scale integral tests were designed to provide heat and mass transfer data for both the inside and outside of the test vessel. The test apparatus consisted of a 3-ft. diameter, 24-ft. high steel pressure vessel that was heated by steam supplied at various pressures. The pressure vessel was surrounded by a clear, plexiglass shield that formed a 15-in. wide annulus for either forced or natural circulation driven air flow and allowed observation of the applied external film flow.

The tests were conducted with varying steam supply flow rates, water film flow rates, water film temperatures, inlet air flow rates, inlet air temperature and humidity. Instrumentation was provided to measure internal steam condensation rates, external water evaporation rates, inner and outer wall temperatures, film temperatures, air velocity, temperatures and humidity. A summary of the test data from Ref 6. (for tests with measured water coverage) is provided in Table 4.

The following conclusions and observations (with respect to the water film) were drawn from these tests:

- The water film behavior was stable at average, evaporating heat fluxes in the range of those expected on the AP600.

Table 3 - Summary of STC Wet Flat Plate Tests

STC Flat Plate Evaporation Tests

a, b, c

Test	Coverage (%)	Tf-in (F)	Tf-out (F)	Mdot-in (lbm/hr)	Mdot-out (lbm/hr)	Measured Inlet Gamma	Measured Exit Gamma	Avg. Qflux (B/hrft2)	Avg. Wet Max	Plate Tem Min
13										
10										
14										
29										
22										
11										
16										
15										
23										
27										
17										
30										
18										
32										
19										
25										
20										
26										
21										
12										
28										
24										
31										

STC Flat Plate Tests with film completely evaporated by exit

a, b, c

Test	% Plate Coverage	Tf-in (F)	Tf-out (F)	Mdot-in (lbm/hr)	Mdot-out (lbm/hr)	Inlet Gamma	Avg. Wet Qflux	Dry Plate Tem	Avg. Wet Max	Plate Tem Min
8										
9										

Table 4 - Summary of Small Scale Tests

Small Scale Tests

Test	Coverage (%)	Tf-in (F)	Tf-out (F)	Mdot-in (lbm/hr)	Mdot-out (lbm/hr)	Approx. Inlet Gamma	Measured Exit Gamma	Avg. Qflux	Avg. Wet Shell Tem Max	Min
107A-15U										
107A-5U										
113A-15U										
114A-15U										
107A-5P										
111-5P										
132B-15U										

a,b,c

Small Scale Tests with Film Completely Evaporated at Exit

Test	Coverage @ 4-ft El	Tf-in (F)	Tf-out (F)	Mdot-in (lbm/hr)	Mdot-out (lbm/hr)	Approx. Inlet Gamma	Avg. Qflux	Avg. Wet Shell Tem Max	Min
105-15U									
107C-15U									
106-15U									
132A-15U									
109B-15U									
121-15U									
114B-15U									

a,b,c

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Preliminary

- A uniform water film was easily formed on the coated steel surface using simple weirs.

- The water film on the vertical side walis of the coated steel surface of the vessel had no tendency to become less uniform or form rivulets, so that no water film redistribution was required on the vertical walls.

Large-Scale Integral Tests

The Westinghouse large-scale PCS test facility was built to provide test data fcr a geometrically similar model of the AP600 containment vessel and PCS. The tests provide experimental data that can be used for evaluating the physics in containment, determining the relative importance of various parameters that affect heat and mass transfer and validating computer codes. Three series of tests were run at the Westinghouse large-scale test facility. The steady-state pressure, annulus air flow rate, water coverage, steam flow rate, injection velocity, location and orientation, and noncondensible gas concentration were varied between the tests.

The large-scale PCS test facility uses a 20-ft. tall, 15-ft. diameter pressure vessel to simulate the AP600 containment vessel. The geometry is approximately a 1/8-scale of the AP600 containment vessel. A plexiglas cylinder is installed around the vessel to form the air cooling annulus. Air flows upward through the annulus via natural convection to cool the vessel, resulting in condensation of the steam inside the vessel. A fan is located at the top of the annulus shell to provide the capability to induce higher air velocities than can be achieved during purely natural convection. A liquid film is applied to the outside of the test vessel to provide evaporative cooling.

Test conditions (pressure, steam flow rate, cooling air flow rate, water coverage, etc.) were selected to provide heat and mass transfer validation over a range of conditions representative of a DBA. The Baseline and Phase 2 test data related to water coverage from Ref. 7 and Ref. 8 (excluding the tests with forced water coverage) is summarized in Table 5.

The liquid film was applied to the elliptical dome surface by J-tubes to produce a series of uniformly spaced water streams. At water flow rates scaled to the initial PCS flow rate on the AP600, the water streams spread within a few inches of their application point to form a relatively thick, continuous wavy laminar film. At lower scaled PCS flow rates, the individual source streams were not able to spread to complete circumferential coverage. Evaporation and spreading on the inclined surface of the dome caused the thickness of the steams to decrease and the width (or coverage area) to increase as they flowed down the outer surface of the elliptical dome. The stream width was observed to remain relatively constant as it flowed down the vertical sidewall.

