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WINCOF-I Code for Prediction of Fan Compressor Unit With Water Ingestion

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PREFACE

The Interim Report is devoted to the research on Tasks 1 and 2 of the Statement of Work of NASA Grant No. NAG3-481 related to NASA-DOT Agreement DTF A03-83-A-00328. Task 1 of the Statement of Work states that the WINCOF code is to be modified to obtain steady state performance of a fan-compressor unit taking into account (1) the scoop factor, (2) the time required for the setting-in of a quasi-steady distribution of water and (3) the heat and mass transfer processes over the time calculated under (2). Task 2 requires obtaining the performance of the fan-compressor unit of the generic engine utilizing the code developed under Task 1. These tasks have been completed. While the current interim report provides a description of the foregoing, a copy of the modified WINCOF-I code and illustrative predictions is provided separately.

Mr. R. Steinke has been the technical monitor at the NASA Lewis Research Center. Dr. Howard Banilower has been the technical monitor at the FAA Technical Center, Atlantic City, N.J. The Interim Report has also been reviewed by Mr. G. Klueg. Mr. W.T. Westfield has continuously encouraged and critically examined all aspects of the research project.

ABSTRACT

The PURDUE-WINCOF code, which provides a numerical method of obtaining the performance of a fan-compressor unit of a jet engine with water ingestion into the inlet, has been modified to take into account (1) the scoop factor, (2) the time required for the setting-in of a quasi-steady distribution of water and (3) the heat and mass transfer processes over the time calculated under (2). The modified code, named WINCOF-I, has been utilized to obtain the performance of a fan-compressor unit of a generic jet engine. The results illustrate the manner in which (i) quasi-equilibrium conditions become established in the machine and (ii) the redistribution of ingested water in various stages in the form of (a) film out the casing wall, (b) droplets across the span and (c) vapor due to mass transfer.

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1. INTRODUCTION

Under the Statement of Work for continuation of NASA Grant NAG 3-481 related to NASA-DOT agreement No. DTF A03-83-A-00328, Tasks 1 and 2 read as follows.

1. Modify WINCOF code to obtain steady state performance of a fan-compressor unit taking into account (1) the scoop factor, (2) the time required for the setting-in of a quasi-steady distribution of water and (3) the heat and mass transfer processes over the time calculated under (2).

2. Obtain performance of the fan-compressor unit of the generic engine utilizing the modified WINCOF code with typical distributions of water at inlet to the fan.

Both of the Tasks have been accomplished as described in the current Report.

2. DETERMINATION OF STATE OF AIR-WATER MIXTURE IN A FAN-COMPRESSOR UNIT

The objectives set under the main part of Task 1 are as follows: given the entry conditions into a fan-compressor unit of a typical high bypass ratio engine operating at specified supercharger and core speeds,

(i) to develop a numerical code that can be utilized for predicting the state of air-water mixture downstream of any stage of the machine as a function of spanwise distance along the blade, including the casing clearance region; and

(ii) to demonstrate the applicability of the code to the case of a typical high bypass ratio engine for determining the spanwise distribution of air-water mixture.

2.1. Background

In the past, a numerical code, the so-called PURDU-WINCOF code, has been developed at Purdue University (Ref. 1) for obtaining the performance of a fan-compressor unit of a typical high bypass ratio engine when it is subjected to water ingestion at entry to the unit. The code takes into account the following processes of interest:

(i) ingestion of the air-water droplet mixture;

(ii) impact, rebound and motion of droplet at blade surfaces;

(iii) centrifugal action due to the rotation of the unit;

(iv) heat and mass transfer processes between the two phases of the working fluid; and

(v) reingestion and equilibration of water at the trailing edges.

Some of the major assumptions introduced in the code are as follows:

(i) A specific streamline is chosen as providing the boundary between the core and the bypass streams, as illustrated in Figure 1.1.

(ii) The aerodynamic performance of the unit is obtained for a series of designated stream tubes, as illustrated in Figure 1.1, and a stage-stacking procedure is adopted to combine the performance of one stage with another.

(iii) Centrifugal action on water droplets is calculated in each stage of the unit based on the following assumptions:

(a) centrifugal action in a stage occurs over a period of time corresponding to the residence time of air-water mixture in the stage;

(b) liquid water centrifuged moves radially towards the casing wall and accumulates and moves along the casing wall at an arbitrary speed; and

(c) water vapor centrifuged moves radially inwards towards the hub and is immediately fully mixed with the air flow. However, one has also to take into account the thermal inertia of various components and flows.

(iv) Heat and mass transfer processes, being rate-dependent, occur over a period of time, once again, equal to the residence time of the air-water mixture in the stage.

2.1.1. *Some Recent Observations*

While the model developed in the code PURDU-WINCOF has served in general to establish a method of obtaining changes in performance of fan-compressor unit and engine due to water ingestion, analysis of a series of test results obtained by engine manufacturers over several years has introduced certain new considerations as follows:

(i) Liquid water centrifuged towards the casing should properly be considered as residing and moving in the blade-casing clearance region. If the amount of water accumulating therein gives rise to a moving film of thickness that becomes equal to the clearance space, any further quantity of water centrifuged may only be considered as being splashed back into the span of the blade.

(ii) The velocity of liquid motion at the casing wall cannot be equal to the velocity of motion of the air-water droplet mixture in the neighborhood, at the tip of the blade under consideration. The film of water can move only due to the shearing action of the air-water droplet mixture. Furthermore, there is a reduction in the velocity of the film due to the radial deposition and mixing of the centrifuged water with the existing film.

A steady state of operation of a fan-compressor unit with water ingestion may be identified taking into account such a difference in velocity of the film and that of air-water mixture. In other words, considering an instant of time $t = t_o$ at which a stage has the first impact with air-water mixture across itself, one has to allow a lapse of time equal to, say, t_s, at the end of which the film and the air-water mixture are in mechanical equilibrium. Thus, at the time $t = (t_o + t_s)$, one can consider a steady state to have been reached, although only with respect to the centrifugal action. In general, the time interval t_s may be two orders of magnitude (several hundred times) larger than the air-water mixture residence time in the stage.

(iii) The state of air-water mixture at the exit of the core compressor depends upon (a) the mechanical redistribution of the mixture, as well as (b) the heat and mass transfer processes between the two phases of the mixture.

There are also reasons to believe that the vapor content of the mixture is substantially larger at the end of the core compressor than is generally predicted by the PURDU-WINCOF code. Since the heat and mass transfer processes are rate dependent, the residence time of water must be larger than the residence time of air in a stage and in the unit.

Considering a steady state operation, it is clear that the heat and mass transfer processes should also be calculated over a period of time of the $O(t_s)$, rather than $t_m = l_s/V_z$, where l_s and V_z represent the characteristic stage length and axial velocity of mixture, respectively.

Accordingly, the PURDU-WINCOF code has been modified to account for the above observations, Section 2.2.

2.1.2. *The Concept of a Steady State of Operation*

The dynamics of the atmosphere and the variety of length and time scales associated with the various processes occurring as parts of a general thunder storm do not permit the visualization of steady state conditions with respect to the air-water mixture ingested into an aircraft engine. However, purely for purposes of rational analysis, one considers a steady state of air-water mixture ingested into the engine.

As stated in Section 2.1.1, the motion of the air-water mixture and the transformations in state that the mixture undergoes in the engine are also governed by a variety of time and length scales. It is, therefore, again necessary to proceed with a definition of an idealized steady state wherein, with respect to a selected process, equilibrium conditions may be expected to have been attained in the local environment. However, various processes may involve different time scales for the attainment of equilibrium conditions, for example mechanical and heat and mass transfer processes. It may then be necessary to identify a maximum or a mean interval of time for such processes and utilize that interval for the attainment of equilibrium conditions.

Considering an engine and its control system, ingestion of water may be expected to produce a series of responses and a steady state of operation may become entirely impossible. However, if no oscillatory or run-away conditions arise, it is again possible to consider, in an idealized fashion, a steady state of operation as a result of the possibly nonlinear interaction between the given design and state of operation of the engine and the entering air-water mixture.

Finally, when action is initiated externally for a change in power demand, for example, there are again the possibilities of attaining a steady state or an oscillatory or run-away condition. In fact, one of the principal interests in water ingestion problems is the prediction of the transient performance of the engine and the establishment of the end state following the transient operation.

In the current investigation, considering only the fan-compressor unit and the centrifugal action therein, a steady state is visualized on the following bases:

(i) The state of air-water mixture and its distributions at entry to the fan, the low pressure compressor (LPC) and the high pressure compressor (HPC) are steady in time.

(ii) In a given stage, the film of a certain thickness in the casing-blade clearance zone moves at a speed that is determined by the local shearing action of the air-water mixture. Eventually as centrifugal action continues, a thickness of film is attained whose momentum is equal to the momentum that can be transferred to it by the air-water mixture. That condition, defined earlier as the equilibrium state, becomes the steady state condition in that stage.

(iii) In the case of a multi-stage unit then, one proceeds from stage 1 to the last stage to obtain the steady state condition by a series of sweeps through all of the stages.

The details of the foregoing may be explained as follows:

(a) A calculation step interval of time, t_m, is chosen that is small compared to the time scales connected with the motion of the air-water mixture, machine and film and, at the same time, large compared to the time scales in the centrifuging process, growth rate of film and other air-droplet interaction processes.

(b) One starts with stage 1 of the multi-stage unit under consideration and performs the centrifugal action calculation in that stage. This yields a redistribution of water in the stage and the accumulation of a certain amount of water in the casing-blade clearance zone. It is then possible to proceed to examine the balance of momentum between the film and the adjoining air-water mixture taking into account the viscosity of the two fluids and hence obtain the speed of the interface between the two fluids as well as the mean speed of the film.

The foregoing provide initial conditions for the next stage downstream and the calculations can be repeated in that stage, and so on for various succeeding stages.

Beginning with the calculation in the first stage, designated for example by the instant of time $t = t_o$, a clock is started that keeps account of the $\Sigma\, t_m$ over all of the stages considered.

(c) When the calculations have been completed in all of the stages of the unit in one pass, one starts the calculations again starting with stage 1 through all of the stages up to the exit of the unit until "equilibrium" or "filled in" conditions are reached in all stages.

In successive passes it is possible to visualize several types of situations that may arise, namely:

(1) In certain stages, the interface velocity may become sufficiently small that one can assume attainment of equilibrium or steady state condition in those stages.

(2) In a number of stages, whether or not the equilibrium state has been reached, the clearance may be entirely filled with water, that is the film thickness may be nearly equal to the clearance. In that case, one can assume that further displacement of water into the clearance zone is not possible and all such centrifuged water may only splash back into the span of the blade.

(3) One may encounter a situation in which the film in the clearance zone is still thin and also not yet in an equilibrium state, while the span of the blade has become almost completely depleted of water.

(4) Finally, in view of the fact that the performance of any intermediate stage of a multi-stage unit depends upon the performance of all of the upstream stages, it is necessary to ensure that (a) equilibrium conditions are established in sequential order in various stages and (b) the performance of all of the stages that have attained equilibrium

conditions must be kept "frozen", with the use of an appropriate "flag" in the computational program, during succeeding sweeps across the compressor.

The foregoing add complexities to the calculations, but the principle of establishing steady state conditions remains the same.

2.2. Equilibrium Conditions in a Stage with respect to Centrifugal Action

A typical stage of compressor unit or a fan unit is considered with the following initial and operating conditions:

(i) Air-water mixture with a specified content of water vapor and water enters the stage with a given non-uniformity in velocity and composition across the span of the stage; the composition includes droplet size, designated on a suitable basis as large and small.

(ii) A film of known thickness enters the stage in the space generally identified as the blade-casing clearance and with a certain mean velocity of motion.

(iii) The stage is operating at a certain rotational velocity with a specified nominal (air-based) flow coefficient.

Now, as a result of centrifugal action, water towards the hub is displaced towards the tip while water vapor is displaced towards the hub. A model can be constructed, as in Ref. 1 and illustrated in Figure 2.1, for the motion of water and water vapor. A certain amount of water reaches the blade-casing clearance zone.

The objective then is to obtain a means of predicting the growth and the motion of the film up to the instant of time when there is equilibrium locally between the film and the air-water mixture.

A model is developed as illustrated in Figure 2.2 and is fully discussed in Appendix I to this Report. The following assumptions are introduced:

(i) The film of water and the air-water mixture are associated with specific values of viscosity.

(ii) The film of water has zero velocity at the casing wall.

(iii) The air-water mixture exercises a shearing action on the film as a consequence of which the film attains a certain value of velocity.

(iv) The total amount of momentum that can be delivered by the air-water mixture to the film of water is a fixed quantity.

(v) There is a gain in the momentum of the film due to the impacting of the (newly) centrifugally-displaced water droplets while there is a loss due to mixing. The net loss may be considered parametrically.

(vi) In view of (iv) and (v), when the film thickness attains a certain value, the air-water mixture is no longer able to "shear" the film to a higher velocity. Under that condition, the velocity of the interface between the film and the air-water mixture must be negligibly small. One can then consider that an equilibrium state has been attained.

(vii) The length of time required for the attainment of equilibrium state from $t = t_o$, the instant of first encounter between the mixture and the blade, is the interval of time over which centrifugal action has added to the growth of the film. The same interval of time may also be considered in a first-estimate as the interval of time over which heat and mass transfer process should be calculated although this may be grossly in error depending upon the thermal inertial of the medium and of the material parts of the machine.

2.3. Scoop factor

The Purdue WINCOF code works with any given distribution of water (content and droplet size) and water vapor (content) at entry to a stage. There are some ambiguities in specifying the entry conditions at several locations, some of which are as follows:

(i) the entry to the core compressor following a connecting goose-neck in which there may also be a bleed valve;

(ii) a location where a bleed valve may exist;

(iii) the entry to the low pressure compressor following the fan stages where a splitter divides the core flow from the bypass flow; and

(iv) the entry to the first fan rotor.

Various assumptions are made in each case to obtain a set of operational parameters than can be investigated over design ranges. There is considerable evidence to show that particular attention should be paid to (iv) above since the amount of water that enters the engine as a whole and the core in particular are determined by (iv) directly and in combination with (iii).

The Purdue WINCOF code does not include the influence of an inlet to the fan-compressor unit. It also does not include the role of the spinner, which is both a collector of on-coming water and a distributor of such collected water by centrifugal tearing. Finally the PURDU-WINCOF code does not include a means of establishing the amount of water "scooped" into an inlet from the atmosphere when an installed engine is in flight. However, as stated earlier, the code does permit the use of any desired distribution of air-water mixture as part of the initial conditions to any stage.

Some tentative definitions for scoop factor are illustrated in Figure 2.3.

It may be pointed out the inlet scoop factor becomes equal to unity in two circumstances: (i) testing an engine on-ground in a direct-connect mode and (ii) testing an engine in-flight with injection of water directly into the inlet. In both cases, there may arise some complexities in regard to other scoop factors also.

The distribution of water along the span of the fan and that of the low pressure compressor may be expressed in terms of scoop factors. The WINCOF code, however, requires only a distribution of water to be specified at entry to each stage.

Some further remarks are included in Section 4 concerning the spinner and the splitter plate.

2.4. Modifications of WINCOF Code

Several subroutines have been modified in the WINCOF code to obtain the modified code WINCOF-I. The modifications consist of additions to and of various subroutines; these are described in Appendix I.

Block diagrams for illustrating the use of the new subroutines for undertaking calculation of the effects of centrifugal action and heat and mass transfer are provided in Figure 2.4.

2.4.1. *Clearance Distribution*

One of the principal design parameters affecting the accumulation and motion of the film as well as the occurrence of critical conditions, such as splash back, is the distribution of clearances between the blading and the casing throughout the fan-compressor unit. It is a necessary input into the calculation procedure.

There is some ambiguity in regard to the actual clearance obtained in a unit at various power demand levels even during operation with air. When there arises water ingestion, no clearly rational procedure is available for estimation of the clearance taking into account the thermal inertial of the system, the complex cooling air passages and the heat transfer between the fluid mixture and the machine elements. In view of the time-dependent calculation that has been adopted for estimating the eventual attainment of steady state conditions, one also faces the problem of specifying transient values of clearances.

The modified WINCOF code requires specification of a clearance for each stage of the unit, and provision has been made to specify a desired clearance value in each stage.

2.4.2. *Calculation Step Interval of Time*

A scenario is visualized as follows: the fan-compressor unit of an engine is supplied with or becomes subjected to ingestion of a specified air-water mixture when it is operating at a given rotational speed. The air-water mixture flows from the fan entry into, on the one hand, the fan exit into the bypass stream and, on the other, the low and high pressure compressor sections. There is obviously a flow time required, the period of time for motion of air-water mixture from front to back of the unit. In any chosen stage of the unit also, it is possible to obtain a measure of this time as $t_m = l_s/V_z$, where l_s and V_z are the characteristic streamwise length of the stage and axial velocity through it, respectively; reference may also be made to Section 2.1.1.

A certain amount of water and water vapor is subjected to centrifugal action in that interval of time in the stage under consideration. Therefore, even during the motion of the air-water mixture into the next stage, a part of the span in the vicinity of the hub would have become depleted and that needs to be taken into account in establishing the local distribution of water in that stage and its redistribution.

It may be pointed out here that steady state conditions are unlikely to have been reached in an arbitrary nth stage in the period of time $\sum_{1}^{n} t_m$. It is obviously unlikely that equilibrium conditions would have been reached between the film at the casing and the air-water mixture in that interval of time.

By carrying out successive sweeps of all of the stages, using t_m for the calculation step interval of time, one can establish the total time required in each stage for equilibrium and/or choking (film thickness being equal to clearance at the highest mean velocity of film) condition to be attained. In general, in the nth stage, that interval of time $t_s \sim (p_n.t_m)$, where p_n is of $O\,(10^1 - 10^2)$, Appendix I to this Report.

In each stage, at the end of each time step t_m, one can obtain the following:

(i) thickness of film in the casing-blade clearance region;

(ii) steady state spanwise distribution of water and water vapor; and

(iii) initial conditions for operation of the next stage.

A pictorial representation of the implications of the calculation step period of time is provided in Figure 2.5.

2.4.3. *Splash Back*

Considering the redistribution of water due to centrifugal action, three types of possible conditions have been identified in Section 2.1.2. Among those, the situation of the clearance becoming completely filled by water is of interest whether or not there is equilibrium between the film and the air-water mixture. Once the clearance is nearly completely occupied by water, any further centrifuging results in the centrifuged water becoming splashed back into the span of the blade.

It is assumed that the splashed back water becomes fully mixed with the main air-water mixture.

In certain stages of multi-stage compressor unit, it is possible that the splash back condition may coincide with the span of the stage becoming completely depleted of water. Then the splashed back water provides a new distribution of water that is again subjected to centrifugal action in succeeding stages.

It is also of interest to note that in general the clearance may decrease (or at least remain constant at a low value) in the later stages of a compressor. Therefore, there are opportunities for considerable splash back in the downstream stages of a compressor.

2.4.4. *Inward Centrifuging of Water Vapor*

There is a certain amount of water vapor in the atmosphere depending upon the level of humidity. In the case of rain ingestion, it has been assumed throughout the investigation that air is fully saturated with humidity in the atmosphere.

Utilizing a characteristic residence time for the air-water mixture, corresponding to the attainment of mechanical equilibrium as suggested earlier, it is possible to determine the interphase mass transfer in each stage.

The total amount of water vapor is redistributed in the span of a stage noting that the vapor on account of its low molecular weight tends to move towards the hub. Such redistribution has been taken into account in the Purdue WINCOF code. It is of particular interest to determine the water vapor distribution at the exit of the core compressor since the conditions therein form the initial conditions for the diffuser-combustor section.

It is necessary to observe here that when two gases are mixed together at the molecular level, a difference in molecular weight such as that between water vapor and air does not permit separation of the gases at the rotational speeds under consideration. However, if water vapor is not thoroughly mixed but is in large local concentrations of finitely small volume, then there is a possibility of its separation by centrifugal action or even gravity. Such a situation can only arise in the current context from the formation of vapor pockets due to local heating and mass transfer effects. This is somewhat analogous to the motion of a warm element of gas relative to a colder gas under the action of gravitational or centrifugal action.

In the WINCOF code, it is simply assumed that a designated proposition of water vapor formed due to heat and mass transfer processes is subjected to centrifugal action.

3. WINCOF-I CODE

The modified code is named as WINCOF-I.

The input to the WINCOF-I code is the same as that to the WINCOF code. In addition, it is necessary to introduce a calculation step period of time for use in Subroutine WICFLM. That subroutine is designed to calculate the effect of centrifugal action. Details regarding the choice of the calculation step period of time and its use are provided in Section 2.4. It may be repeated that the period of time required for obtaining equilibrium conditions between the film of water at the casing and the neighboring air-water mixture flow is also utilized currently for determining the heat and mass transfer in each stage.

3.1. Cases Investigated.

All of the cases investigated pertain to the ingestion of large droplets, mean volumetric diameter being approximately 600 μm at inlet to the fan.

The input parameters for the various cases are listed in the following table. The cases 1, 2 and 3 are illustrated in Figures 3.1 (a) and (b).

Cases Investigated

	Flow Coefficient	Speed (Percent)	Cases
A. Fan Tip	0.369	100	1,2,3
B. Fan + LPC	0.820	100	1,2,3
C. HPC	0.464	100	1,2,3

3.2. Results.

3.2.1. WINCOF I Tape and Input-Output Files

A copy of the WINCOF-I code and set of input-output files for illustrative purposes are not part of the current Report but are being provided separately as an addendum to the Report.

3.2.2. Performance

The performance of (A) the fan bypass stream 2 (referred to as Fan), (B) the supercharger stream 5 (referred to as Fan + LPC) and (C) the high pressure compressor stream 5 (referred to as HPC) is provided in Figures 3.2 through 3.4.

The performance includes (a) the overall performance maps (pressure ratio and efficiency as functions of corrected air mass flow), (b) the stage-wise pressure, temperatures of gas phase and liquid phase, efficiency and height of film in the clearance corresponding to "equilibrium" conditions. The latter is expressed in the form of a ratio of height of film to the height of clearance in the stage under consideration.

3.2.3. Water and Water Vapor Distribution

In cases 1 and 2, the redistribution of water across the span of individual blade rows in the various units (Fan, Fan + LPC and HPC) is illustrated in Figures 3.5 through 3.8.

3.2.4. Changes in Performance During the Attainment of 'Equilibrium' Conditions

Changes in performance occur in the units of the air-compression system from the instant when injection begins at the fan entry up to the instant of time when "equilibrium" conditions are reached. In calculation, the period of time for attaining "equilibrium" corresponds to the total time for the required number of sweeps of calculations across the units.

It is particularly of interest to establish the changing conditions at the exit of the HPC unit since they constitute the entry conditions for the pre-diffuser and combustor.

Choosing case 3 of water distribution, the changing values at the exit of the HPC unit for pressure, temperature, water content in the clearance space are shown in Figure 3.9.

It may be observed that each sweep corresponds to a certain length of time and, therefore, a time scale is also included in the Figure 3.9.

4. SUMMARY AND DISCUSSION

The PURDU-WINCOF-I code provides a means of obtaining the performance of any stage of a fan-compressor unit, and also, through a stage-stacking procedure, the performance of a multi-stage unit.

The WINCOF-I code is designed for obtaining the performance of a stage of a fan-compressor unit with a steady ingestion of air-water mixture. The performance calculations are performed in small calculation time-steps. The calculation interval of time is chosen to be small compared to the residence time of the gas phase in a stage. It is implicitly assumed that the performance is nearly steady over such a small interval of time.

A guasi-steady state performance is defined in any stage as one in which the interfacial velocity between the liquid film and the gas phase flow has become sufficiently close to zero due to increase in the film thickness as water accumulates at the outer casing wall due to centrifugal action. In the alternative, it is assumed that a quasi-steady state has been reached when the clearance at the casing wall has become filled with the water film formed by centrifugal action.

Heat and mass transfer are calculated at the end of each calculation time step. When the water film at the outer casing wall has attained the so-defined quasi-steady state, the heat and mass transfer is also assumed to have attained a quasi-steady state.

In applying the WINCOF-I code to a multi-stage unit, calculations are performed in continuous sweeps across all of the stages over the relevant calculation time-intervals in each stage. A quasi-steady state is then defined as one in which the various stages of the multi-stage unit have attained quasi-steady state in succession over the total number of sages. It is important that quasi-steady be reached from stage 1 to the last stage of the unit in succession since the performance of any stage depends upon the performance of all of the stages located upstream to it.

It may be pointed out that calculations of performance can be undertaken in any of the following cases:

i) The fan-compressor unit is operating under steady-state conditions with air under assigned ambient conditions including humidity.

At clock time $t = t_o$, the fan-compressor unit begins to operate with a steady ingestion of a given air-water mixture entering the unit with a given distribution.

It is required to establish the performance of the unit (a) at the end of a certain number of calculation step intervals of time and (b) under quasi-steady state conditions.

(ii) The fan-compressor unit is operating under quasi-steady state conditions with air-water mixture under assigned ambient, ingestion and distribution conditions.

At clock time $t = t_o$, the fan compressor unit begins to operate with a steady ingestion of another air-water mixture or another distribution of air-water mixture.

It is required to obtain the performance of the unit under the conditions (a) or (b) of (i) above.

(iii) The fan-compressor unit is operating with air-water mixture under assigned ambient, ingestion and distribution conditions.

At the end of a certain number of calculation step intervals of time, before quasi-steady state conditions have set in, there arises a change either in the quality of the air-water mixture or in the distribution of air-water mixture.

It is required to obtain the performance of the unit under the conditions (a) or (b) of (i) above.

It is of considerable interest to observe that with the WINCOF-I code it is possible to obtain the entry conditions into the pre-diffuser and the combustor sections on a time-dependent basis from the instant of beginning of ingestion up to the instant of attainment of "equilibrium" conditions. This is useful both in obtaining the time required for quasi-steady state conditions to set in as well as in determining the nature of flow conditions into the diffuser-combustor section.

Finally, one may note that the initial conditions into the fan can be changed from one set to another during a calculation. In other words, considering the three illustrative cases of ingestion discussed earlier, it is possible to switch from one distribution to another even before "equilibrium" conditions have set in corresponding to the initial distribution. This is of great value in predicting the transient performance of an engine which faces different types of ingestion as a function of time.

References

1. Leonardo, M., Tsuchiya, T. and Murthy, S.N.B., "PURDU-WINCOF - A Computer Code for Establishing the Performance of a Fan-Compressor Unit with Water Ingestion," NASA CR-168005, Jan. 1982.

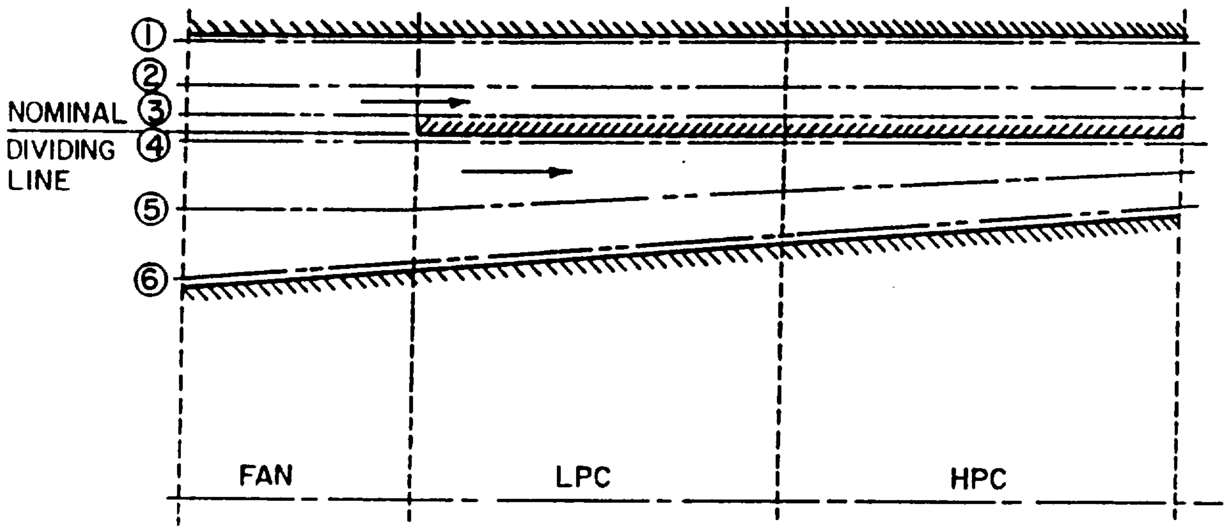


Figure 1.1. Nominal dividing line between core and bypass streams. Designated streamtubes

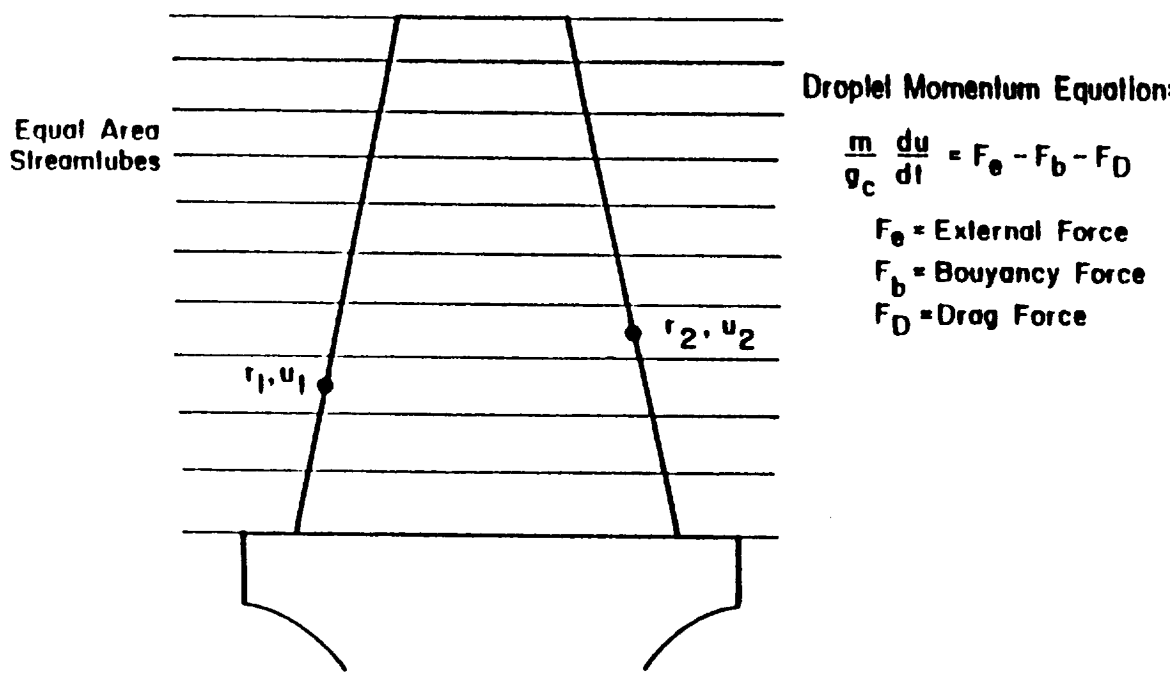


Figure 2.1. Model for motion of water.

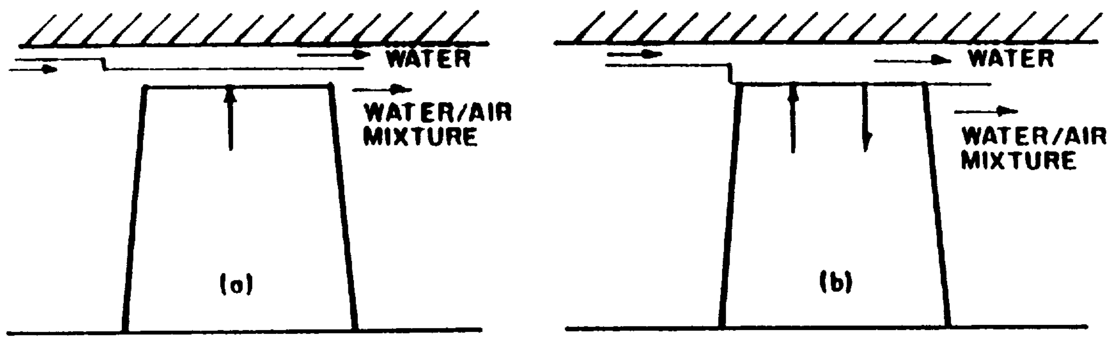


Figure 2.2. Model for growth of film up to equilibrium.

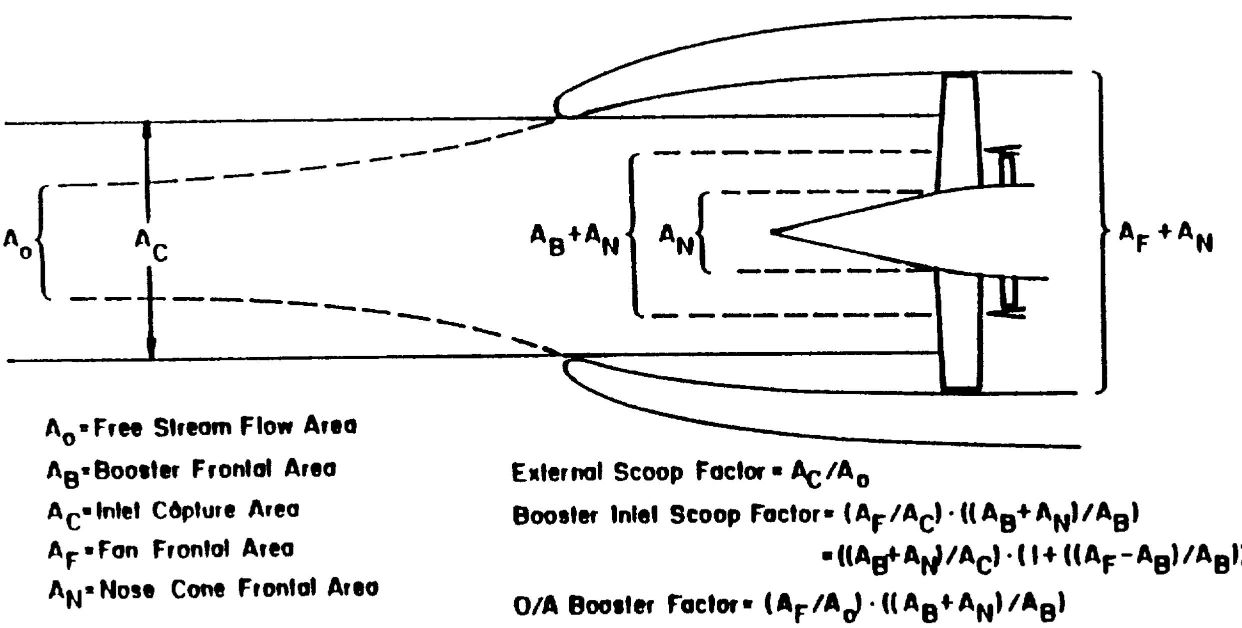
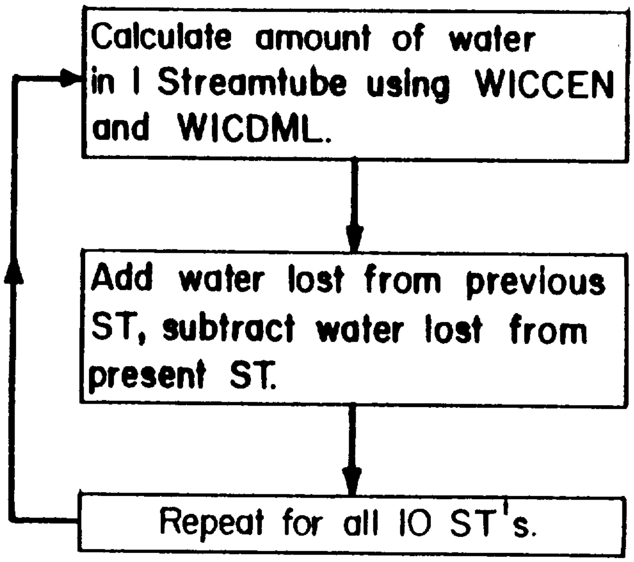


Figure 2.3. Scoop-factor definitions.

Centrifugal:



Perform entire calculation for every sweep of the code.

Figure 2.4.a Block diagrams of centrifugal, heat transfer and mass transfer routines.

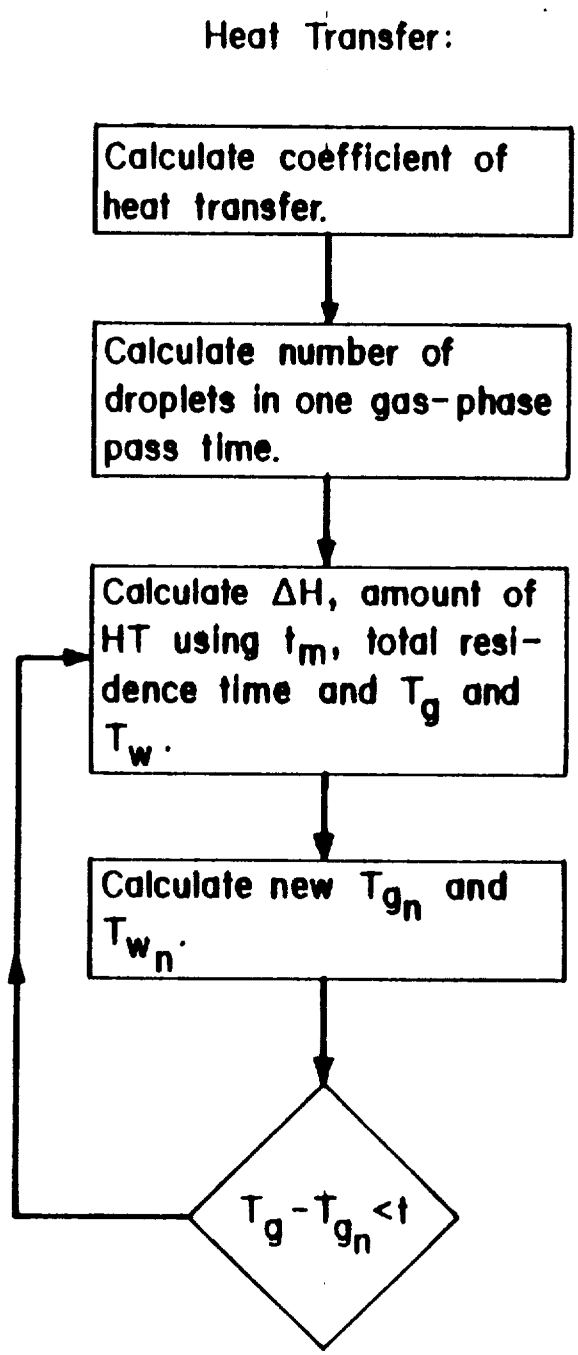


Figure 2.4.b (cont'd)

Mass Transfer:

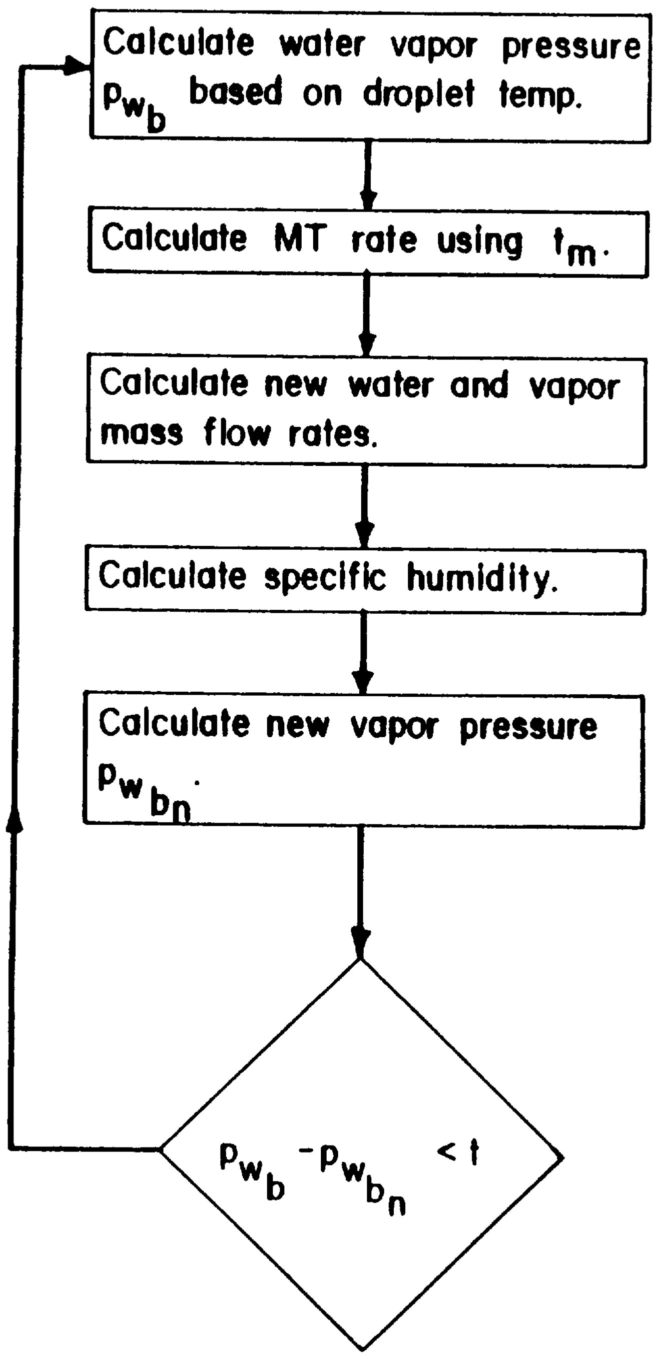


Figure 2.4.c (cont'd)

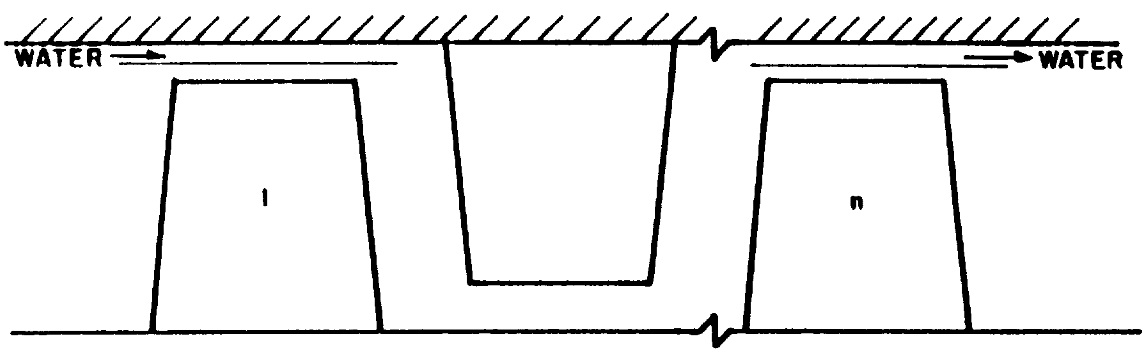


Figure 2.5. Implications of calculation step period of time.

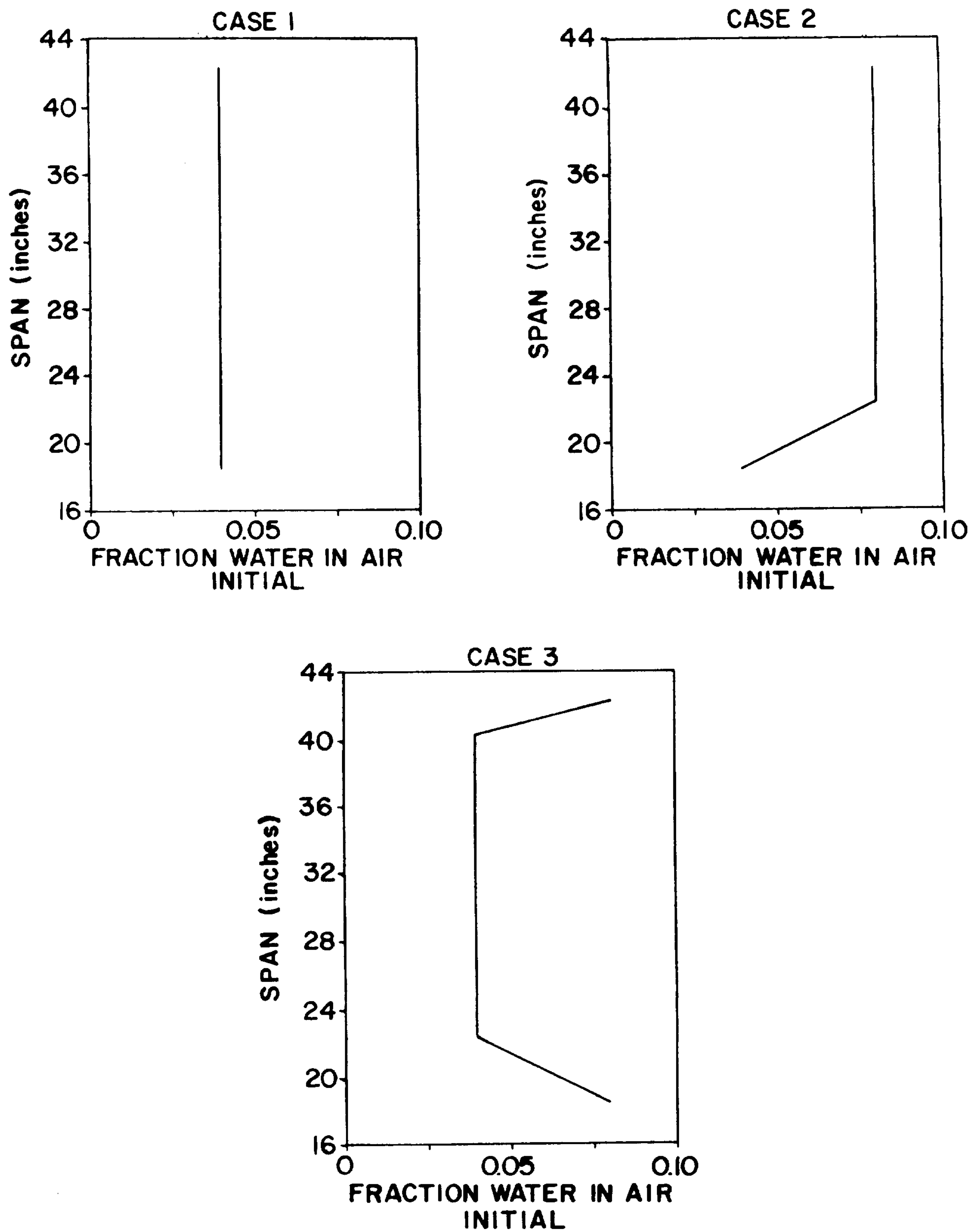


Figure 3.1 a) Fan Initial Water Distribution

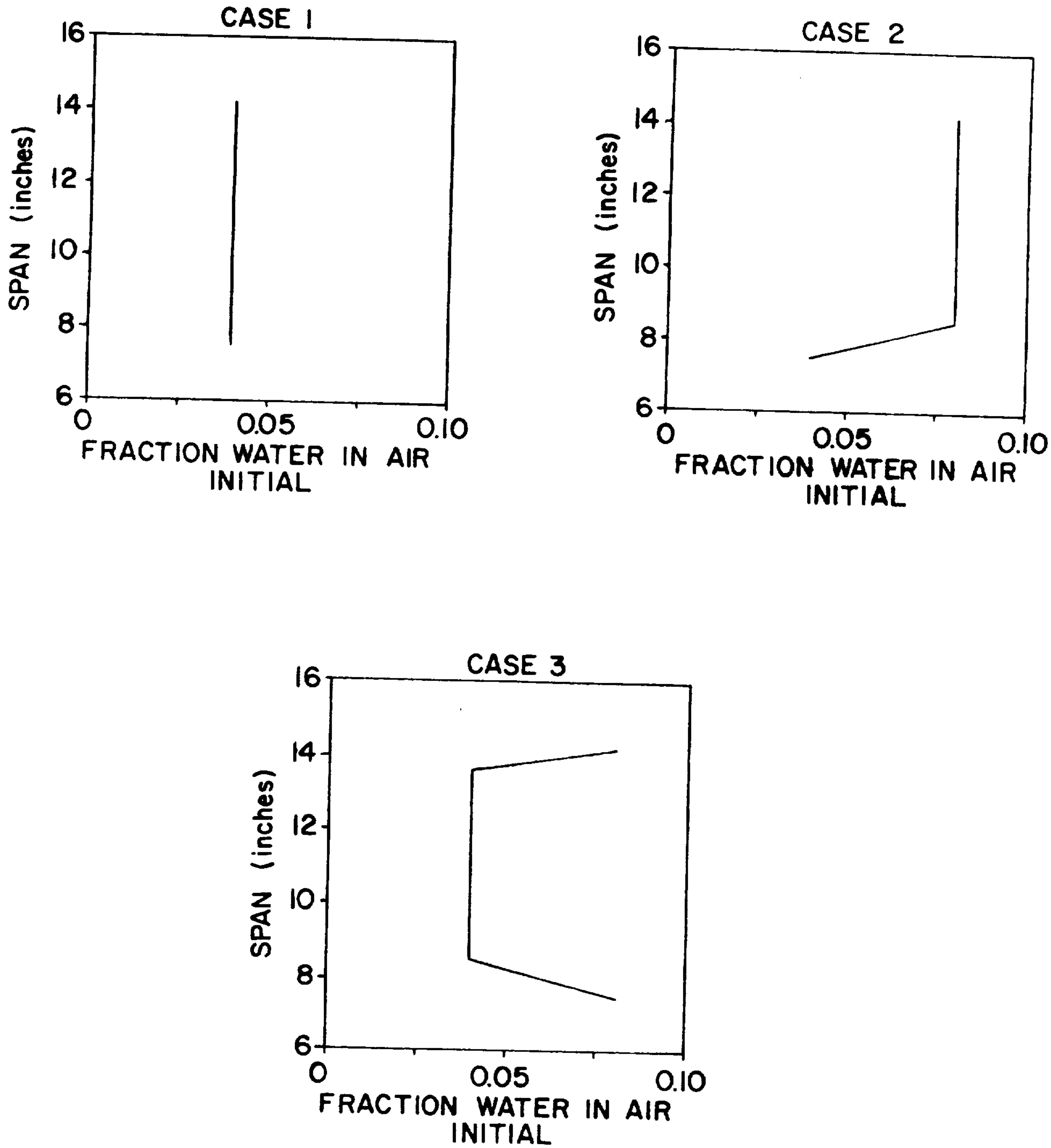


Figure 3.1 b) HPC Initial Water Distribution

FAN (ST 2)