Table 5 - Summary of Large Scale Tests

Large Scale Tests

Test Baseline	Cov rage %)	Tf-in (F)	Tf-out (F)	m-in (lbm/hr)	m-out (lbm/hr)	Measured Exit Gamma	Dome Max Qflux	Exit Max Qflux	Avg. Wet Max	Shell Tem Min
201.1										
202.1										
203.1										
207.2										
201.2										
202.2										
203.2										
204.1										
205.1										
206.1										
207.4										
210.1										
211.1										
Test Phase 2										
202.3										
203.3										
212.1A										
212.1B										
212.1C										
213.1A										
213.1B										
213.1C										
214.1A										
214.1B										
215.1A										
215.1B										
217.1A										
217.1B										
218.1A										
218.1B										
219.1C										
221.1A										
221.1B										

a,b,c

Westinghouse Proprietary Class 3
Preliminary

Expected Film Coverage Parameter Ranges for AP600

It is necessary to estimate the expected film coverage parameter ranges for AP600 to compare with the ranges of the PCS tests. The estimates for the maximum and minimum values of the film parameter range were determined using the simple approach described below.

The initial gravity driven PCS film flow rate (assuming a single failure of 1 of 2 valves to open) is 220 gpm. The transient PCS film flow rate for the first 24 hours is shown in Figure 8. The minimum PCS flow rate is 55 gpm and occurs after about 3 days.

The minimum sidewall Γ value would be 0 lbm/hr-ft, assuming complete evaporation of the applied film. To determine a maximum sidewall Γ, only 25% of the film is assumed to evaporate on the dome. It is likely that there would be more evaporation from the dome, which would reduce the film flow rate to the sidewall, but this could also result in a lower sidewall coverage fraction. Assuming 25% evaporation of the applied PCS flow rate, the maximum sidewall flow rate would be 80000 lbm/hr. Based on measurements from the unheated, phase 3 Water Distribution Tests, a 75% coverage at the top of the sidewall is used to obtain a maximum sidewall Γ of 256 lbm/hr-ft. At the predicted maximum 200°F film temperature, the sidewall Re_{film} would be 1400. The Re_{film} and Γ values on the dome will be higher than the sidewall values since Γ decreases as the diameter increases. A more detailed comparison of the expected AP600 Re_{film} value with test data is given in Ref. 9.

The shell heat flux decreases from the point of PCS film application, on the subcooled region of the shell, downward through the evaporating region of the shell and into the dry portion of the shell. The steady state shell average heat flux and film temperature were calculated for the subcooled, evaporating and dry portions of the shell assuming perfect mixing within containment and an ambient air and film temperature of 120°F. These calculations were performed at the containment design pressure, 60 psia, to bound conditions at the expected DBA peak pressure and at 38.2 psi, for conditions representative of 24 hours after blowdown. The results are tabulated below.

Containment Pressure (psia)	Avg. Subcooled Heat Flux ($BTU/hr\text{-}ft^2$)	Avg. Subcooled Temp. (°F)	Avg. Evaporating Heat Flux ($BTU/hr\text{-}ft^2$)	Avg. Evaporating Temp. (°F)	Avg. Dry Heat Flux ($BTU/hr\text{-}ft^2$)	Avg. Dry Temp. (°F)
60	7740	155	5500	190	455	260
38.2	3700	147	2500	175	300	220

The maximum wet shell heat flux is conservatively estimated to be 50% higher than the average subcooled value (at 60 psia), about 11500 $BTU/hr\text{-}ft^2$. The minimum wet shell heat flux is conservatively estimated to be 50% lower than the average evaporating value (at 38.2 psia), about 1300 $BTU/hr\text{-}ft^2$. Note, the minimum wet shell heat flux could be even lower if the pressure at 24 hours is lower than assumed, however, the minimum wet shell heat flux is not a bounding value anyway.

a,c

Figure 8 - Gravity Driven PCS Flow Rate as a Function of Time

Per the Technical Specifications, the initial PCS film temperature is expected to be between 50 and 120°F. The 120°F value is used in the DBA evaluation model to minimize the benefit of sensible heat removal by the subcooled film. The film temperature will increase as the film flows down the dome and onto the sidewall. The maximum evaporating film temperature was calculated to be less than 200°F. Since the resistance to heat transfer in the thin film is very small (compared with the mass transfer and internal resistance, as shown in Ref. 12) and the heat flux is relatively low, the maximum wet surface temperature is expected to be less than 20°F higher than the maximum film temperature.

The expected range of the AP600 film parameters is summarized in Table 6. A comparison with the PCS test data ranges shows that, with the exception of the maximum evaporating film temperature and maximum sidewall Re_{film} number, the test data bounds the expected range of the AP600 film parameters.

It is more important to bound the lower expected film temperature with the test data, than the higher expected film temperature since the film is less stable at lower film temperatures. Also, it is more important for the tests to bound the minimum sidewall Re_{film} for evaluating the film stability model. Therefore, even though the test data does not bound the expected maximum film temperature or maximum Re_{film}, the ranges are sufficient for evaluating the Zuber-Staub film stability model. Also note, the test data for the maximum sidewall Re_{film} number is within the wavy laminar flow regime, while the maximum AP600 sidewall value is in the transition to turbulent flow regime. Heat transfer within the turbulent flow regime is better than in the laminar flow regime, so even though the tests did not cover the transition regime, the test results are conservative with respect to evaluating the heat transfer.

Table 6 - Expected Range of AP600 Film Coverage Parameters

	AP600			Composite of Test Data		
	Min	Max		Min	Max	a,c
Wet Surface Temperature		220°	F			F
Wet Surface Heat Flux	1300	11500	BTU/hr-ft²			BTU/hr-ft²
Applied Film Flow rate	55	220	gpm			
Sidewall Film Flow rate	0	256	lbm/hr-ft			lbm/hr-ft
Applied Film Temperature	50	120°	F			F
Evap. Film Temperature		200°	F			F
Sidewall Film Reynolds Number	0	1400				

Determination of a Bounding Stability Margin (R_{ref}) Value

To provide a conservative estimate of the initial sidewall water coverage for AP600, it is necessary to determine an upper bounding value for the minimum stable film flow rate on the dome. In the Westinghouse film coverage model, the local Zuber-Staub minimum stable film flow rate on the dome, Γ_{min}, is multiplied by a stability margin value, R_{ref}, to determine an upper bound, below which a continuous film on the dome will split (Ref. 11). The stability margin multiplier is used to account for the effects of subcooling, plate misalignment and the method of film application on the initial film splitting behavior.

The stability margin value that is used in the Westinghouse film coverage model to determine the initial film coverage on the sidewall was obtained by bounding the film coverage test data from the unheated, full-scale Water Distribution Tests and the heated 1/8-scale Large Scale Tests covering a wide range of film flow rates and heat flux. The method used to determine a bounding R_{ref} value of the test data is outlined below.

1. The Zuber-Staub stability model is used with: a wetting angle of [ ]^{a,c}, the measured peak dome heat flux, the initial film flow rate at the point of application, and the initial film temperature to determine a maximum value for Γ_{min}. This Γ_{min} value is multiplied by R_{ref} to determine the dome circumference, CI, at which the average film flow rate becomes unstable.

2. The wetted coverage (width of the film stripes) at the circumference of the vessel springline, CSL, needs to be estimated for comparison with the measured test data and was predicted using the following approximation:

   WDL = (CI + CSL)/2

3. Based on observations from the Large Scale Tests, the width of the film stripe remains relatively constant from the springline down to the point of measurement (at the vessel gutter). Therefore, the predicted film coverage at the springline is compared with the measured film coverage and the R_{ref} value is varied until all of the data is bounded.

This approach yielded a bounding R_{ref} value of [ ]^{a,c} at the assumed [ ]^{a,c} wetting angle. The results are shown in Figure 9. The ratio of the predicted-to-measured film coverage is shown as a function of the maximum heat flux in Figure 10. This shows that this method for determining the coverage bounds the measured test coverage values over a larger range of heat flux than is expected on the AP600 shell.