	initial	dry	case 1	case 2	case 3
Gas Temperature (R)	518.7	629.7	628.3	628.0	628.6
Gas Pressure (psf)	2116	3762	3340	3707	3340
Water Temperature (R)	513.7	513.7	517.0	516.3	515.2
Efficiency		83.6	65.7	82.1	65.5

Clearance = 0.020 inches

Figure 3.2 Performance of Fan (1 of 3)

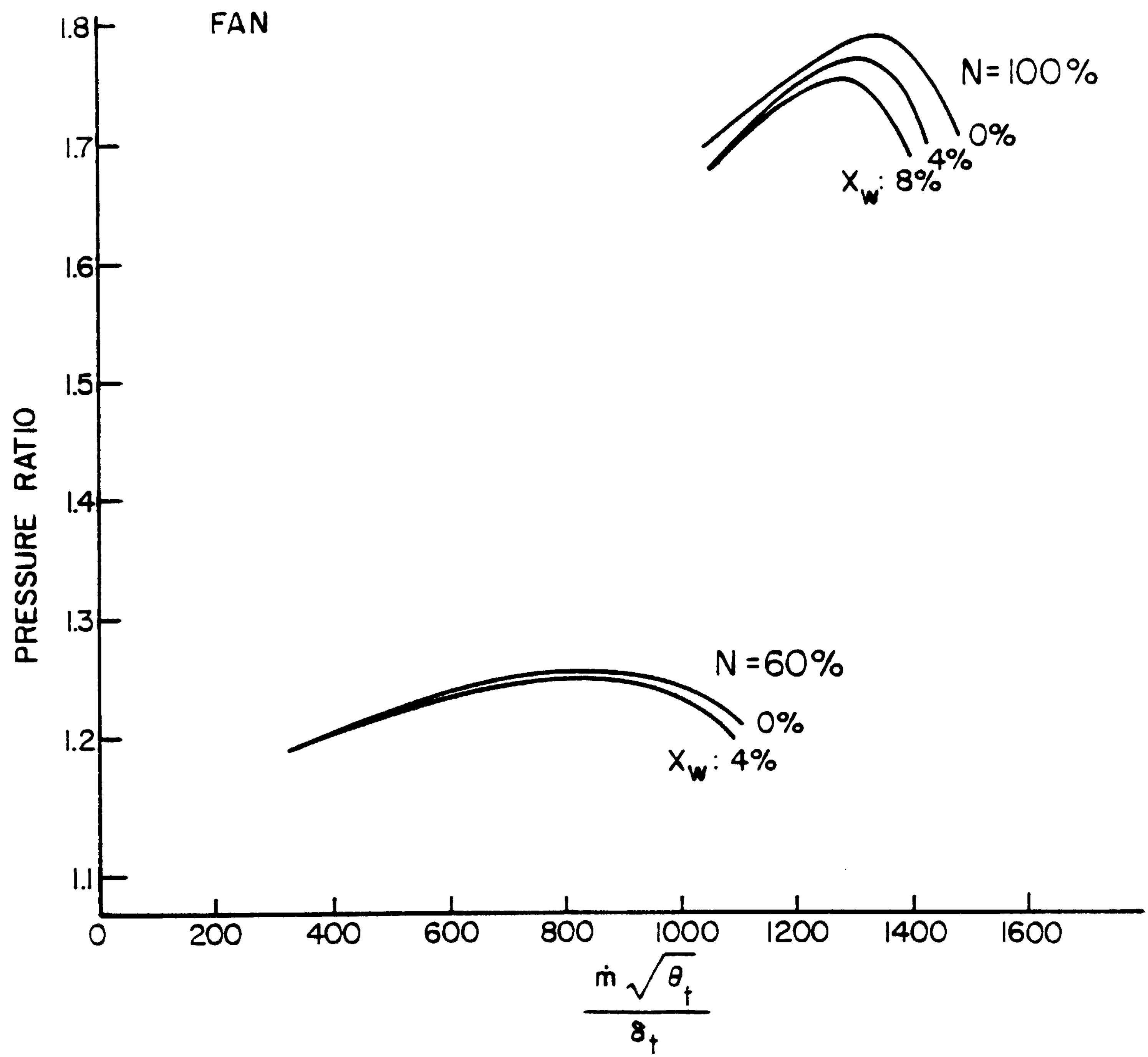


Figure 3.2 (2 of 3)

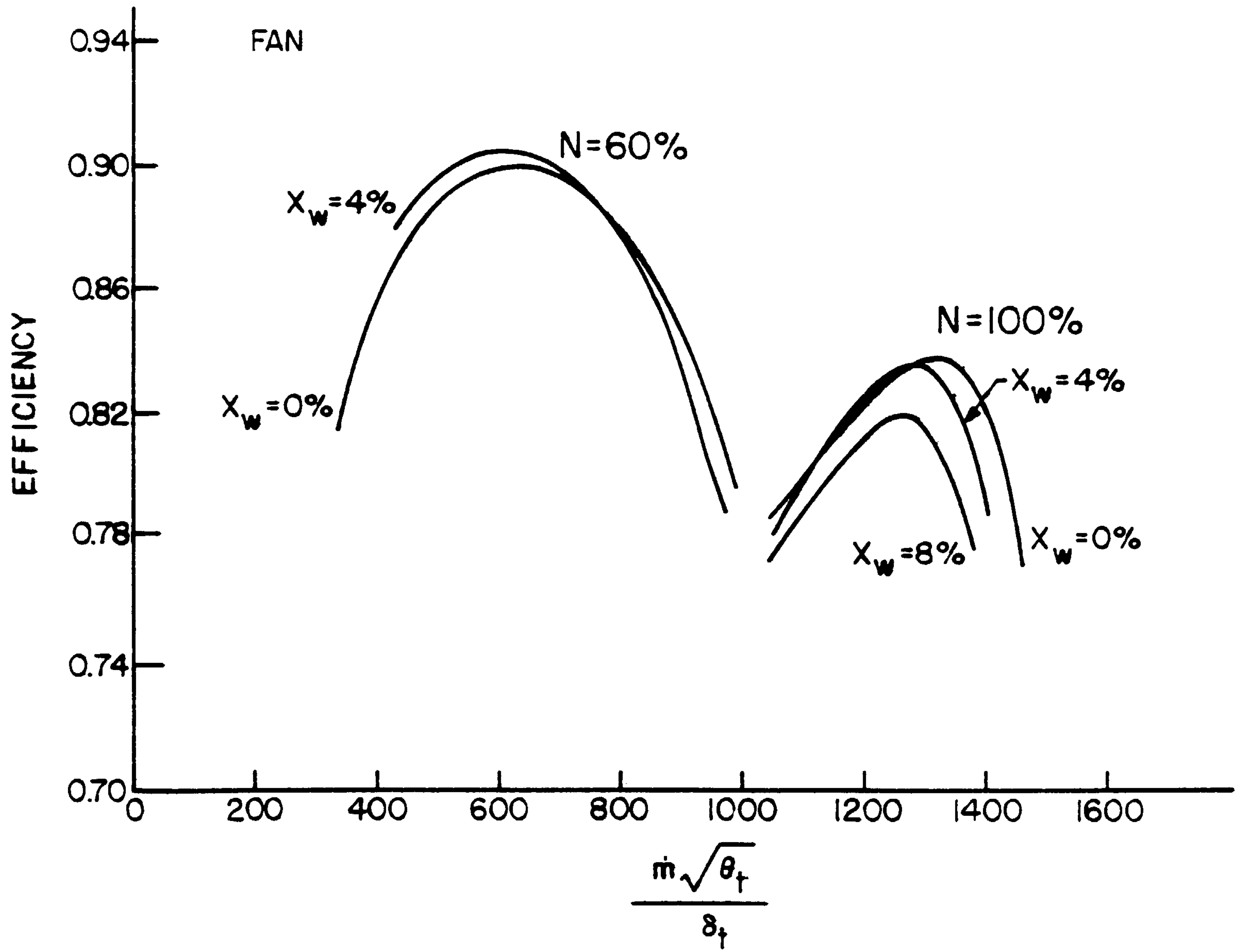


Figure 3.2 (3 of 3)

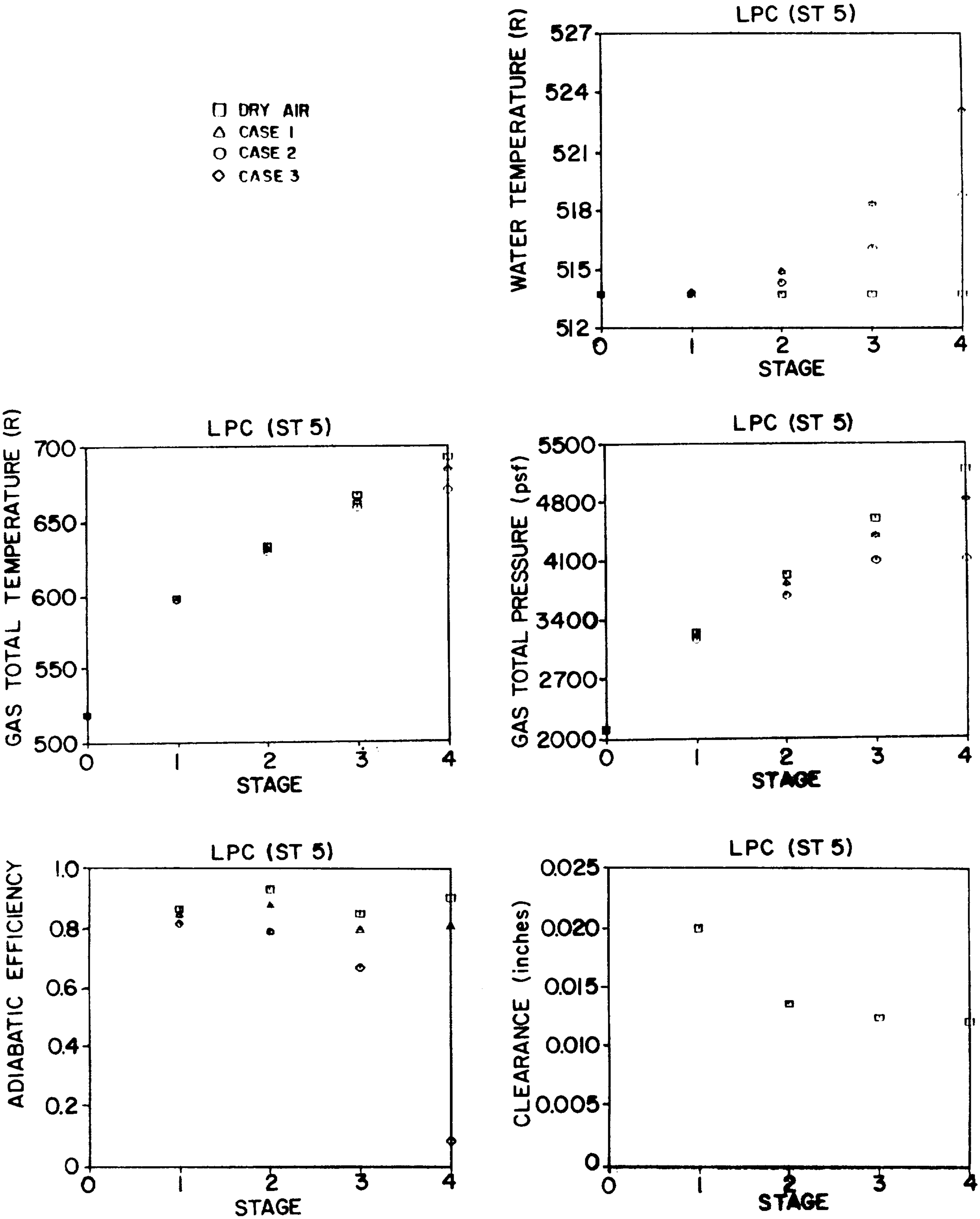
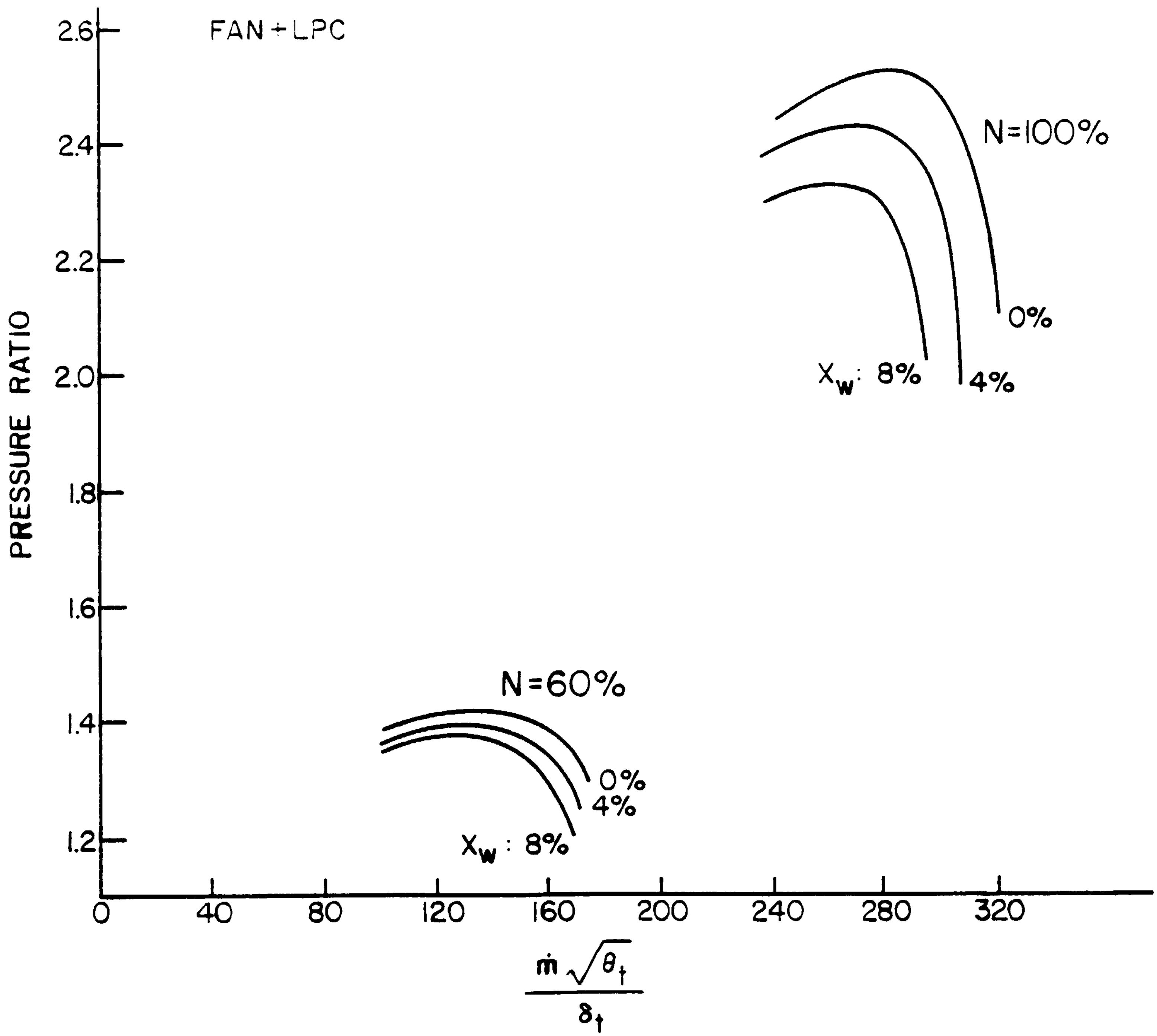


Figure 3.3 Performance of Fan + LPC (1 of 3)



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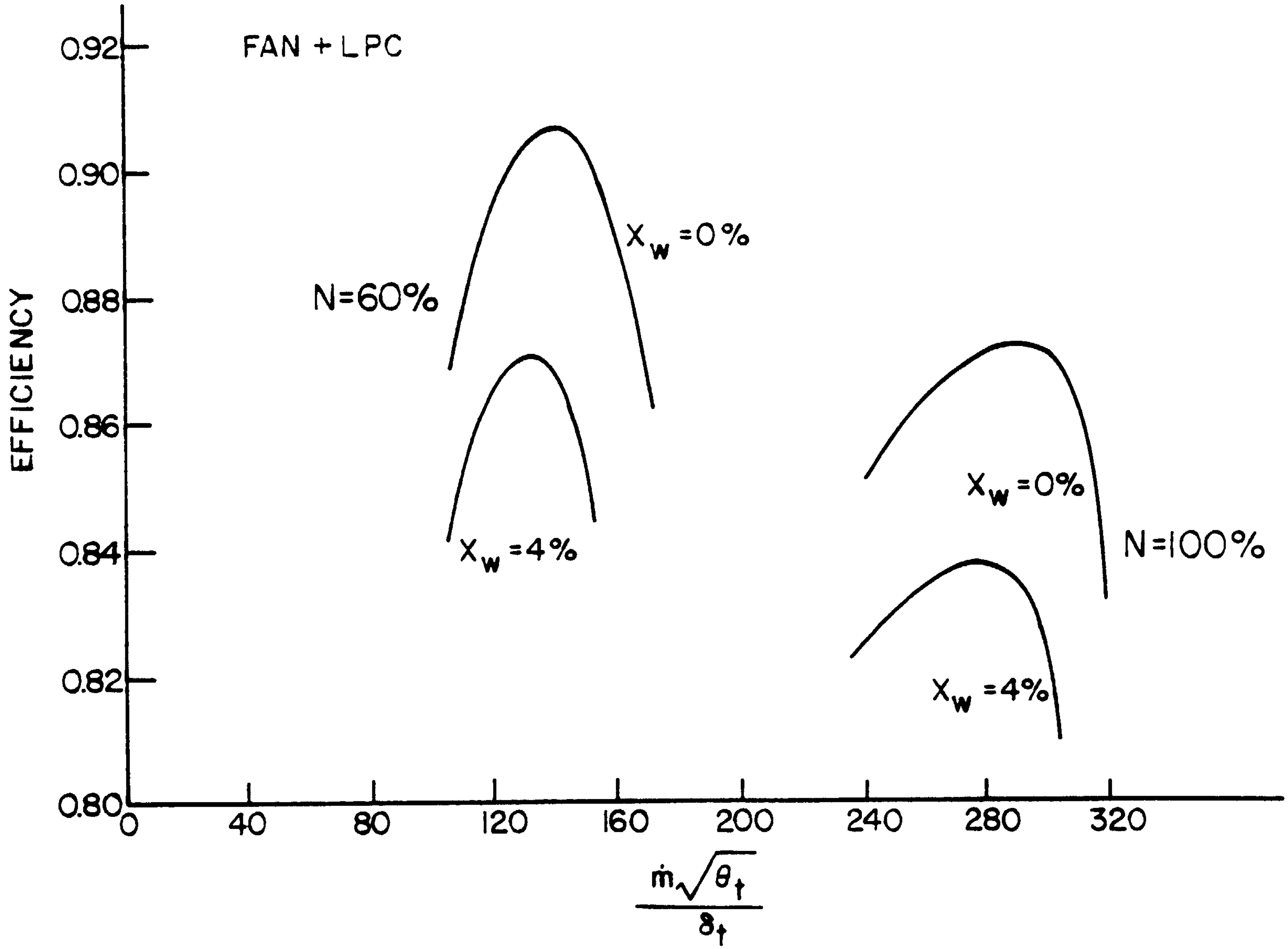


Figure 3.3 (3 of 3)