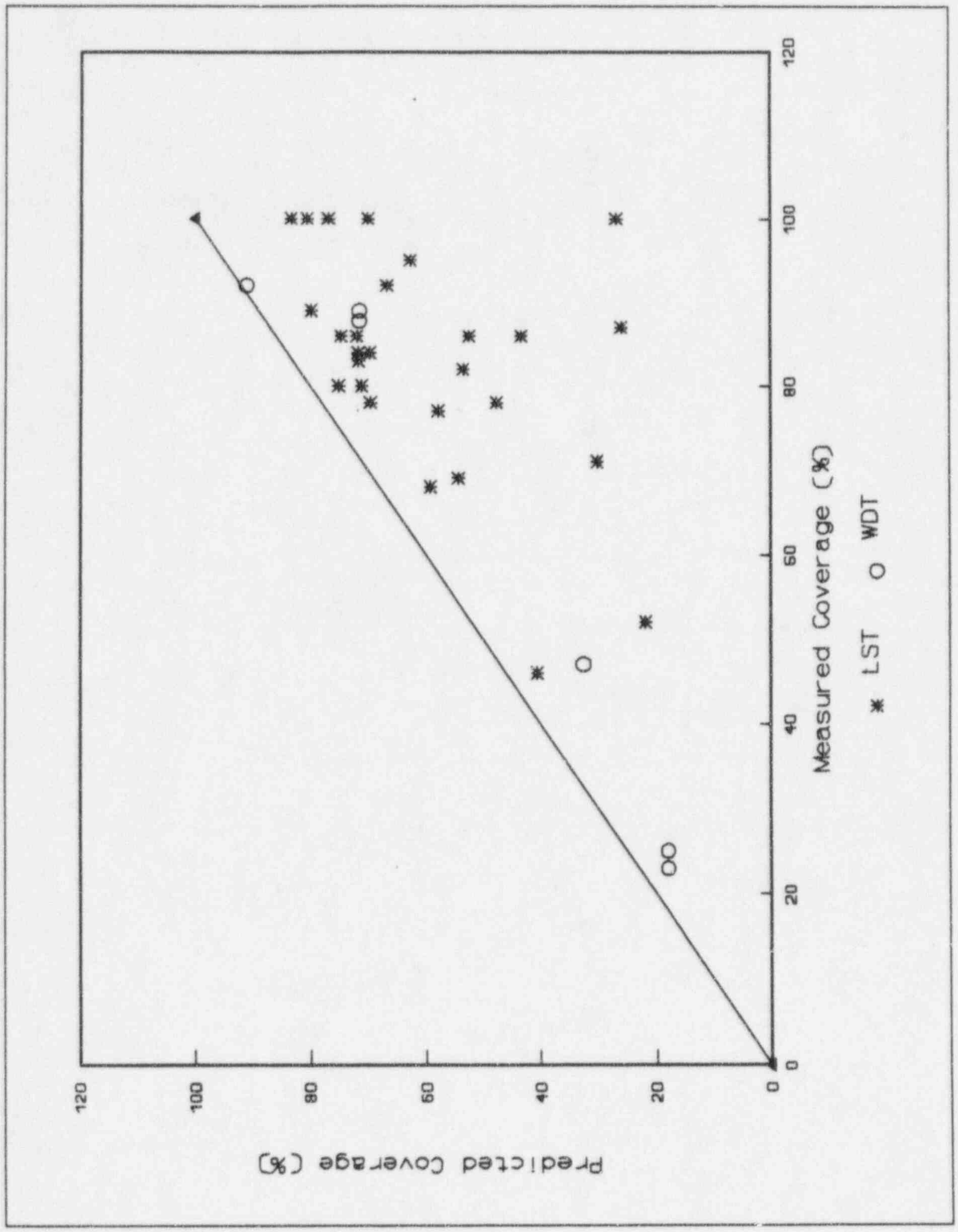

Figure 9 - Bounded Water Coverage Data

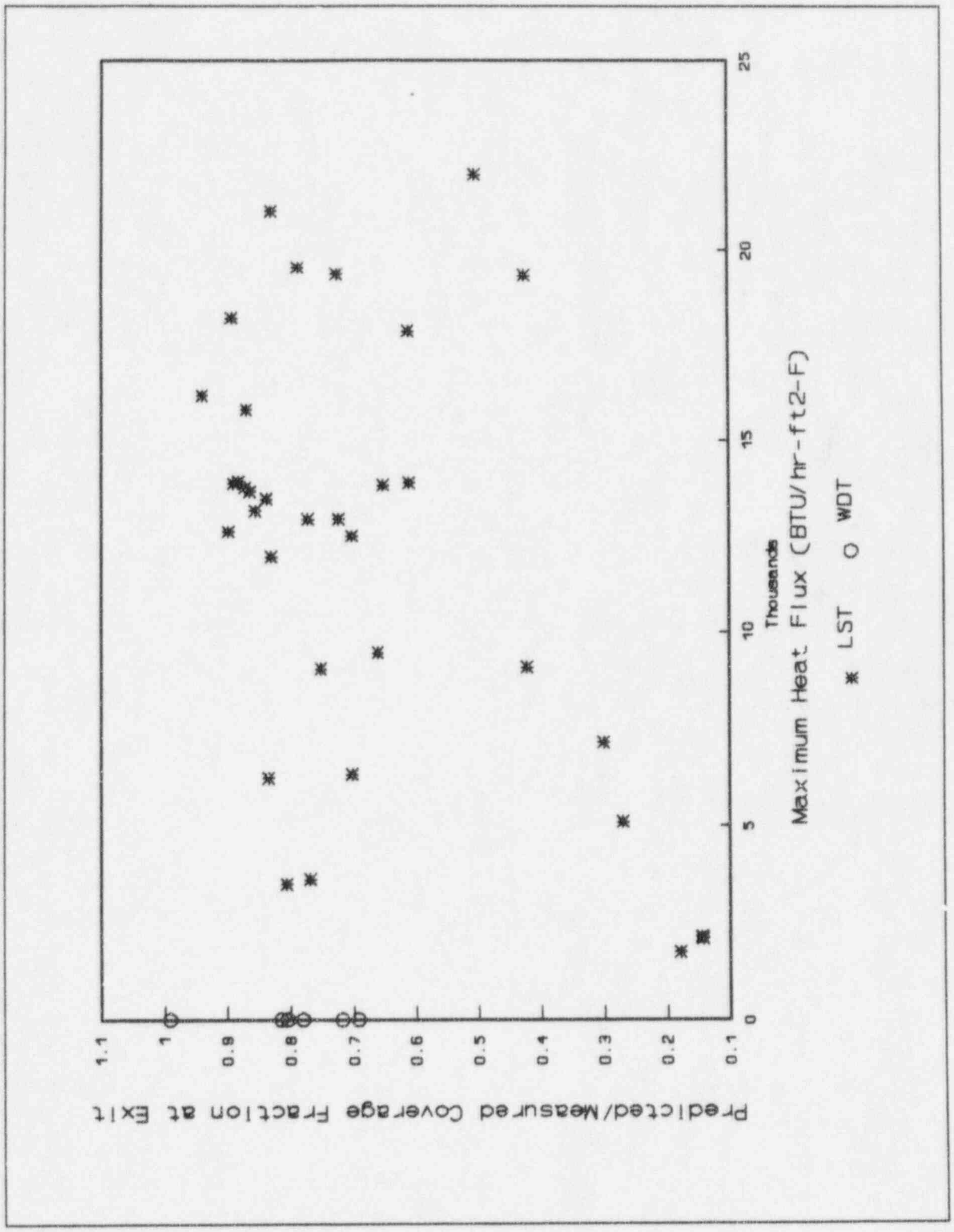

Figure 10 - Bounded Test Coverage Data as a Function of Heat Flux

Sensitivity to the Assumed Wetting Angle

The sensitivity of the predicted Zuber-Staub Γ_{min} value to the wetting angle is shown as a function of heat flux in Figures 11 and 12 (for film temperatures of 120 and 200°F respectively). Using a higher wetting angle or lower film temperature would cause the Zuber-Staub Γ_{min} value to increase, which would cause the bounding R_{ref} value to be lower (since the test data is bounded by the product of Γ_{min} and R_{ref}). Therefore, the method for determining the bounding coverage at the vessel springline is conservative at any assumed wetting angle.

The surface wetting angle (advancing film) was measured as a function of temperature and age of the surface. These results are presented in Ref. 10 and show the advancing film wetting angle for this surface is between [ ]^{a,c}. A value of [ ]^{a,c} was chosen for the film stability calculations because it is the upper bound of the measured, steady state values for a heated, weathered surface. Other test data, presented in Figure 11 and shown in Tables 3, 4 and 5, indicate that the surface wetting angle, which should be used in the Zuber-Staub stability model, should be smaller.