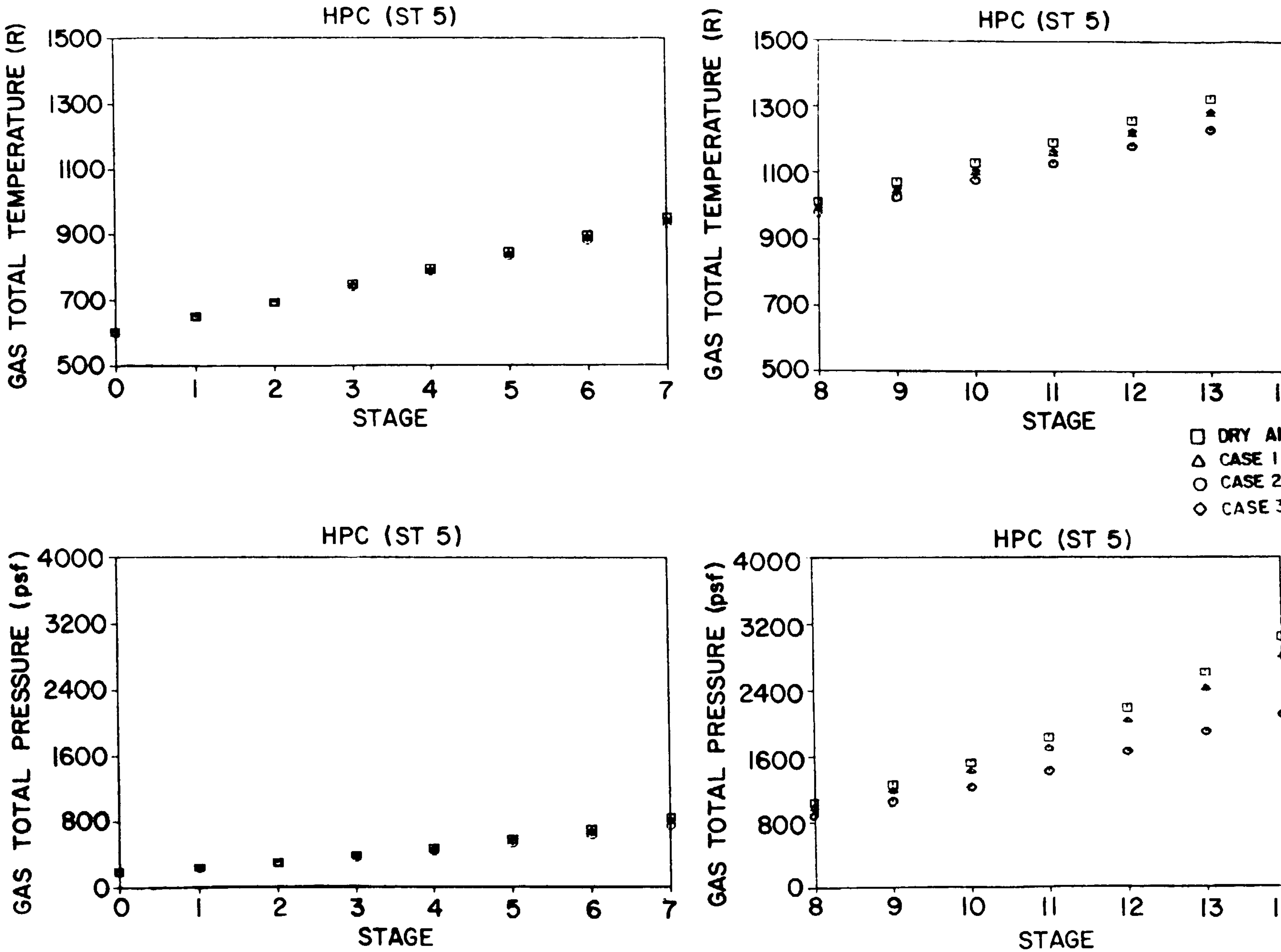
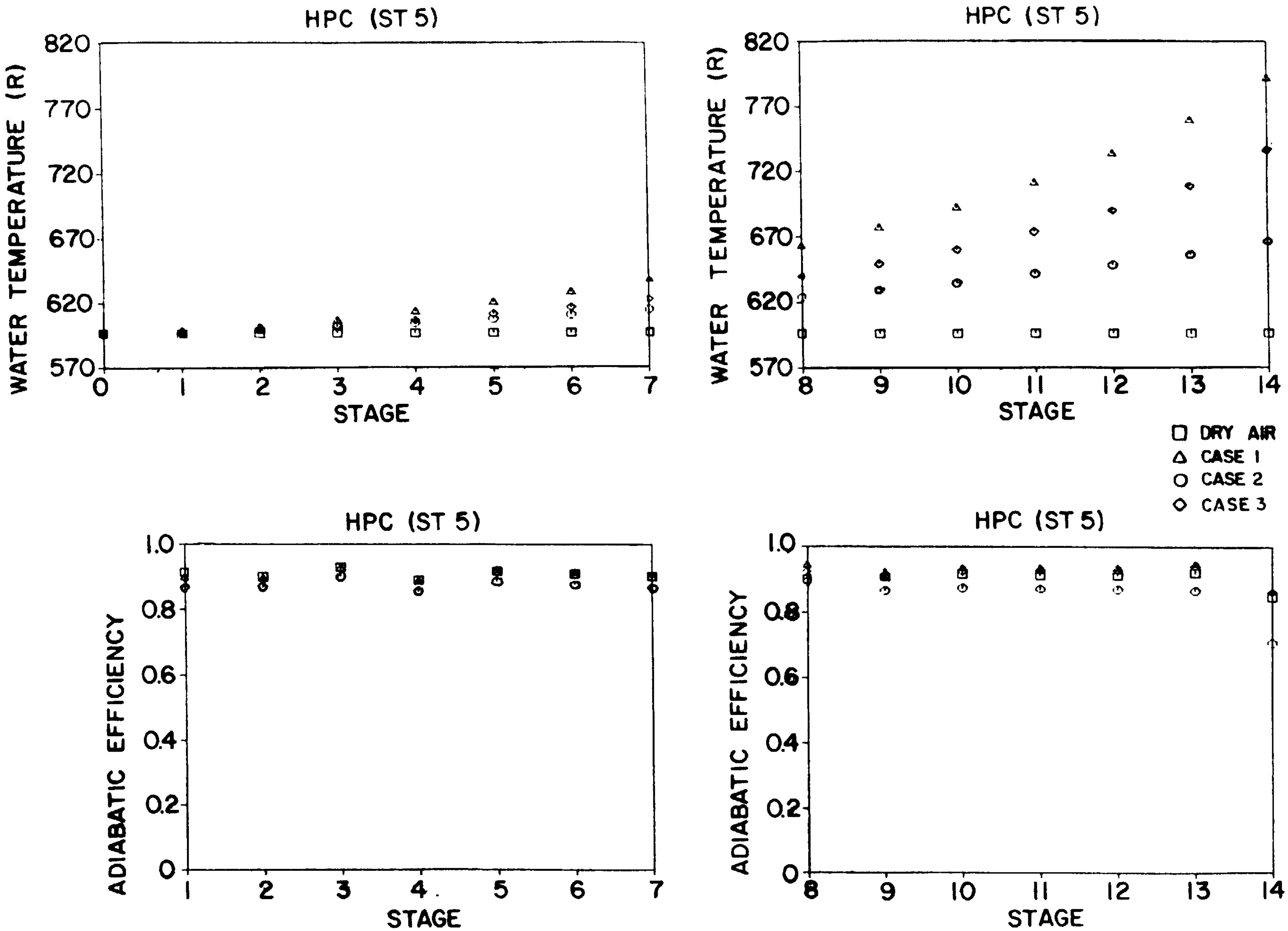


Figure 3.4 Performance of HPC (1 of 5)



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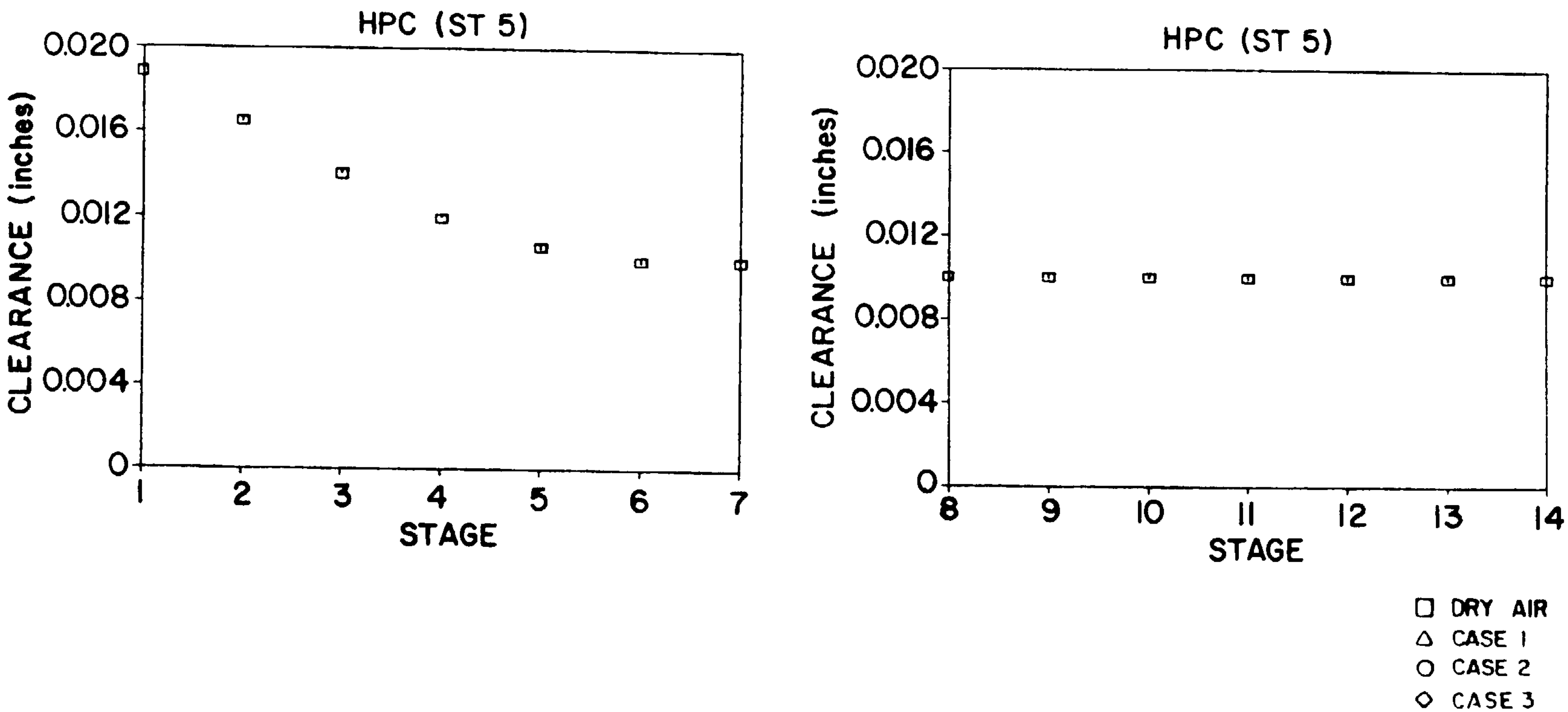


Figure 3.4 (3 of 5)

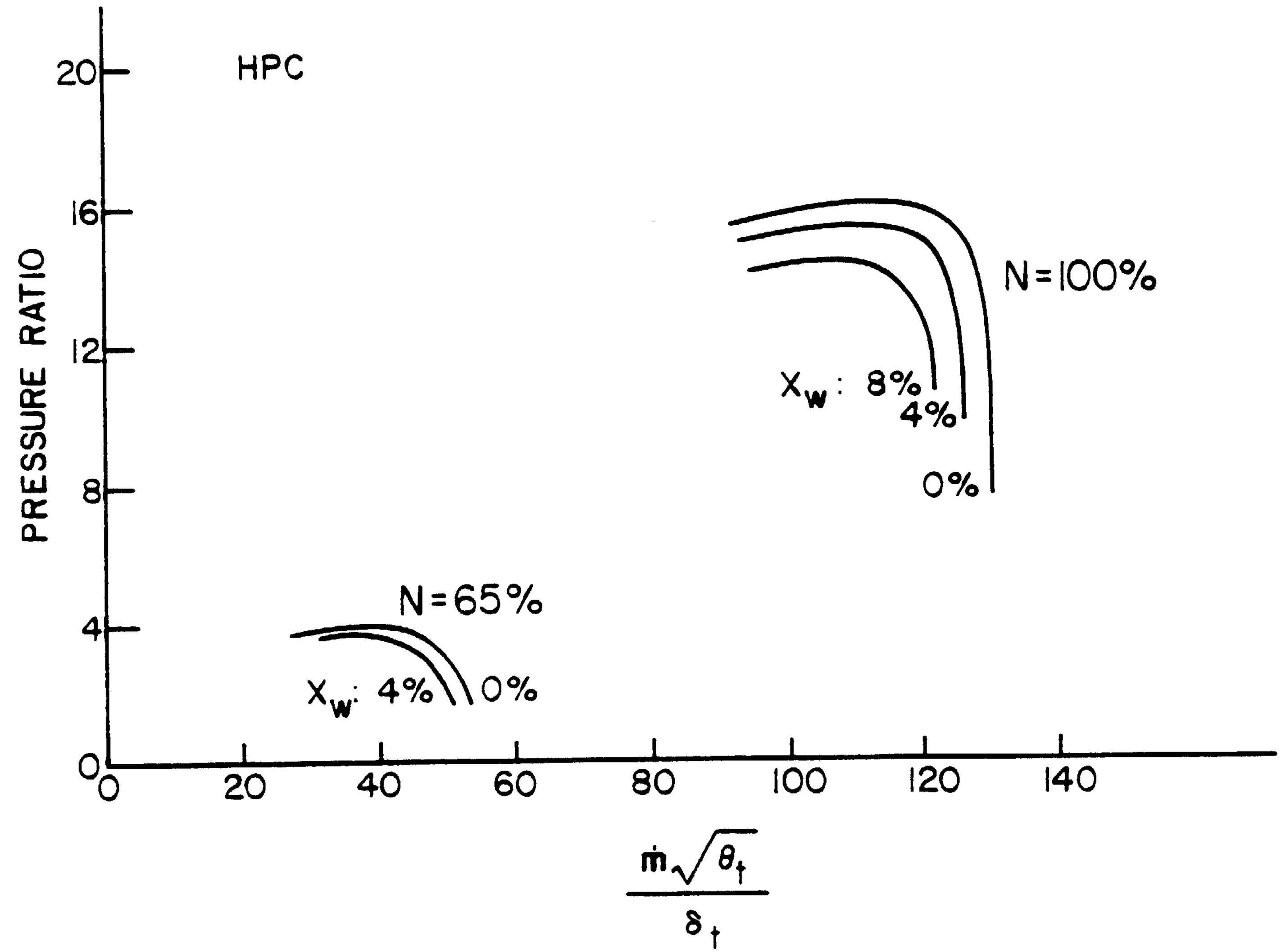


Figure 3.4 (4 of 5)

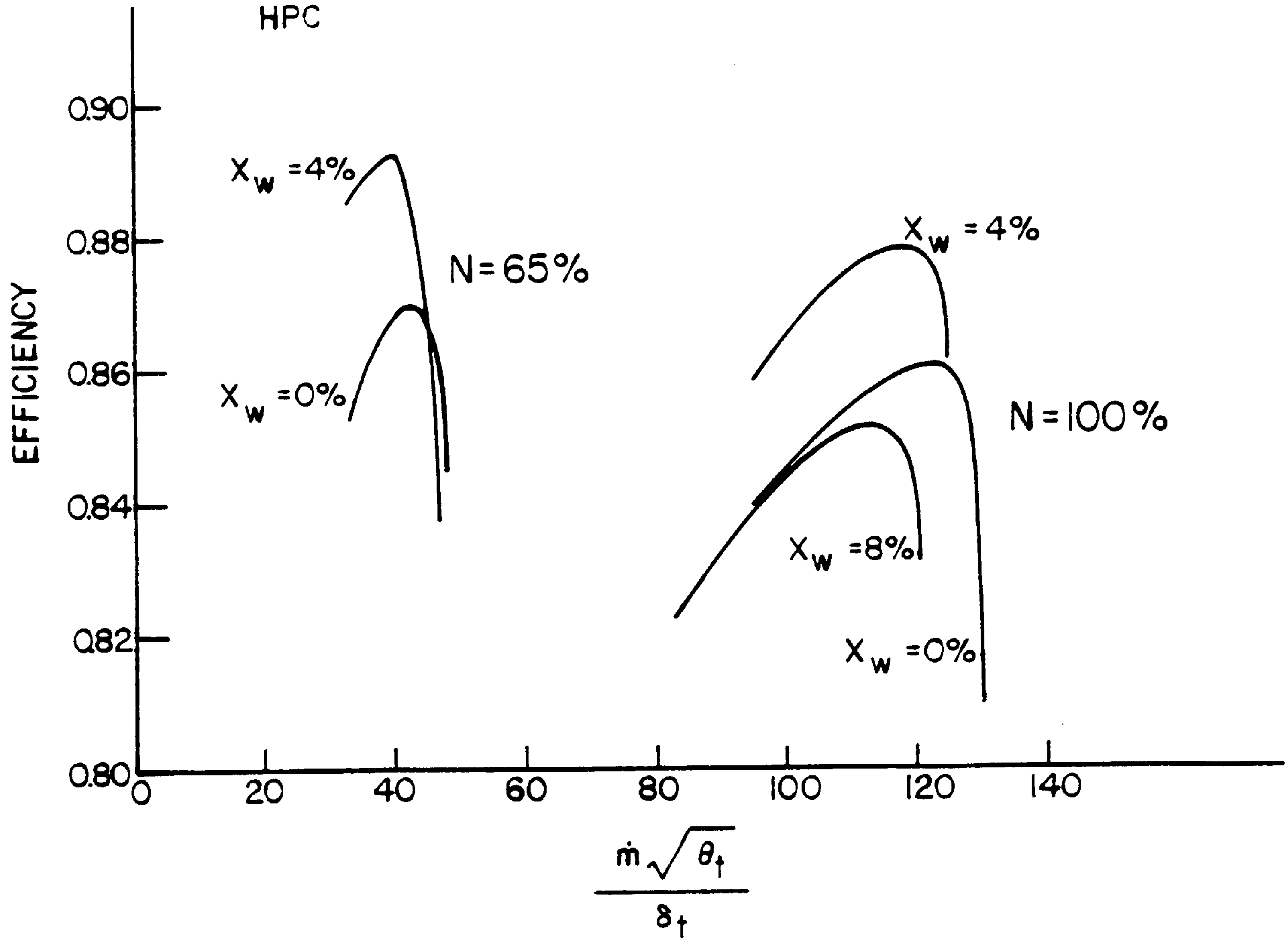


Figure 3.4 (5 of 5)

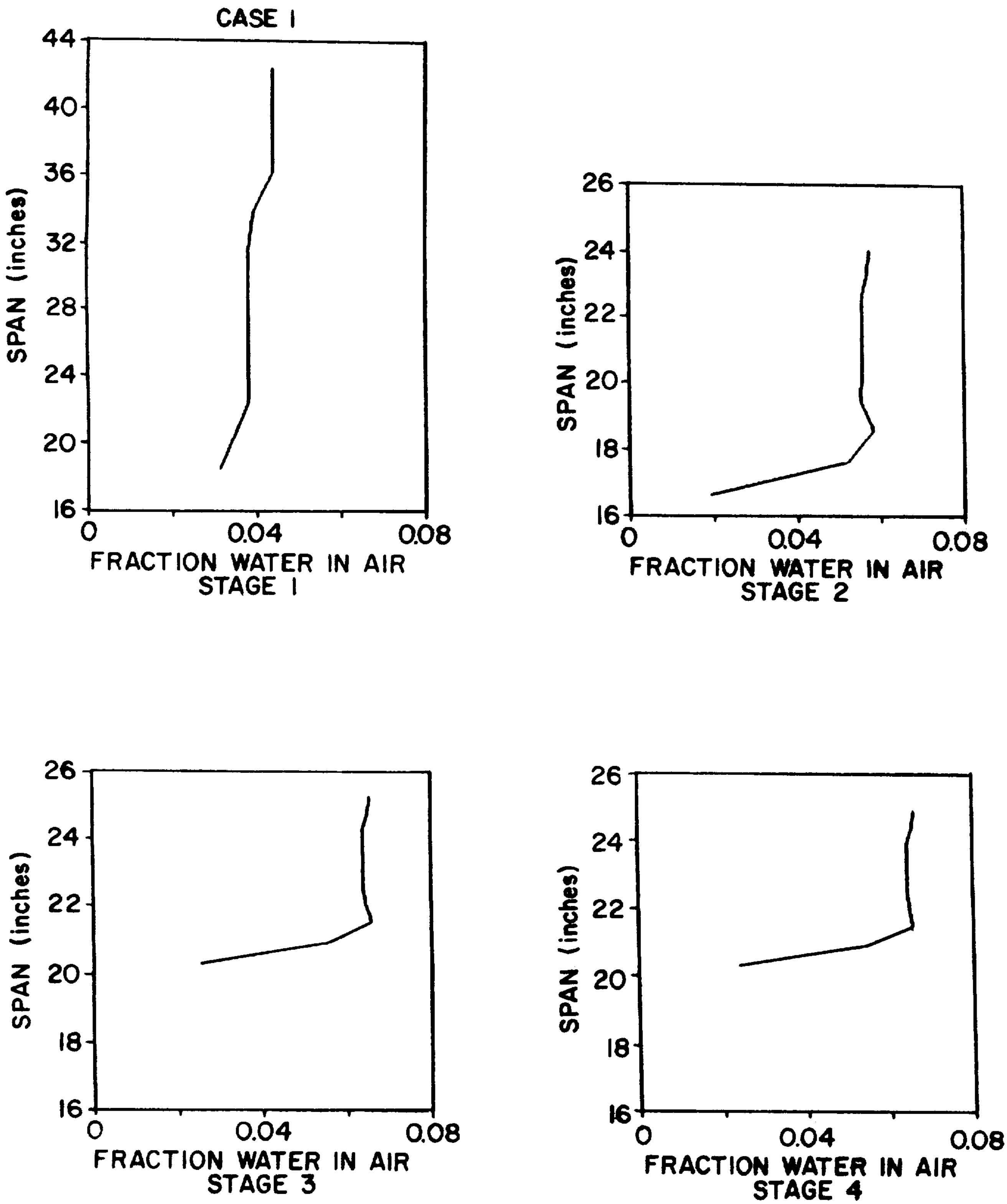


Figure 3.5 Fan + LPC Water Distribution
a) Case 1

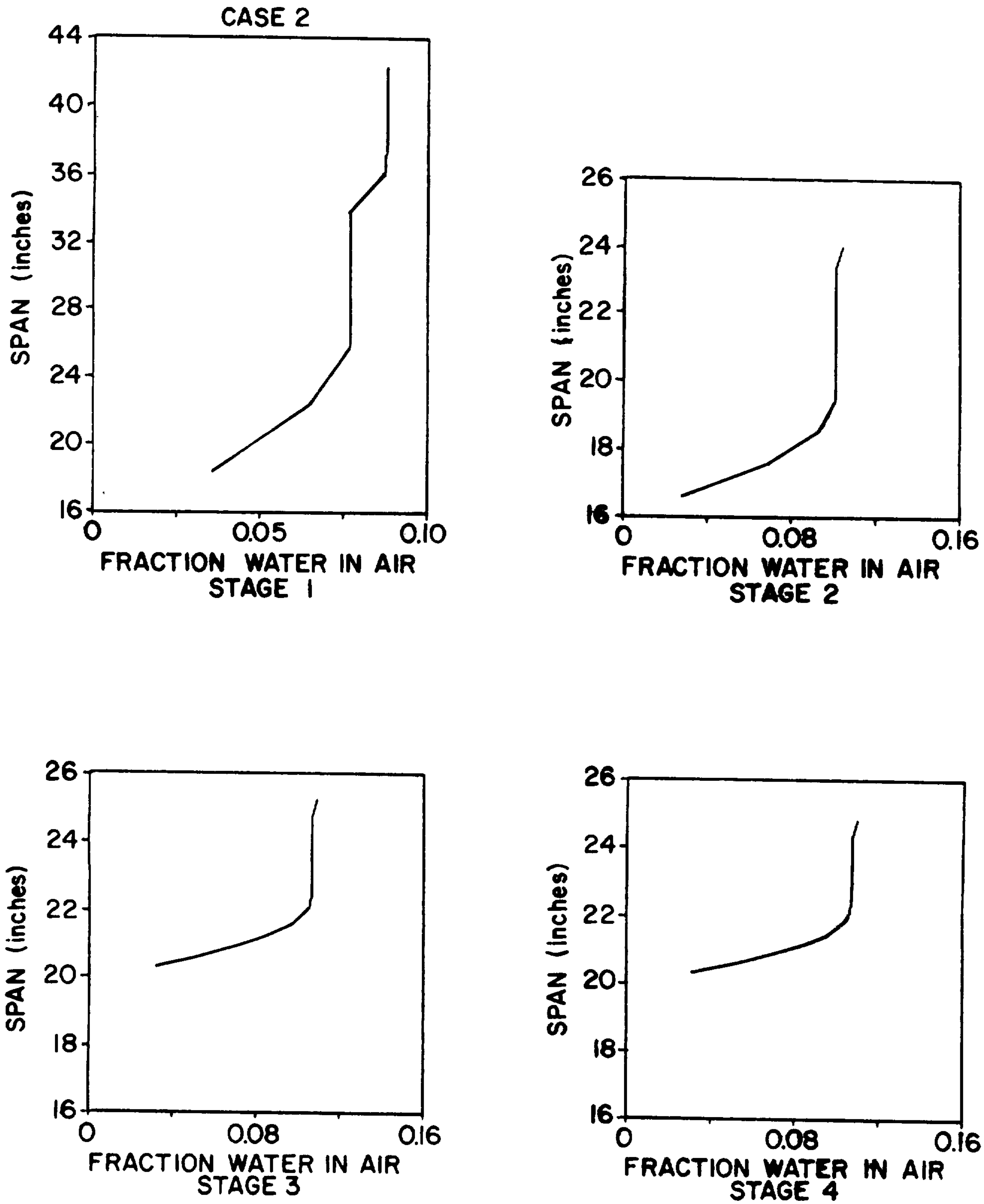


Figure 3.5 Fan + LPC Water Distribution
b) Case 2

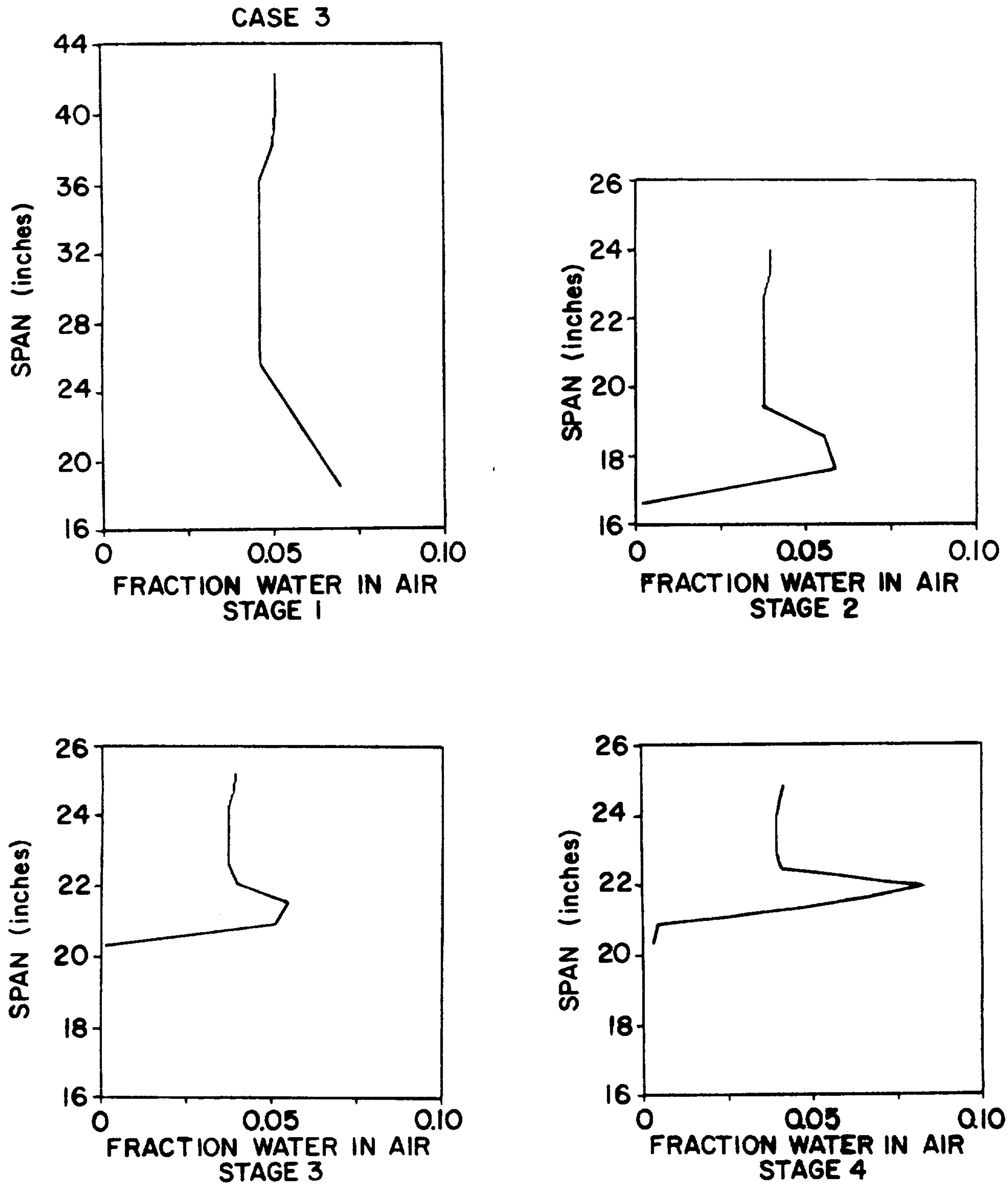


Figure 3.5 Fan + LPC Water Distribution
c) Case 3

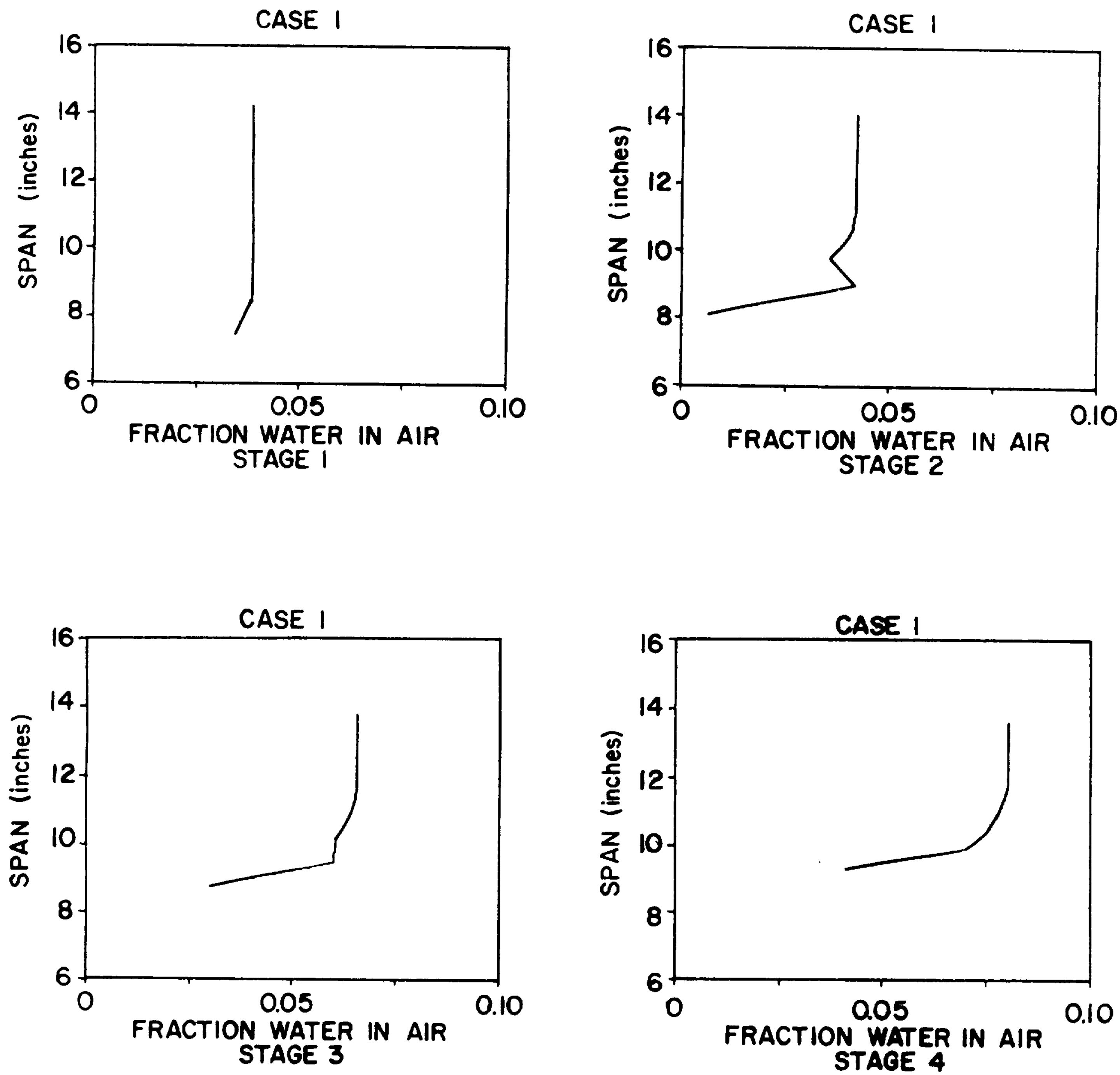


Figure 3.6 HPC Water Distribution (1 of 4)
a) case 1

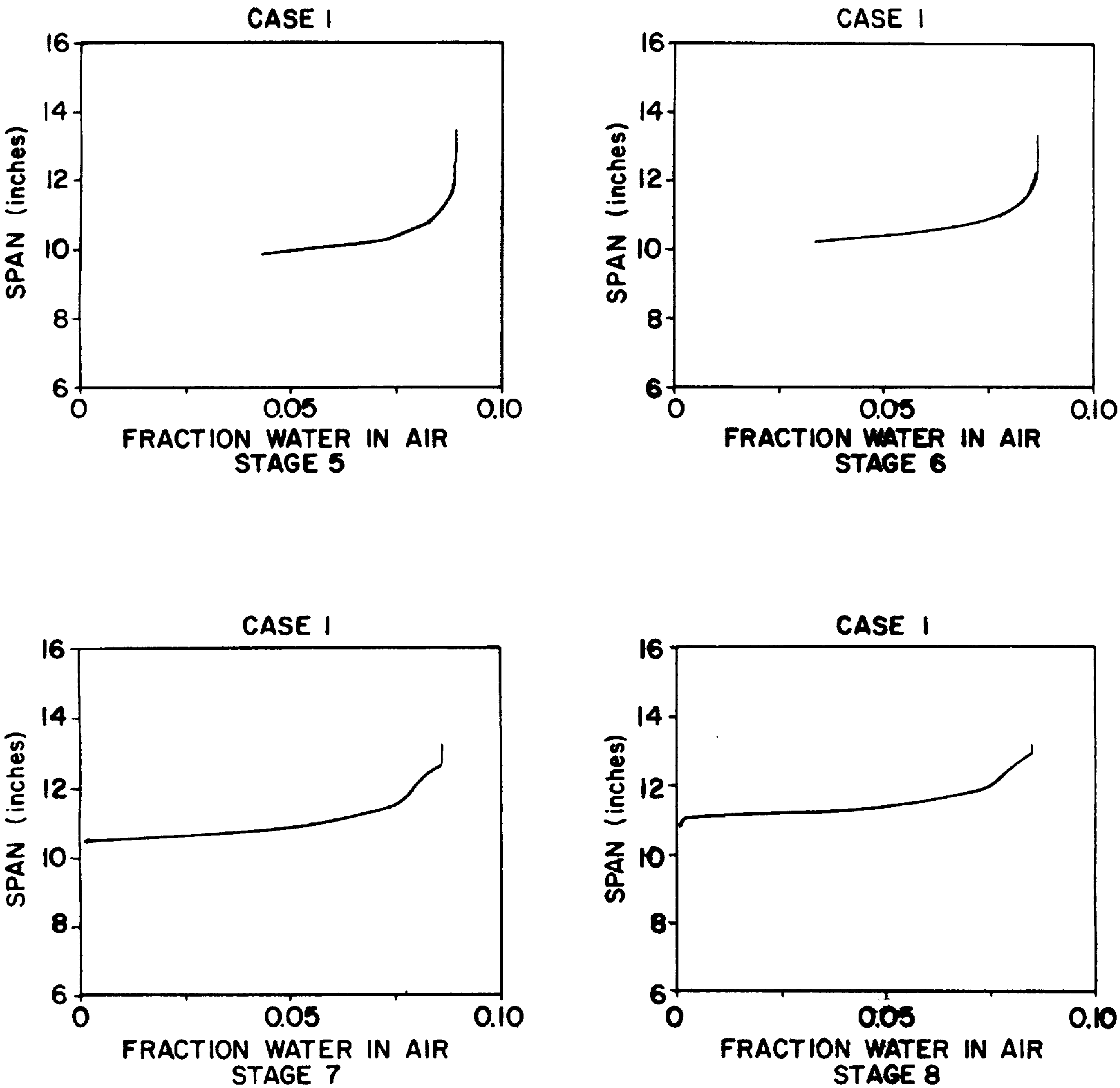


Figure 3.6 a) (2 of 4)

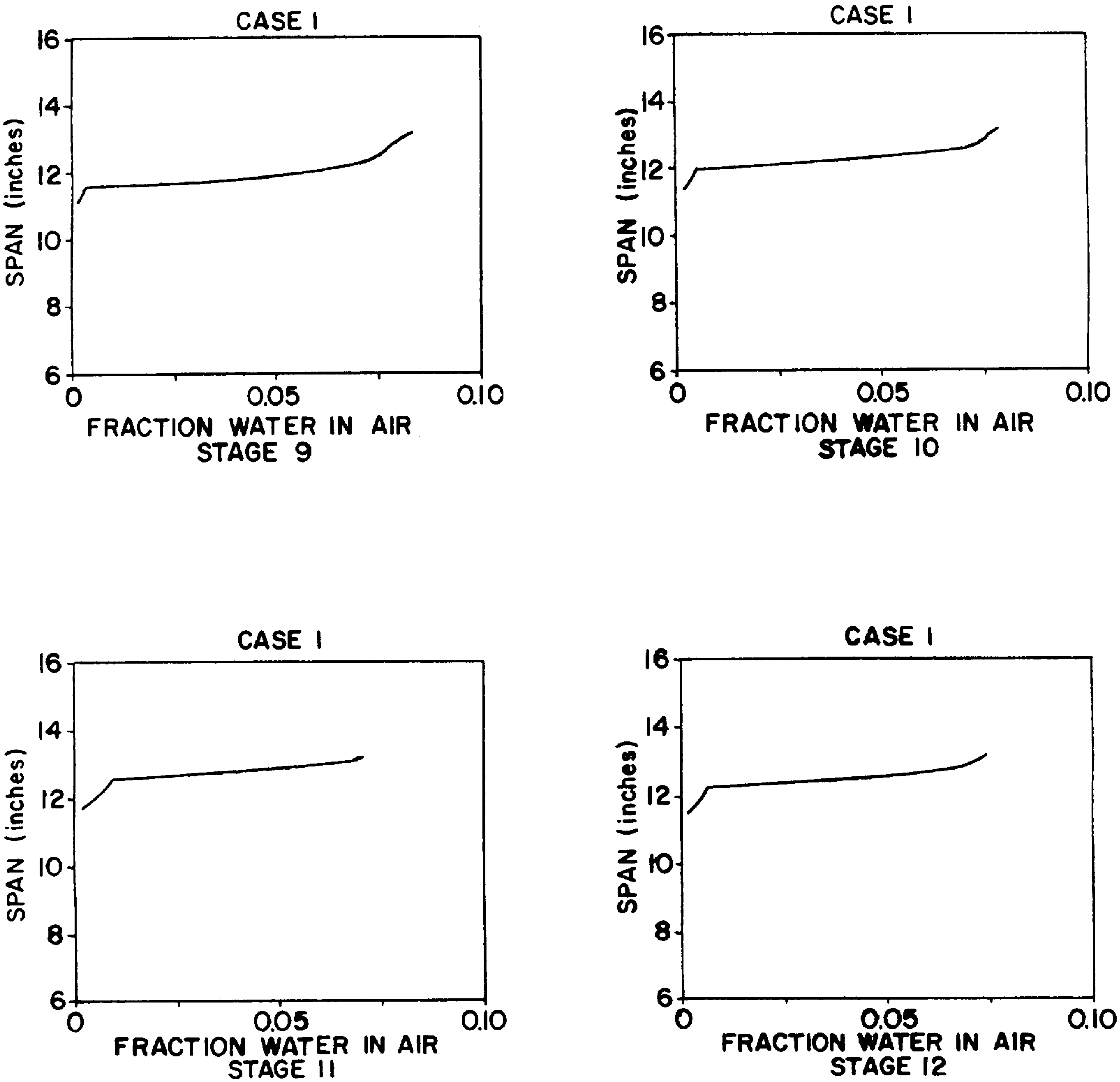


Figure 3.6 a) (3 of 4)

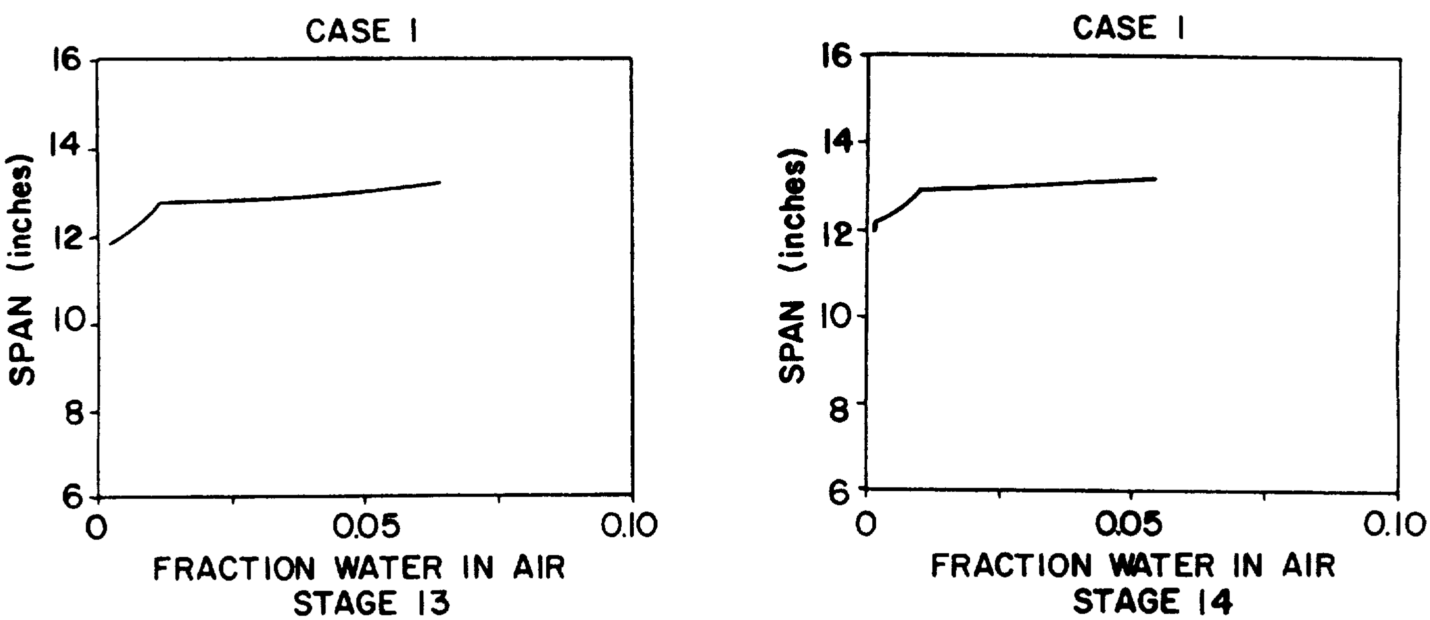


Figure 3.6 a) (4 of 4)