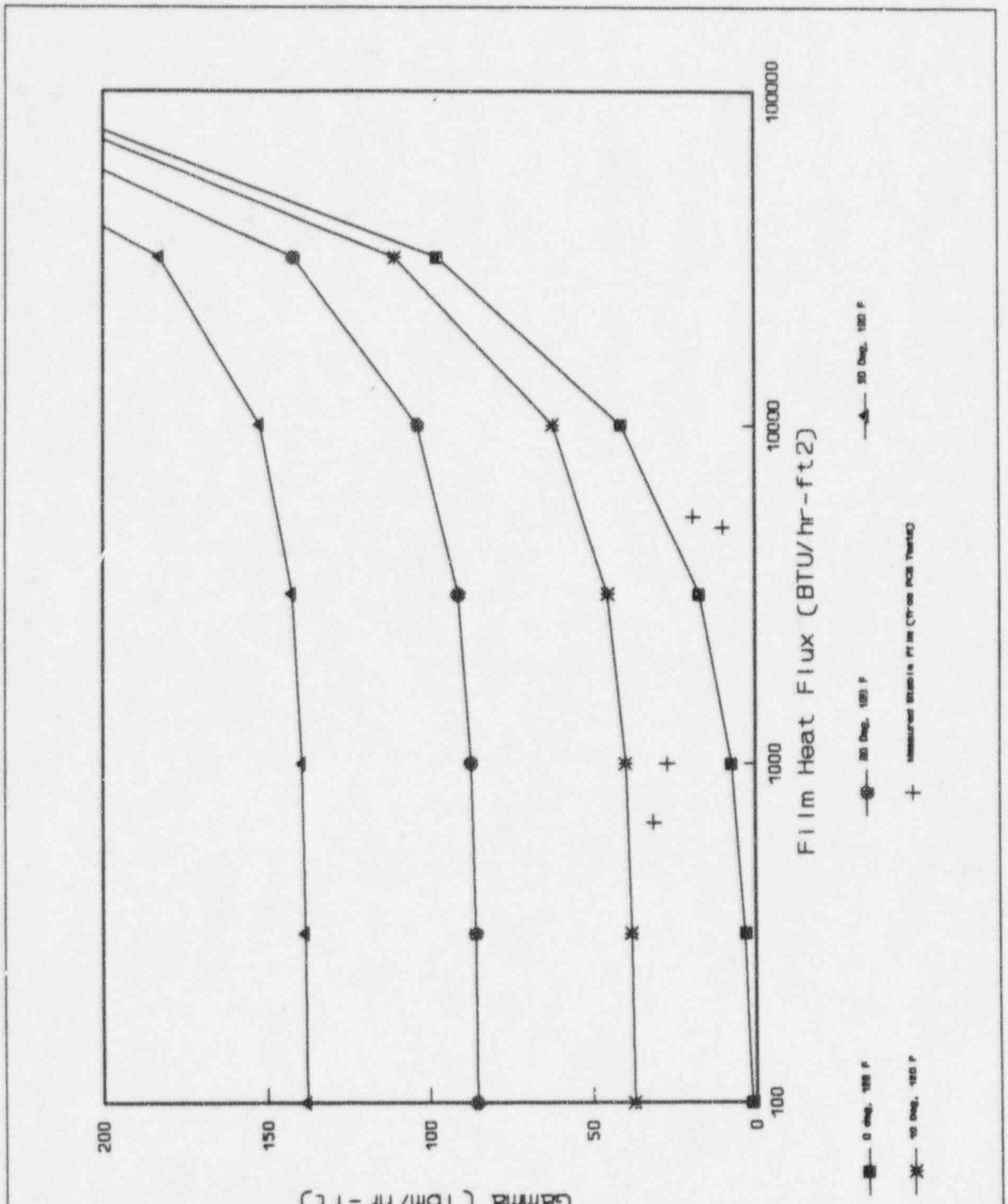

Figure 11 - Minimum Stable Film Flow Rates Predicted by the Zuber-Staub Model Showing Sensitivity to Heat Flux and Wetting Angle at 120°F Film Temperature

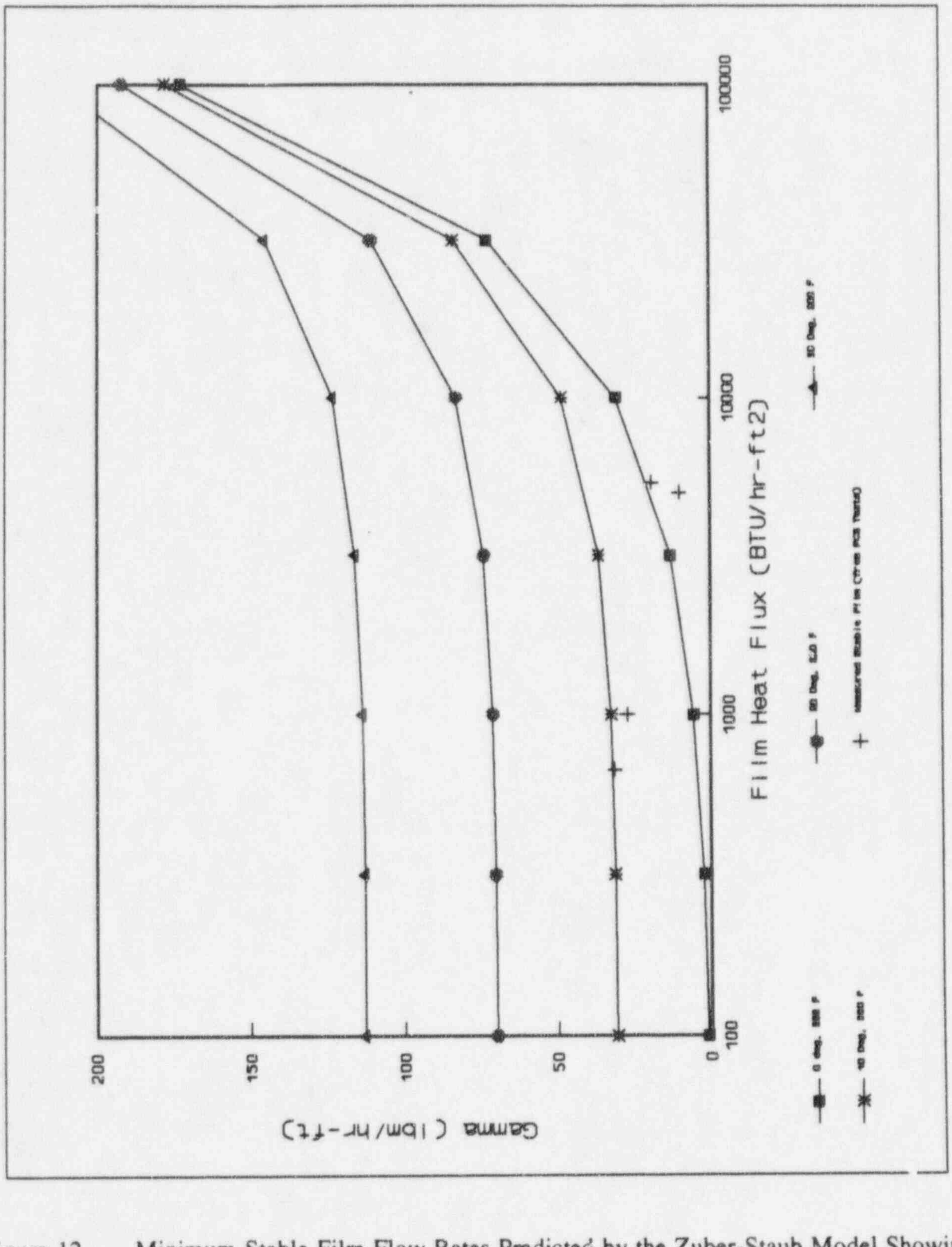

Figure 12 - Minimum Stable Film Flow Rates Predicted by the Zuber-Staub Model Showing Sensitivity to Heat Flux and Wetting Angle at 200°F Film Temperature

Sample PCS Film Flowrate Calculation

The gravity driven PCS film flowrate is conservatively calculated assuming one of two PCS drain valves fails to open. The gravity driven flowrate is based on the PCS water storage tank level and is shown as a function of time in Figure 8. A suitable, maximum value for Γ_{min} that bounds heat fluxes up to 10000 BTU/hr-ft^2-F and film temperatures greater than 120 F (the initial film temperature) for a wetting angle of [ ]^{a,c} was selected from Figure 13.