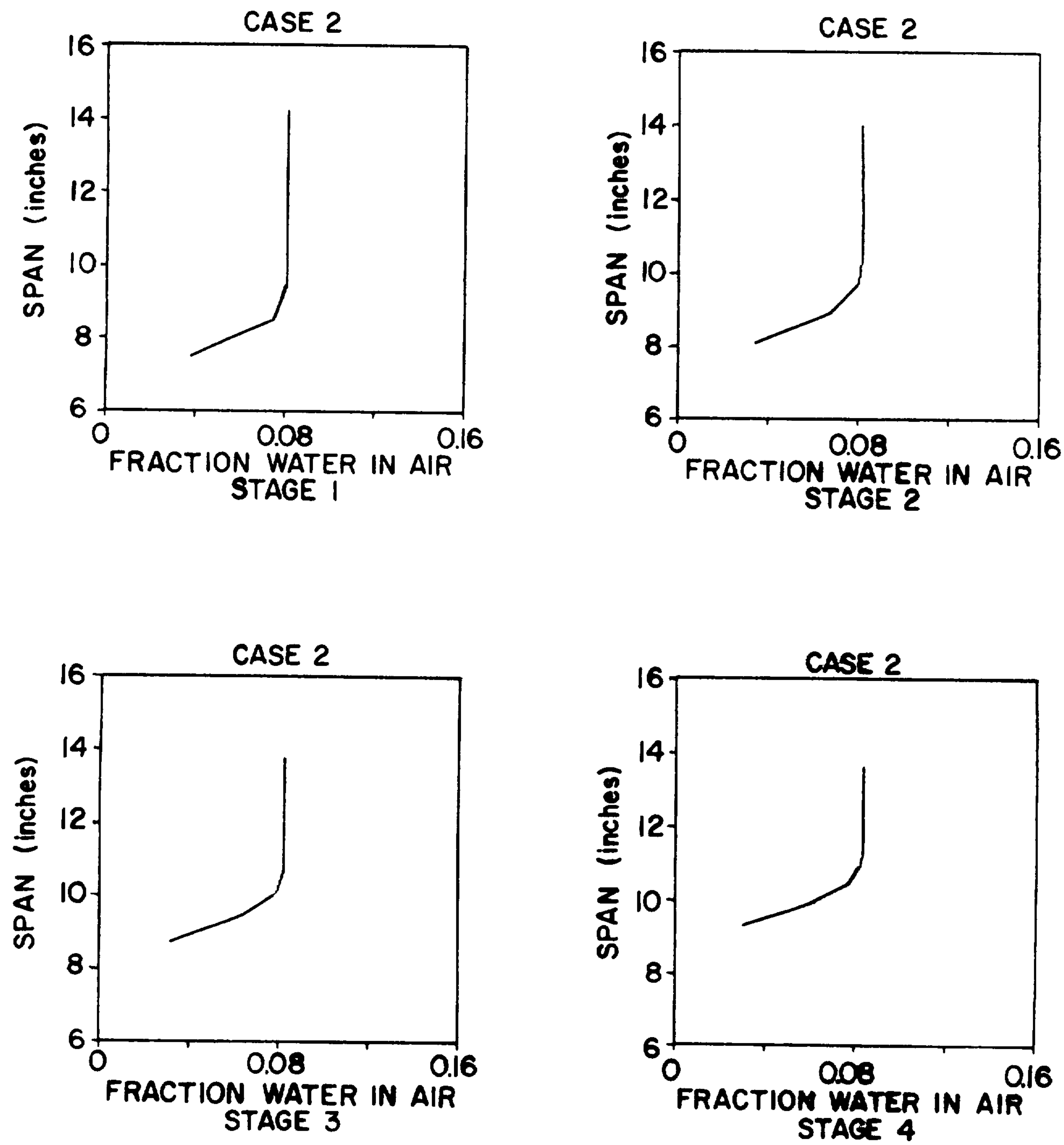
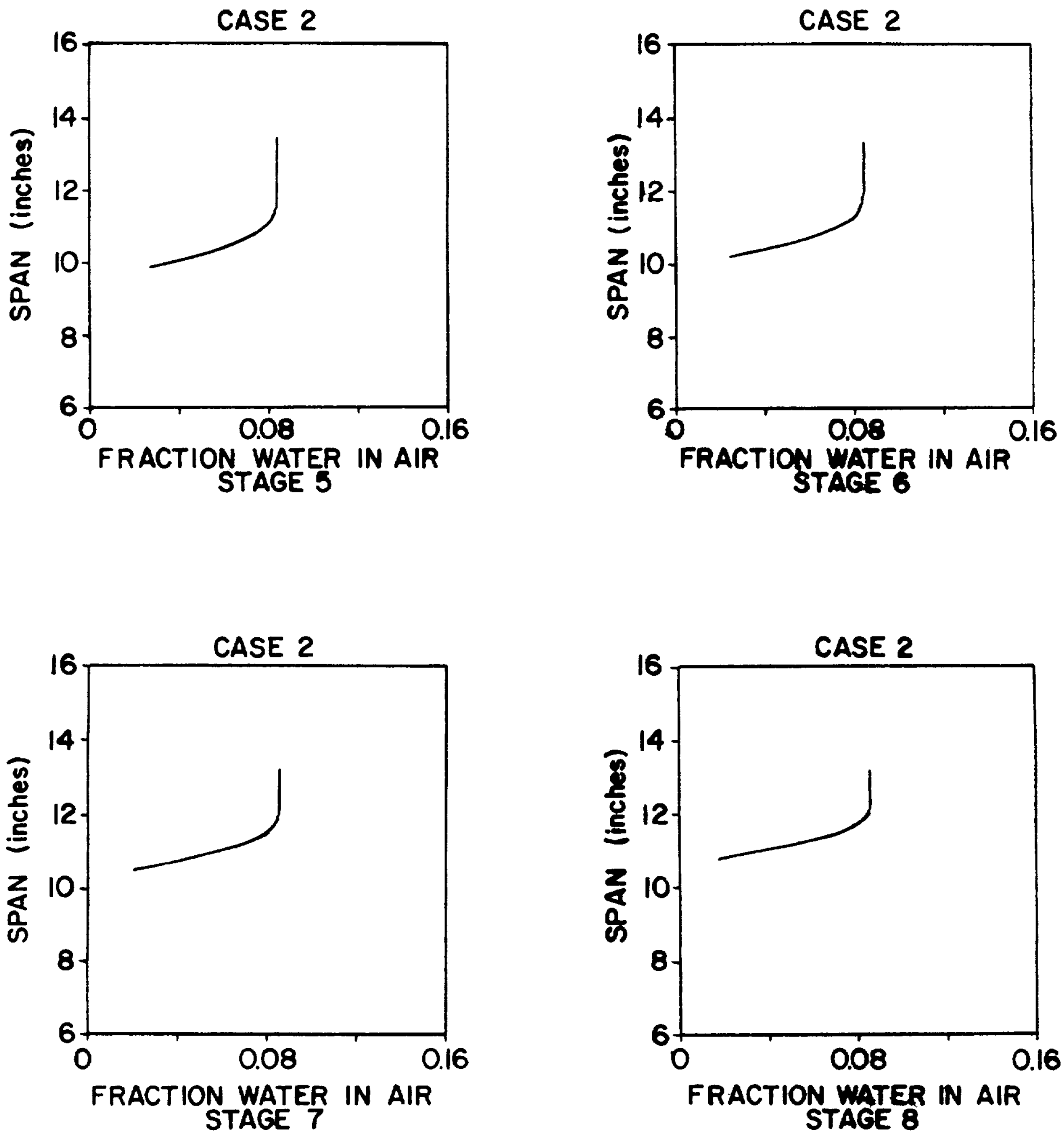


Figure 3.6 HPC Water Distribution (1 of 4)
b) Case 2



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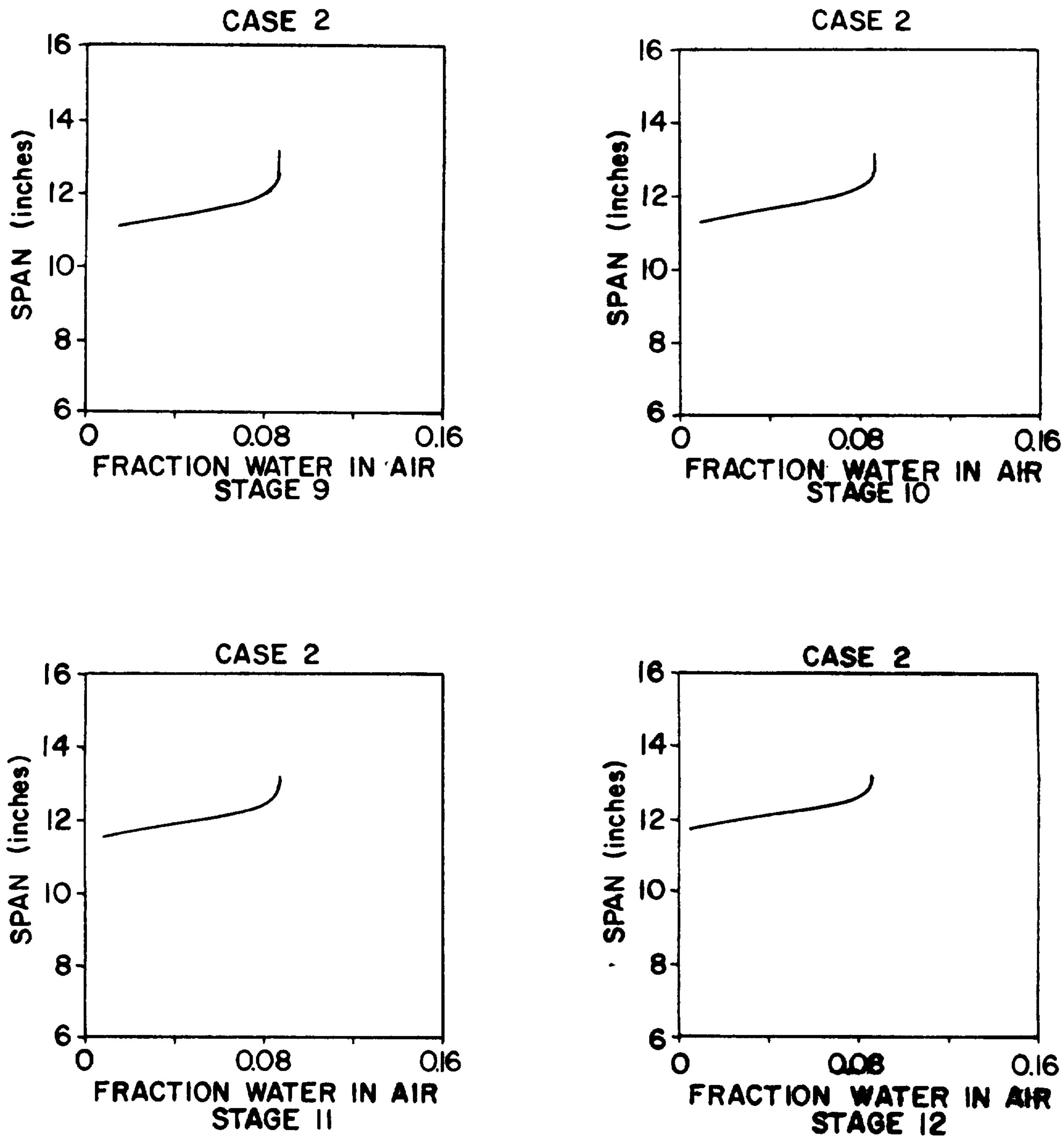

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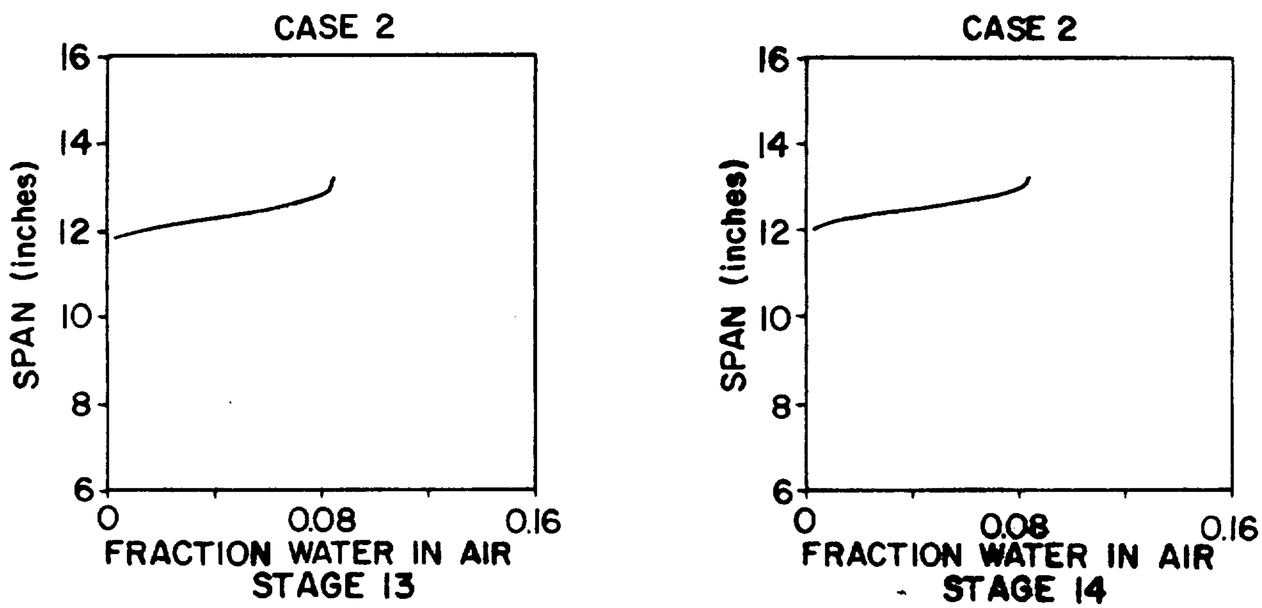

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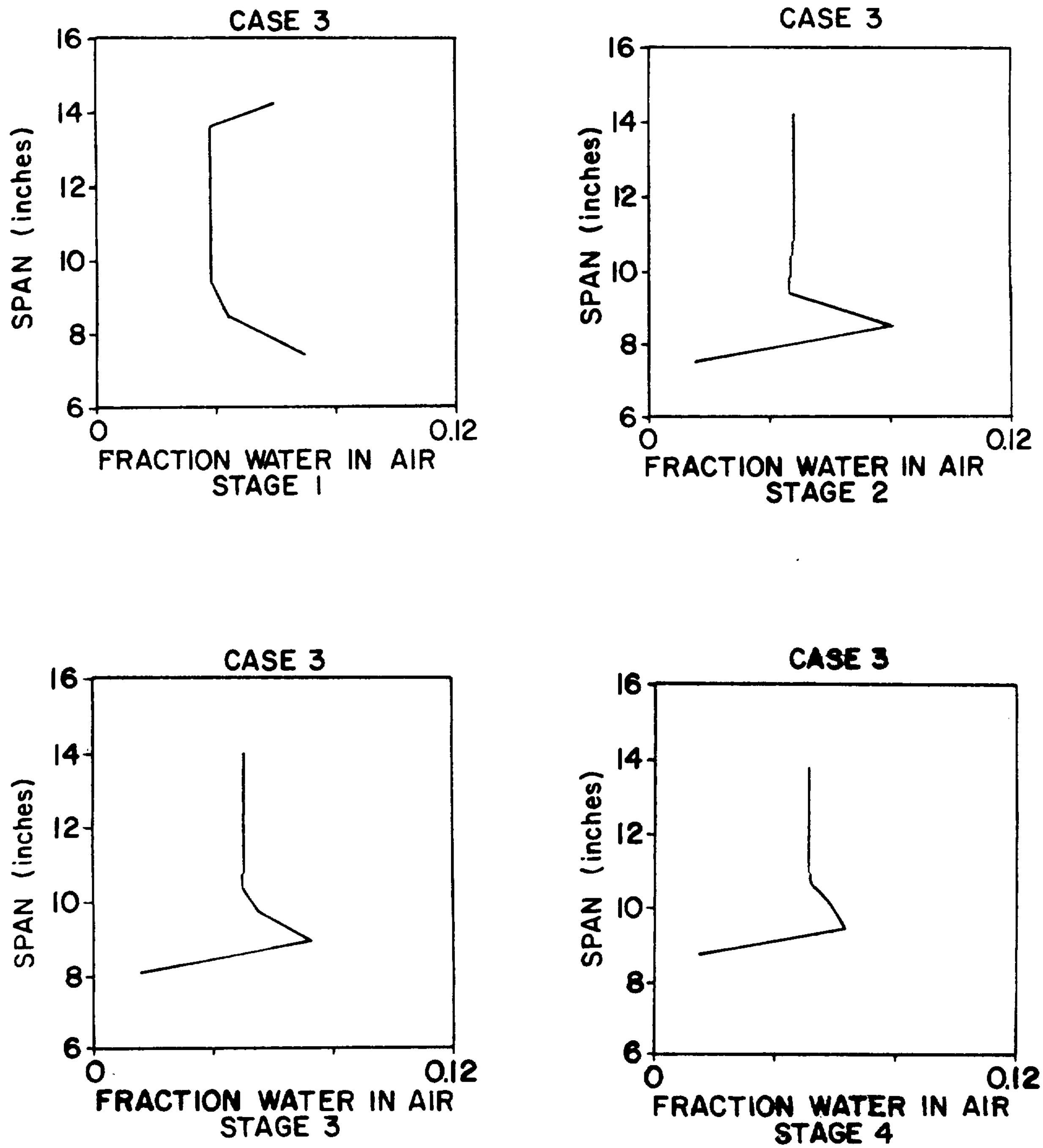
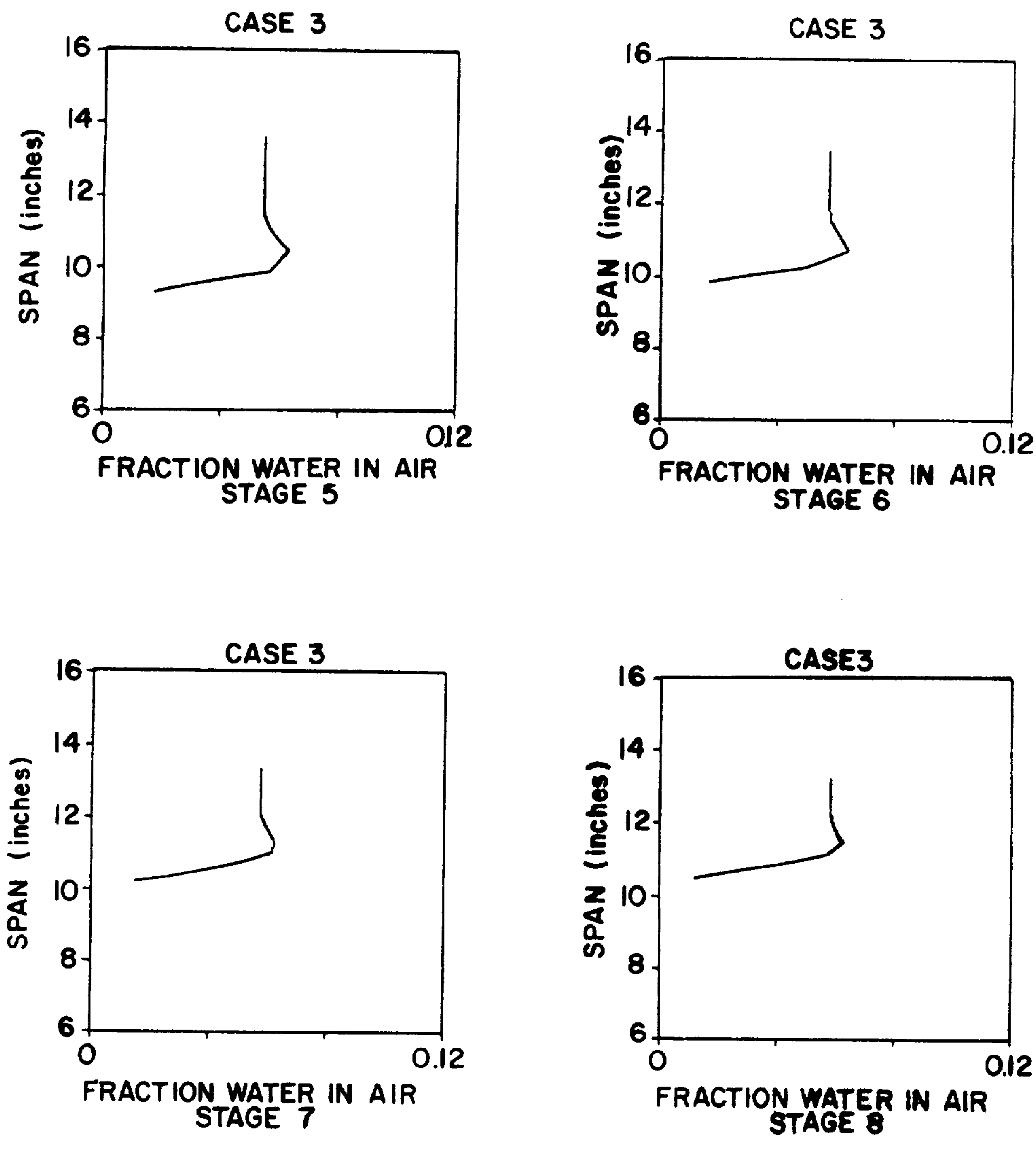


Figure 3.6 HPC Water Distribution (1 of 4)
c) Case 3



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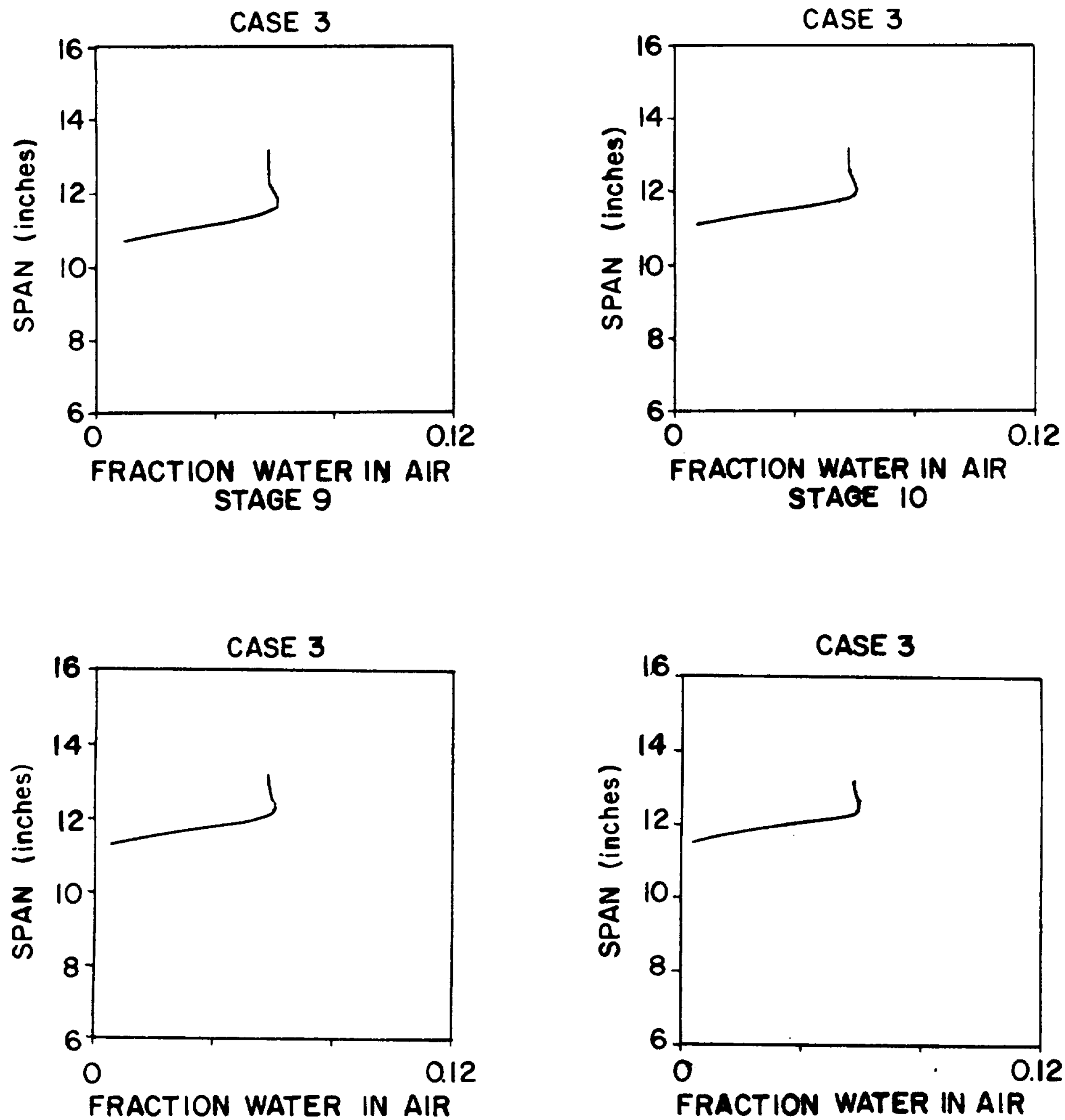

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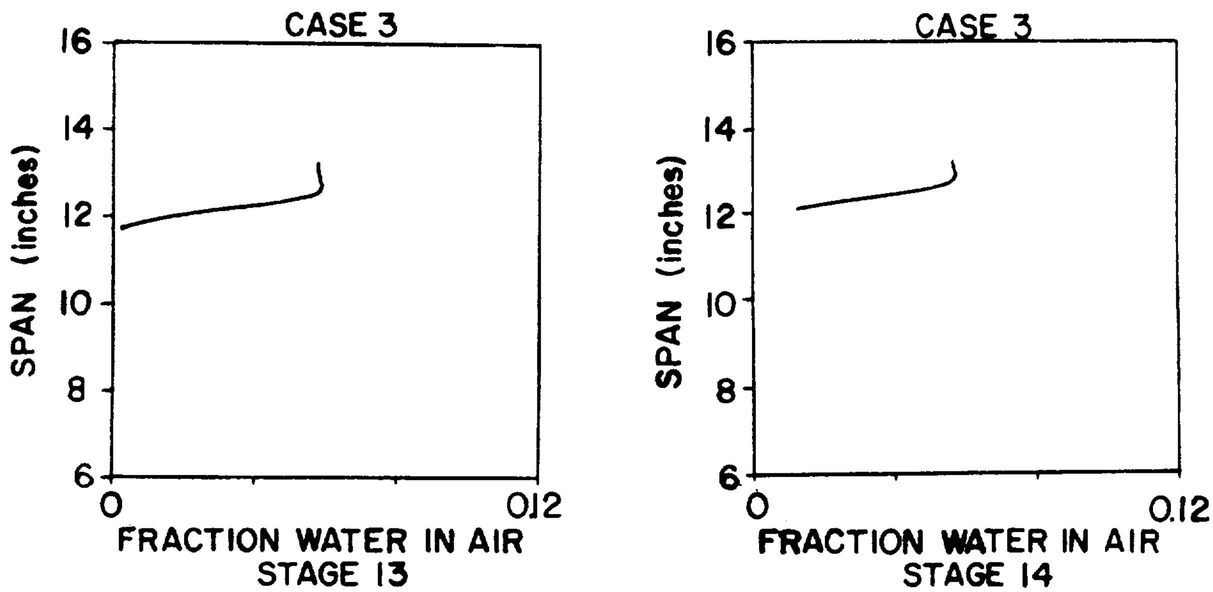