The wetted perimeter at the springline is calculated by first determining the point on the dome where $R_{ref}\Gamma_{min}$ is reached and the film is predicted to split

$$r_{split} = \frac{\dot{m}_{PCS}}{2\pi R_{ref}\Gamma_{min}}$$

The wetted perimeter at the springline is given by the minimum of the vessel circumference, $2\pi r_{vessel}$, and

$$P_{wetted} = \pi(r_{split} + r_{vessel})$$

The film evaporates as it flows down the vertical sidewall, causing Γ to decrease. The average heat flux, Q_{avg}'', is assumed to remain constant over the entire wetted surface. A conservatively low value for Q_{avg}'' is used to minimize the evaporation rate and maximize the amount of film that is calculated to run off the surface. The distance down the vertical sidewall at which the film reaches Γ_{min} is calculated as the minimum of

$$Z_{min} = \frac{(\dot{m}_{PCS} - \Gamma_{min}P_{wetted})\,h_{fg}}{\dot{Q}''_{avg}P_{wetted}}$$

and the sidewall height. From this point on, the wetted perimeter (or film coverage) is conservatively assumed to decrease as the film continues to evaporate at the constant stability limit, Γ_{min}. This assumption is conservative because, in the PCS tests, the film stripes were observed to continue to thin while maintaining a relatively constant width until they were completely evaporated.

The rate of change of the film flowrate with height is related to the evaporation rate

$$\Gamma_{min} \frac{dP_{wetted}}{dz} = P_{wetted} \frac{\dot{Q}''_{avg}}{h_{fg}}$$

Solving for P(z) gives the exponential function

$$P(z) = P_{wetted}\, e^{-\dot{Q}''_{avg} z / \Gamma_{min} h_{fg}}$$

The film runoff flowrate at the bottom, Z_{max} , is

$$\dot{m}_{runoff} = \Gamma_{min} P_{wetted} e^{-\dot{Q}''_{avg} (Z_{max} - Z_{min}) / \Gamma_{min} h_{fg}}$$

The PCS flow that will be applied in the evaluation model is the difference of the gravity driven PCS flowrate and the runoff flowrate. The calculations are summarized in Table 7.