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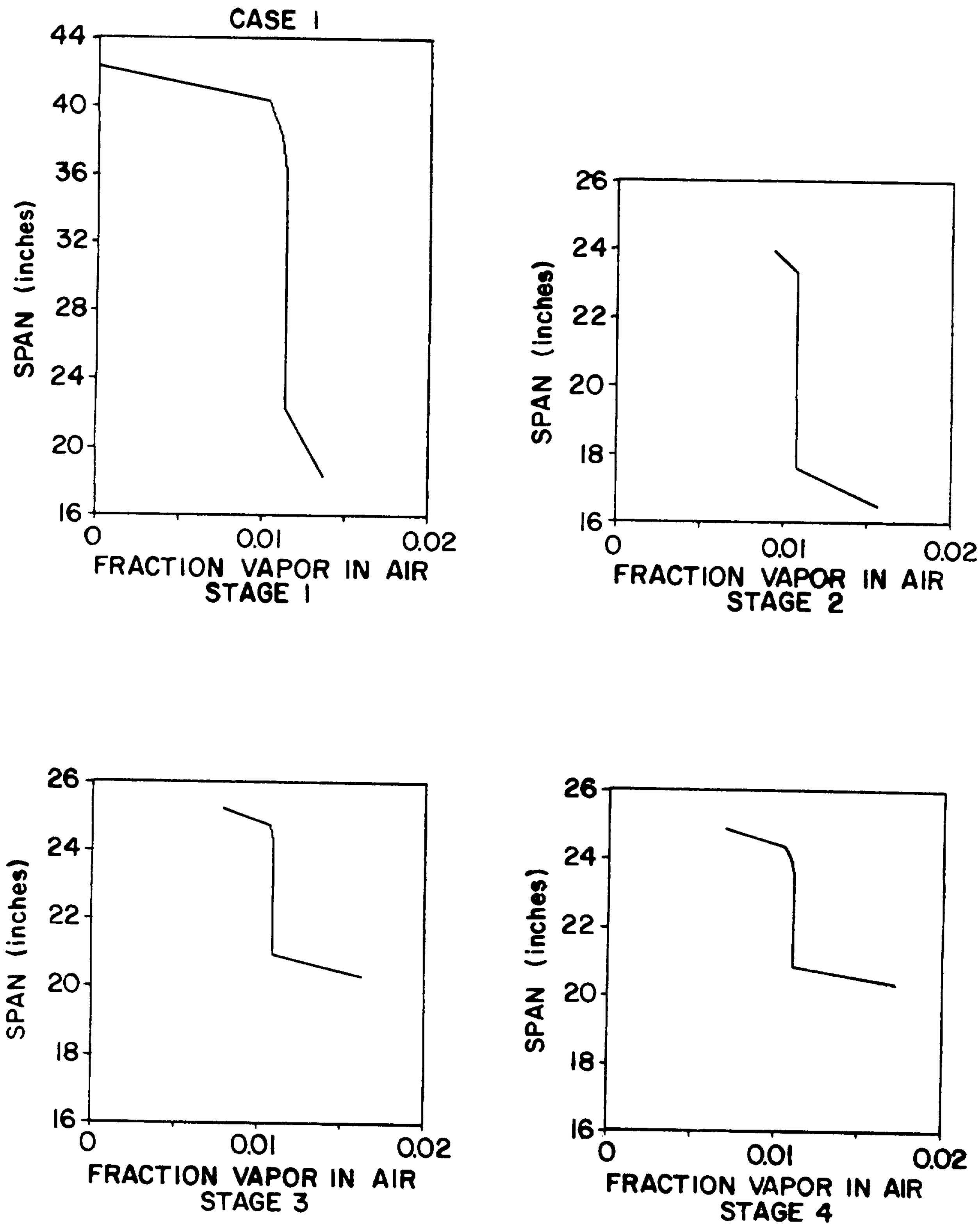


Figure 3.7 Fan + LPC Vapor Distribution
a) Case 1

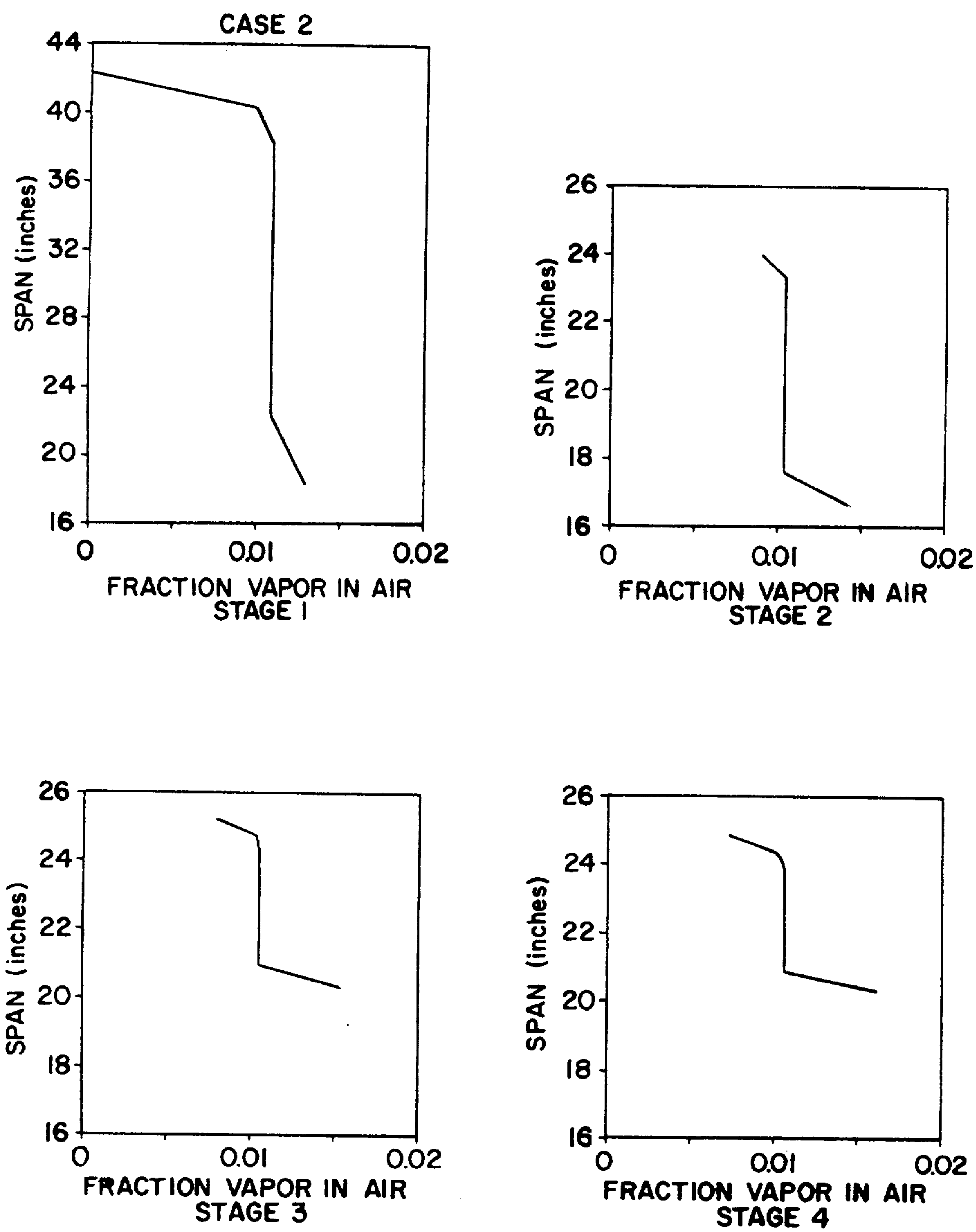


Figure 3.7 Fan + LPC Vapor Distribution
b) Case 2

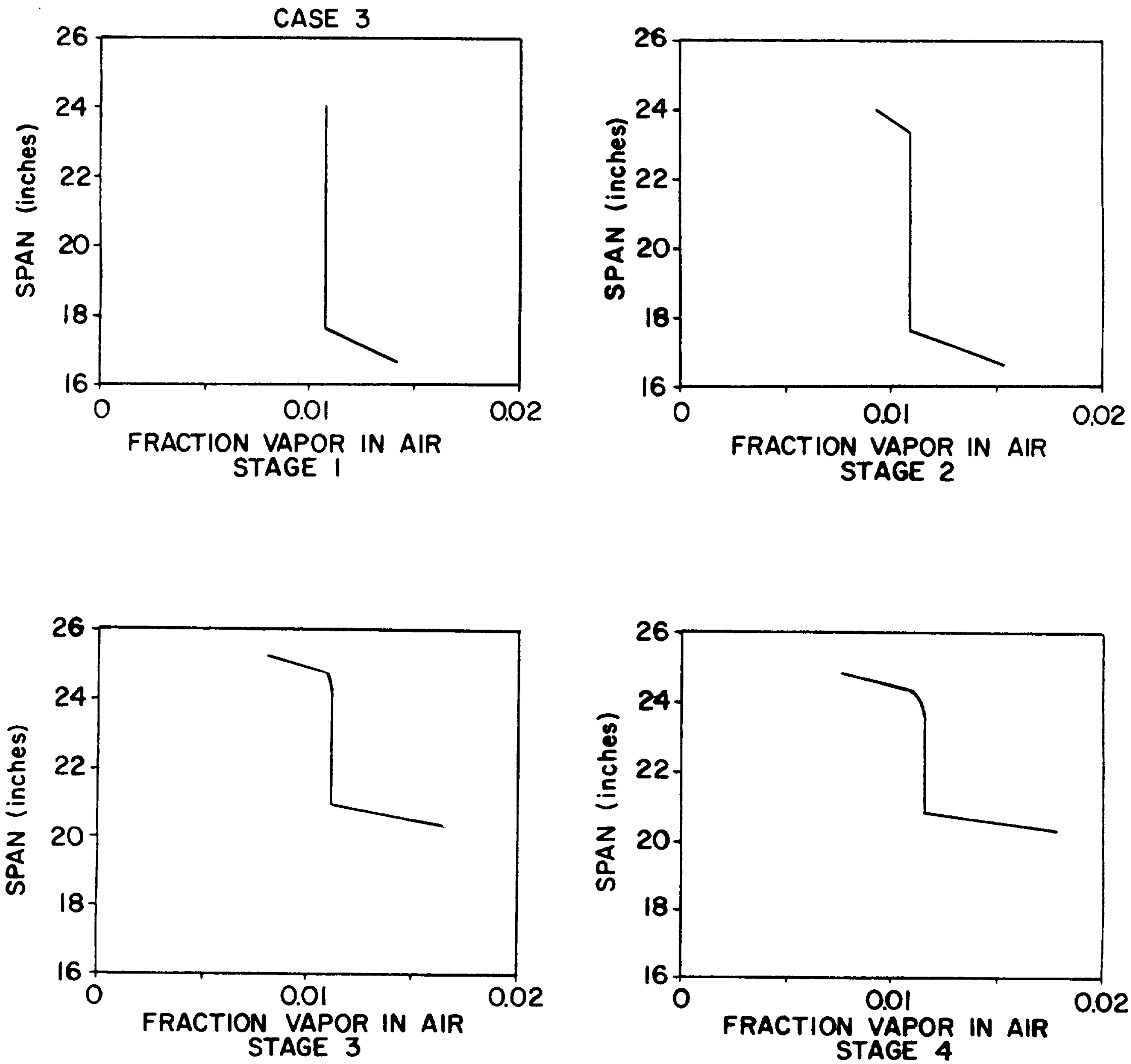


Figure 3.7 Fan + LPC Vapor Distribution
c) Case 3

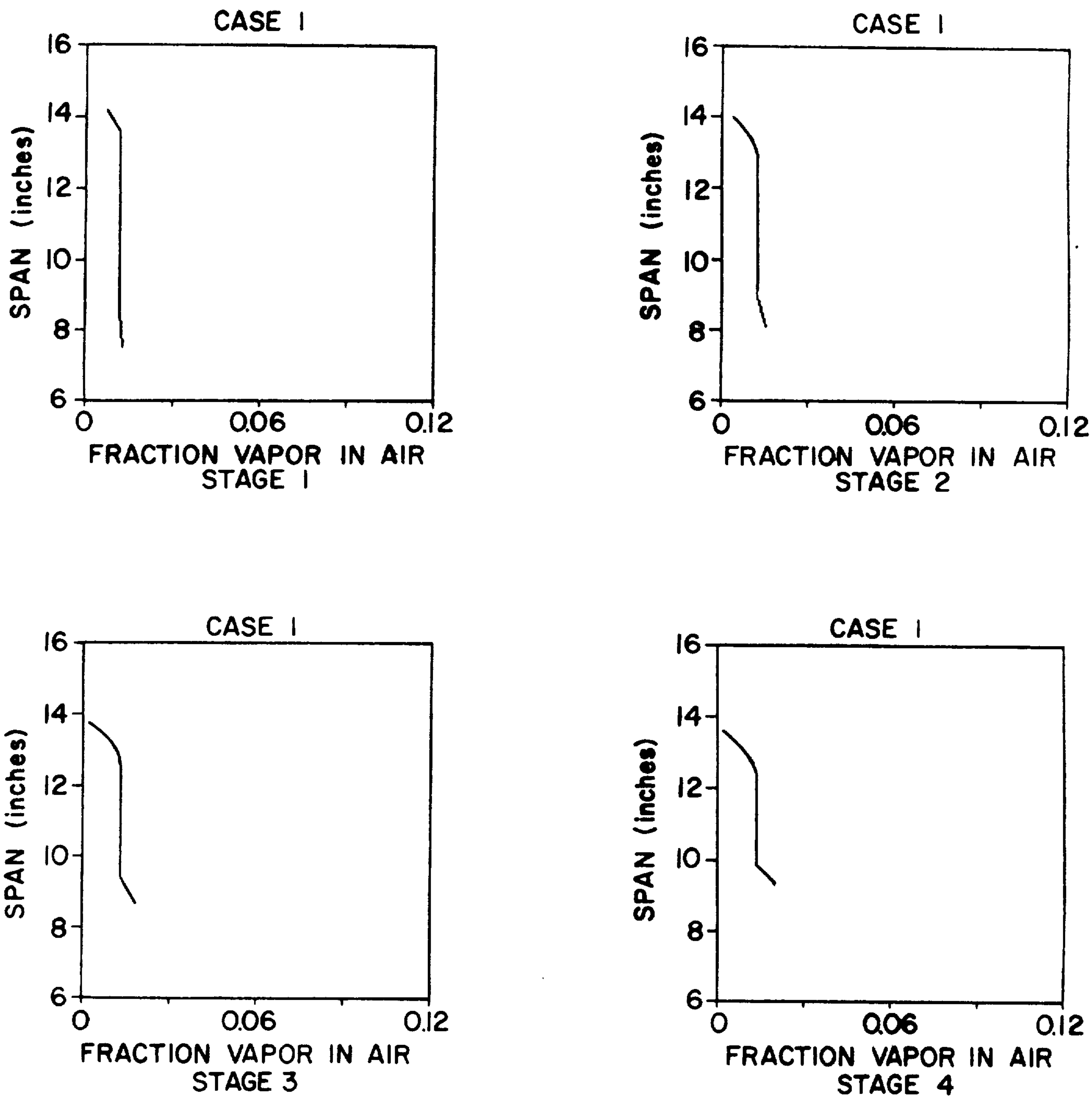
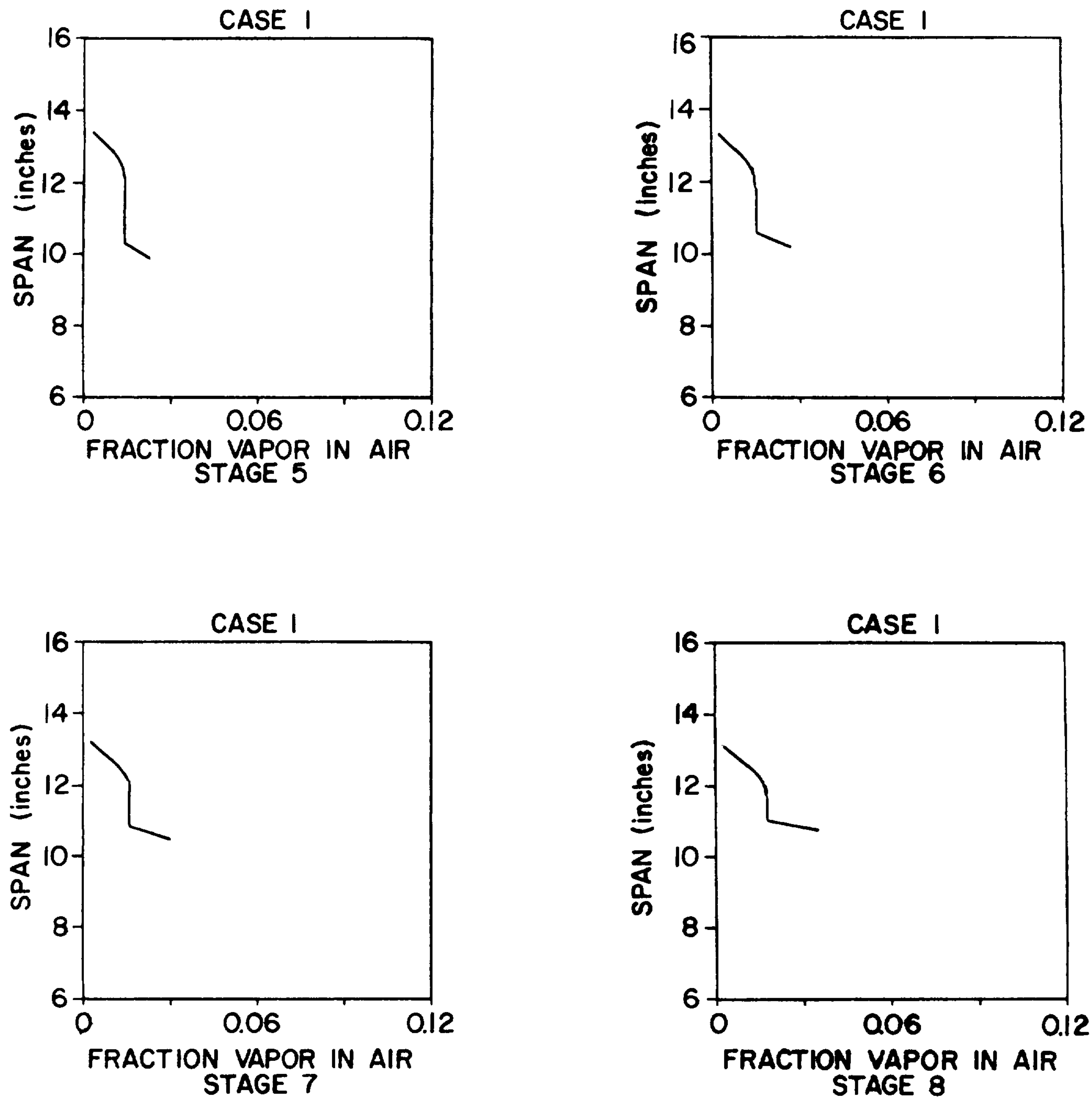


Figure 3.8 HPC Vapor Distribution (1 of 4)
a) Case 1



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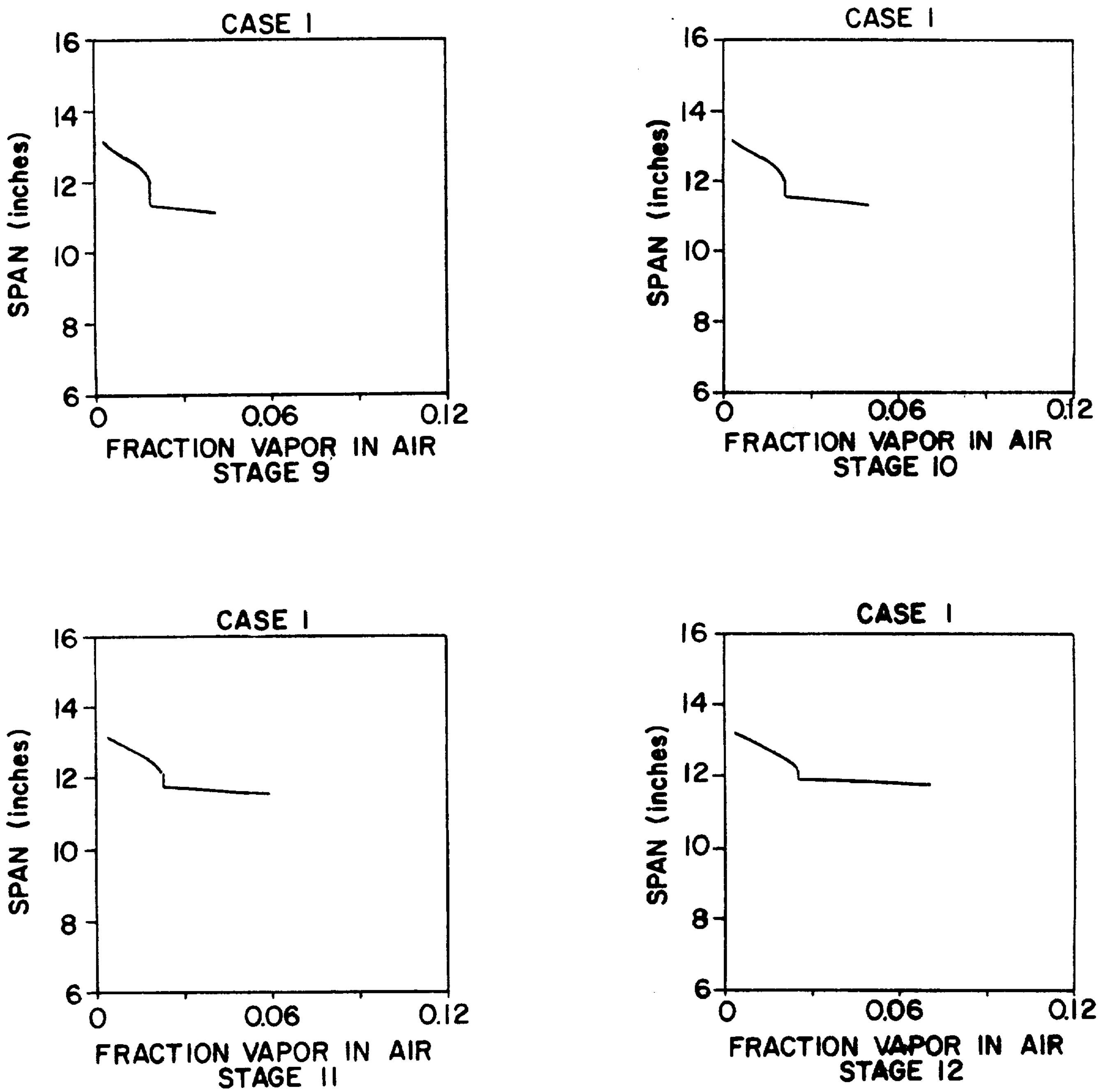