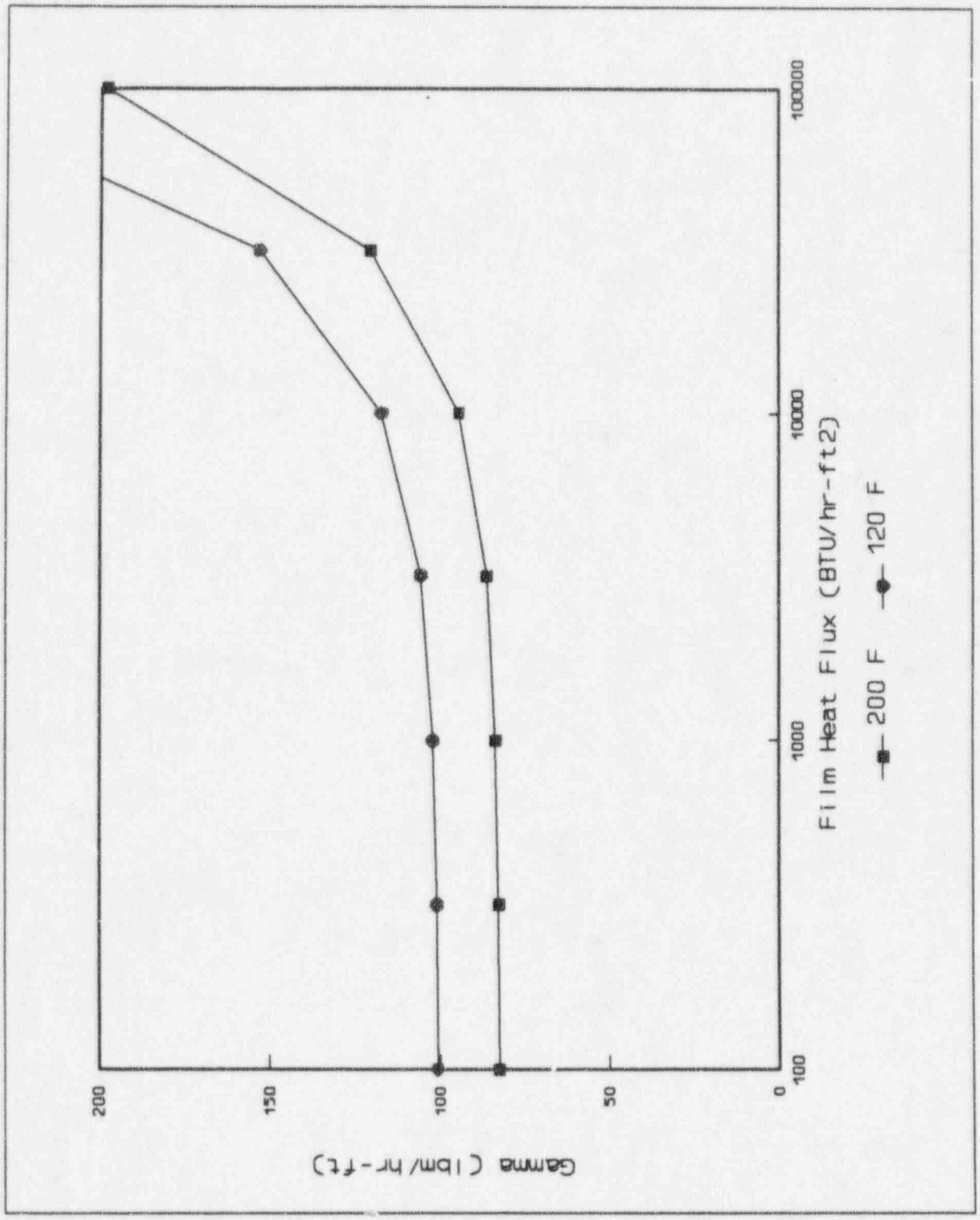

Figure 13 - Minimum Stable Film Flow Rates Predicted by the Zuber-Staub Model Showing Sensitivity to Heat Flux and Film Temperature at a [ ] Wetting Angle

Table 7 - Input PCS Flowrate for the DBA Evaluation Model

Rref = [ ] a,c
Zmax = 83.458
hfg = 1000

Time (s)	PCS Flow (lbm/s)	Gammin (lbm/hr-ft)	Wsprng (ft)	Avg. Q (BTU/hr-ft2)	Zmin (ft)	Wexit (ft)	Runoff (lbm/s)	PCS Net (lbm/s)
0		120	327.4468	7000	30.60318	15.00116	0.500039	
600		120	327.217	4500	47.51855	85.02066	2.834022	
1200		120	326.9873	4500	47.43203	84.68576	2.822859	
1800		120	326.7576	4400	48.42142	90.4271	3.014237	
2400		120	326.5278	4200	50.63424	103.5116	3.450387	
3000		120	326.2981	3800	55.86127	136.1715	4.53905	
3600		120	326.0684	3400	62.31803	179.1353	5.971176	
7200		120	324.69	2300	83.458	324.69	10.823	
18000		120	320.4738	1500	83.458	320.4738	10.68246	
19800		120	267.7711	1400	64.86209	215.5473	7.184909	
32400		120	266.3116	1300	66.99671	222.8138	7.427127	
54000		120	263.8792	1200	67.3493	224.6187	7.487291	
75600		120	261.2846	1200	61.6628	210.1157	7.003856	
77400		120	253.3387	1200	43.5233	169.9289	5.664297	
93600		120	251.8792	1200	40.06714	163.2105	5.440351	

PCS Flow: [ ] a,c

PCS Net: [ ] a,c

References

1. Frank Kreith, "Principles of Heat Transfer", 3rd Edition, 1973

2. W. A. Stewart, "Natural Convection Cooling of AP-600 Containment", Westinghouse R&D Report 87-8J0-PASIV-R1, April 1987

3. A. T. Pieczynski, W. A. Stewart, WCAP-13884, "Water Film Formation on AP600 Reactor Containment Surface", February 1988

4. J. E. Gilmore, WCAP-13960, "PCS Water Distribution Phase 3 Test Data Report", December 1993

5. W. A. Stewart, A. T. Pieczynski, L. E. Conway, WCAP-12665 Rev 1, "Tests of Heat Transfer and Water Film Evaporation on a Heated Plate Simulating Cooling of the AP600 Reactor Containment", April 1992

6 R. E. Batiste, WCAP-14134, "AP600 Passive Containment Cooling System Integral Small-scale Tests Final Report", August 1994

7 F. E. Peters, WCAP-13566, "AP600 1/8th Large Scale Passive Containment Cooling System Heat Transfer Test Baseline Data Report", October 1992

8. F. E. Peters, WCAP-14135, "Final Data Report for PCS Large-Scale Tests, Phase 2 and Phase 3", July 1994

9. D. R. Spencer, Enclosure 2 to Westinghouse Letter NTD-NRC-94-4100, "Liquid Film Model Validation", January 1994

10. R. Wright, PCS-GSR-003, "A Method for Determining Film Flow Coverage for the AP600 Passive Containment Cooling System", July 1994

11. R. Ofstun, Letter NTD-NRC-96-4635, "Summary of Applicability of the Zuber-Staub Film stability Model and Method to Address Water Coverage in the AP600 PCS Evaluation Model", January 1996

12. D. R. Spencer, WCAP-14190, "Scaling Analysis for AP600 Passive Containment Cooling System", October 1994