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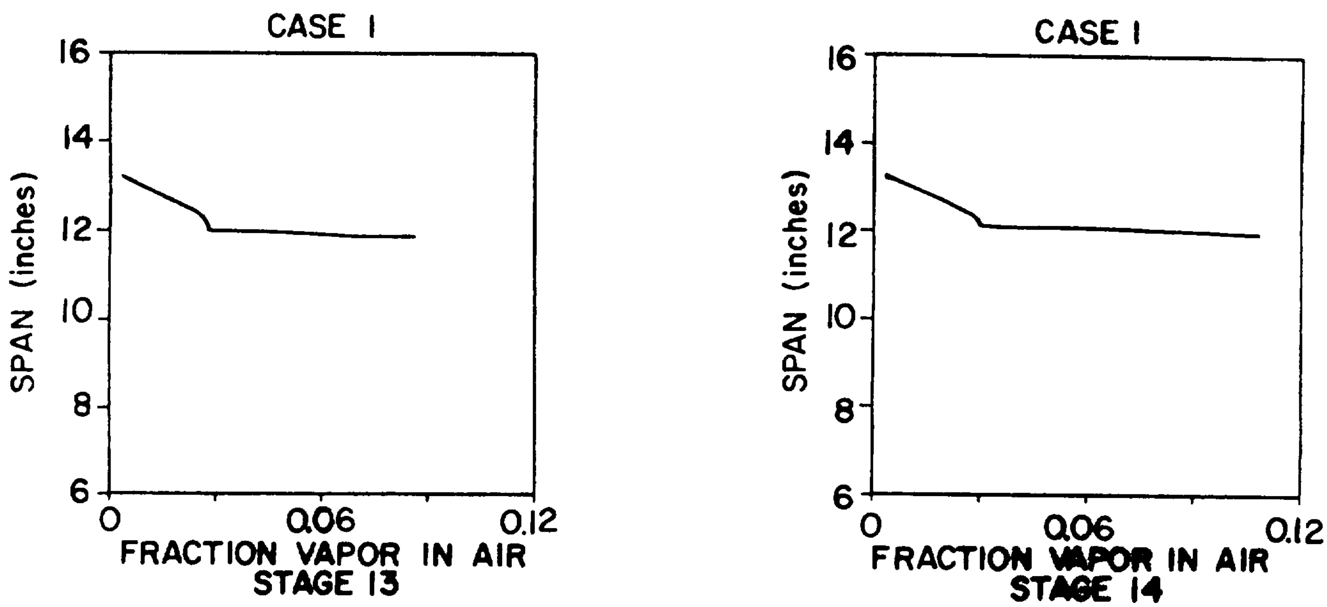

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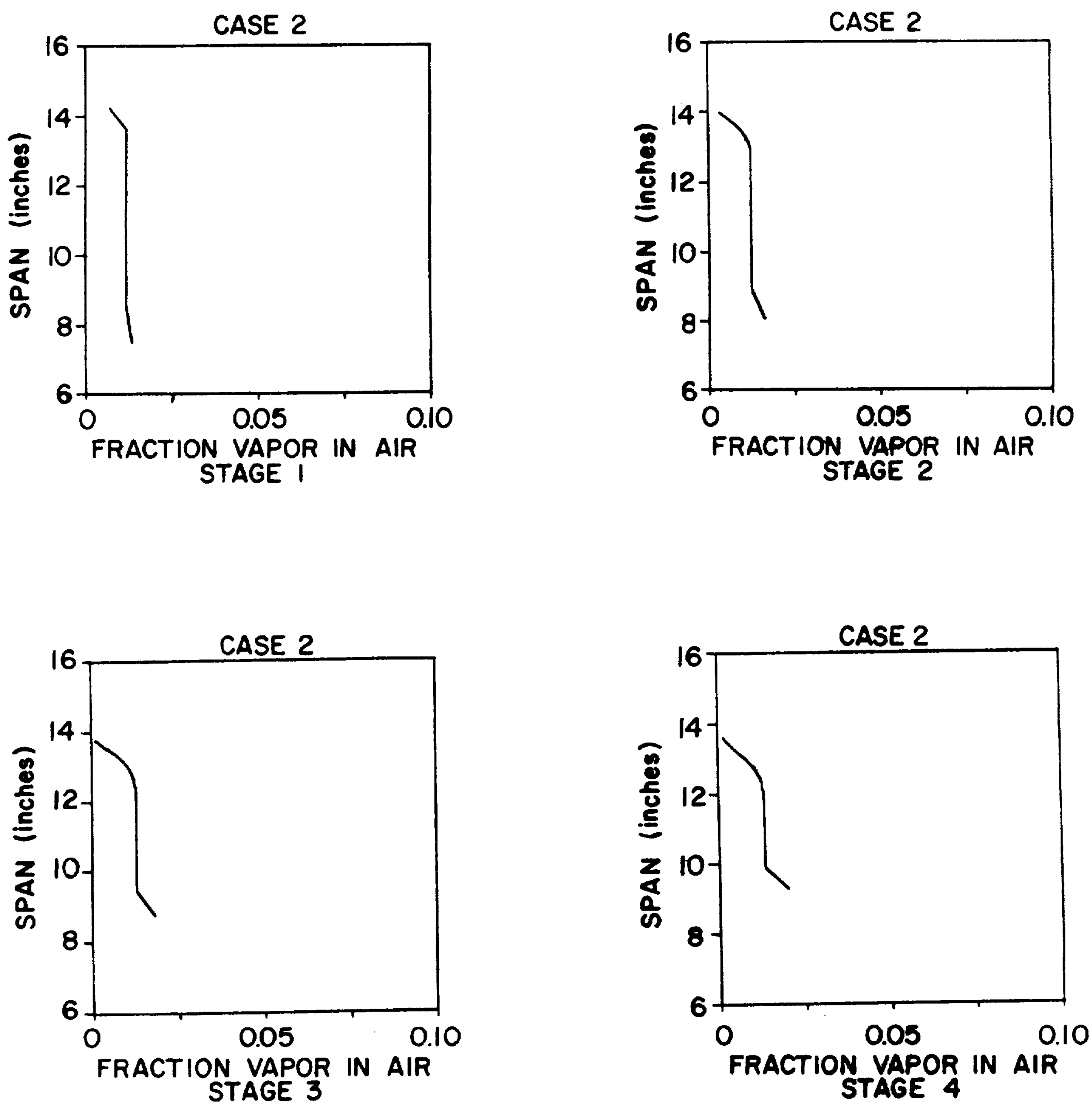
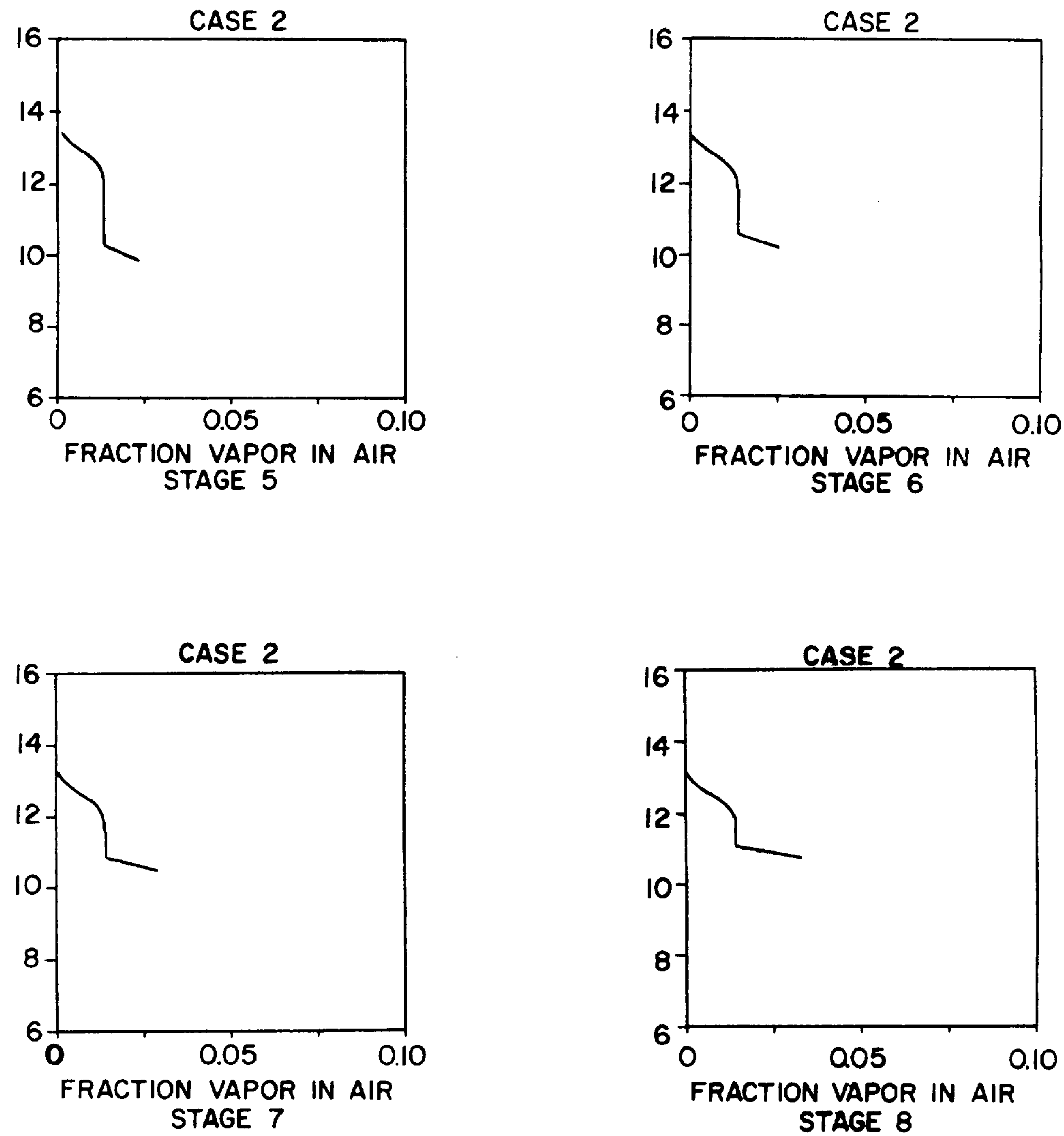


Figure 3.8 HPC Vapor Distribution (1 of 4)
b) Case 2



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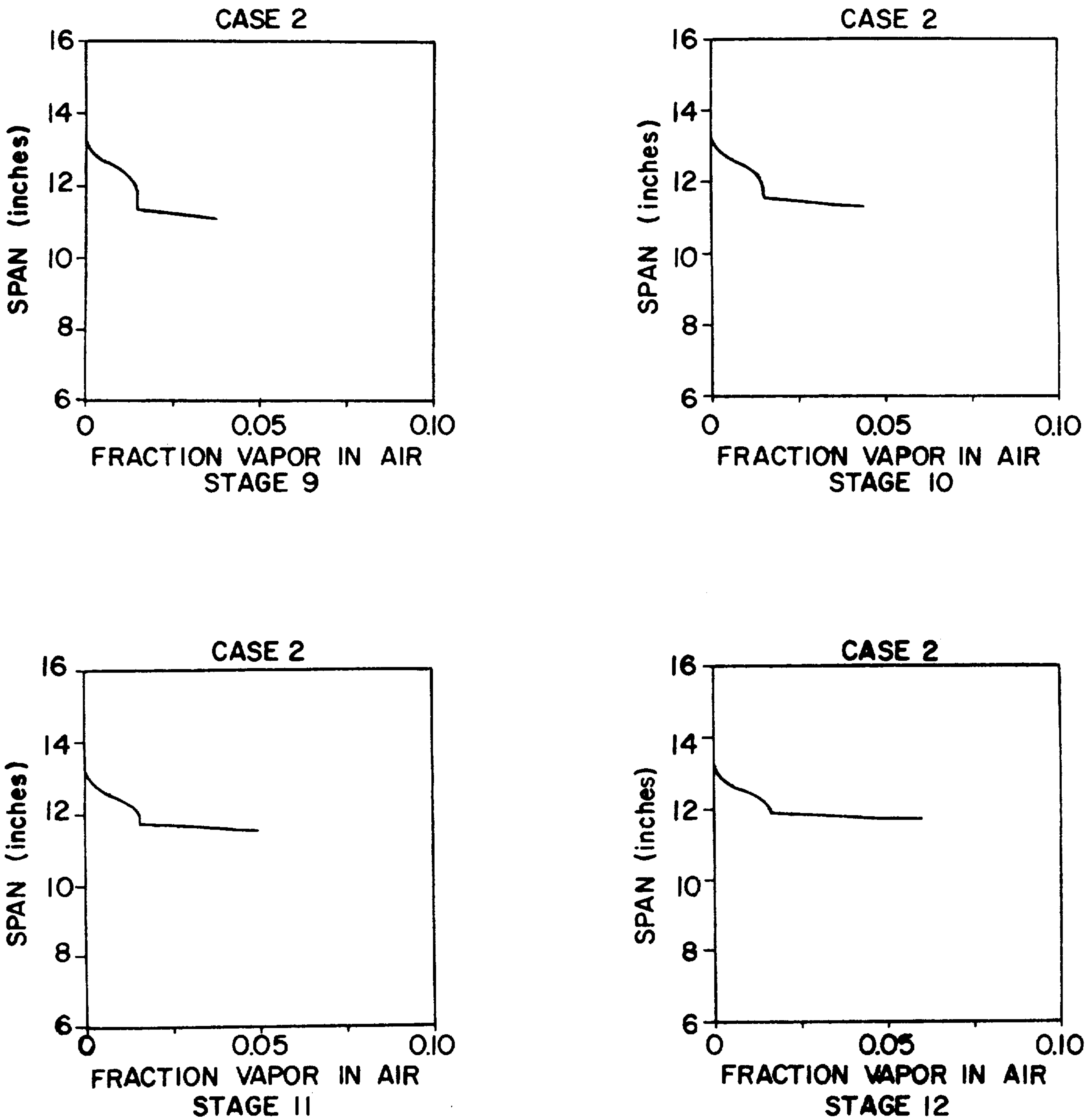

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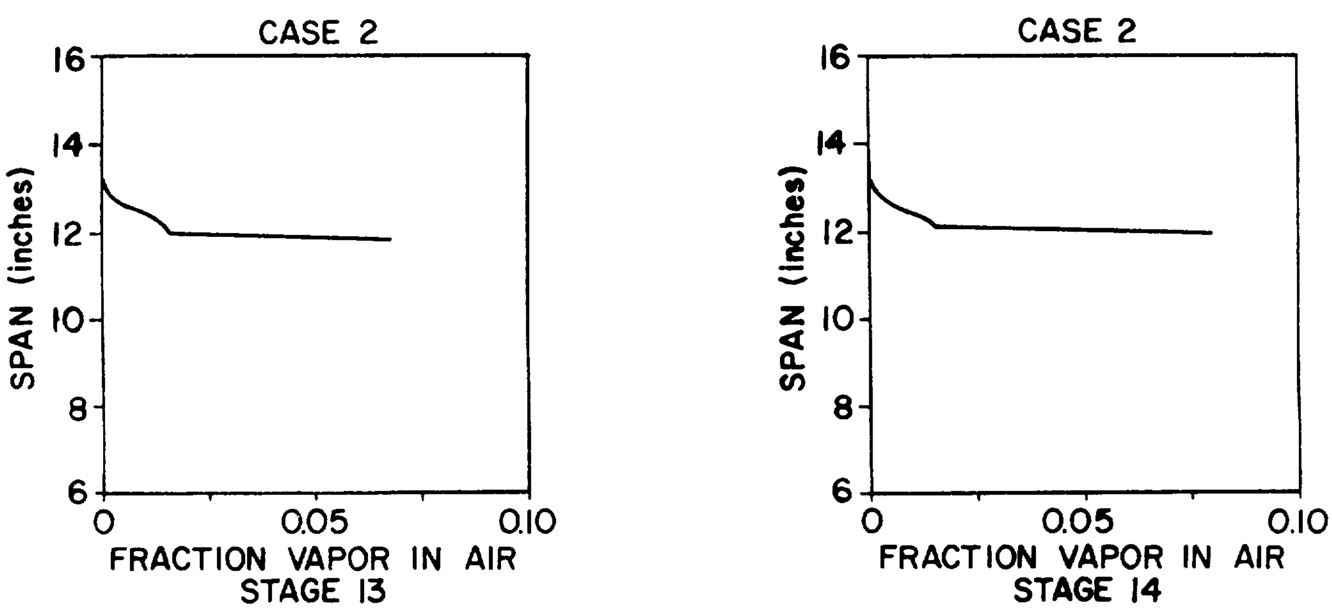

Figure 3.8 b) (4 of 4)

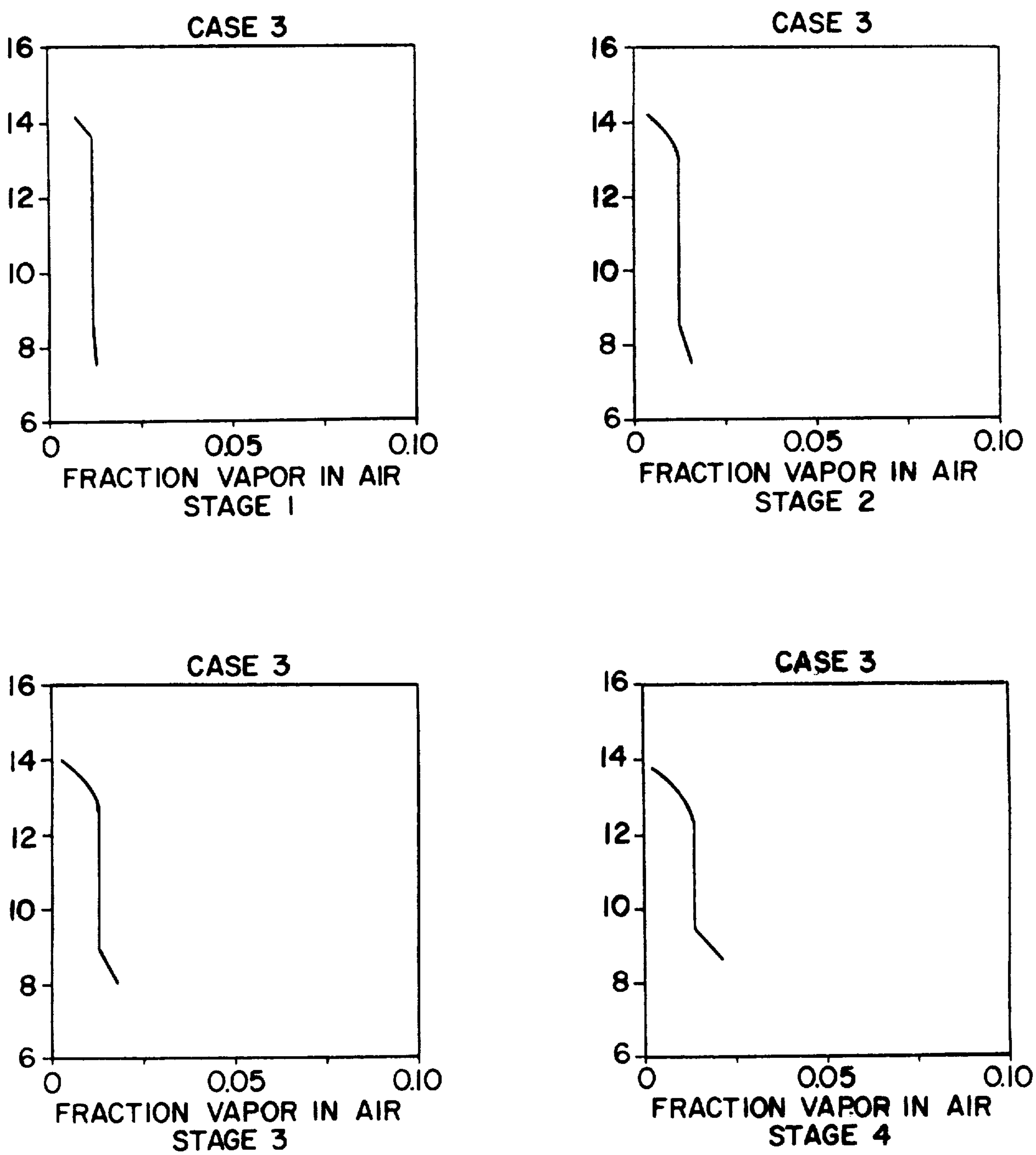

Figure 3.8 HPC Vapor Distribution (1 of 4)
c) Case 3

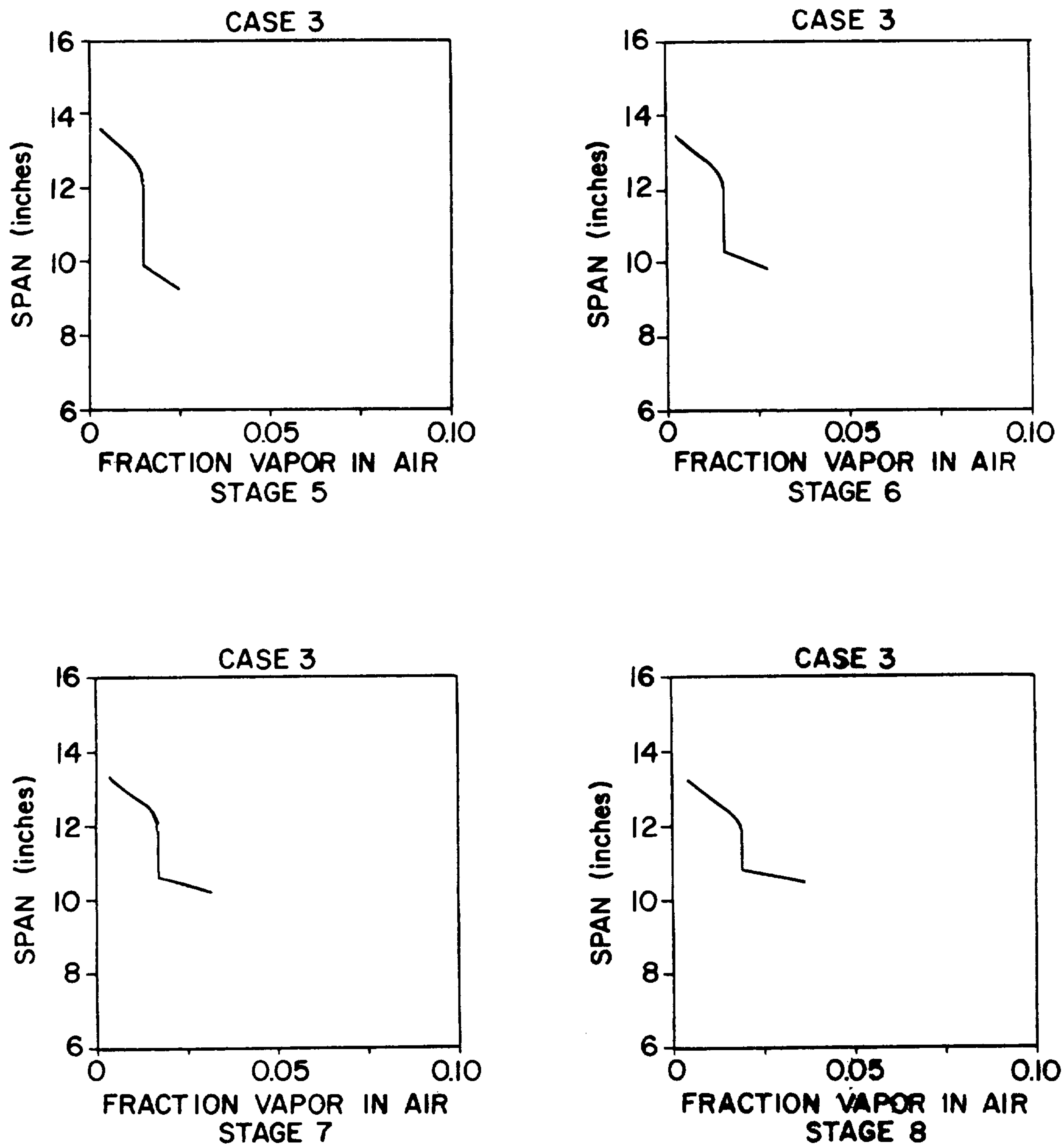

Figure 3.8 c) (2 of 4)

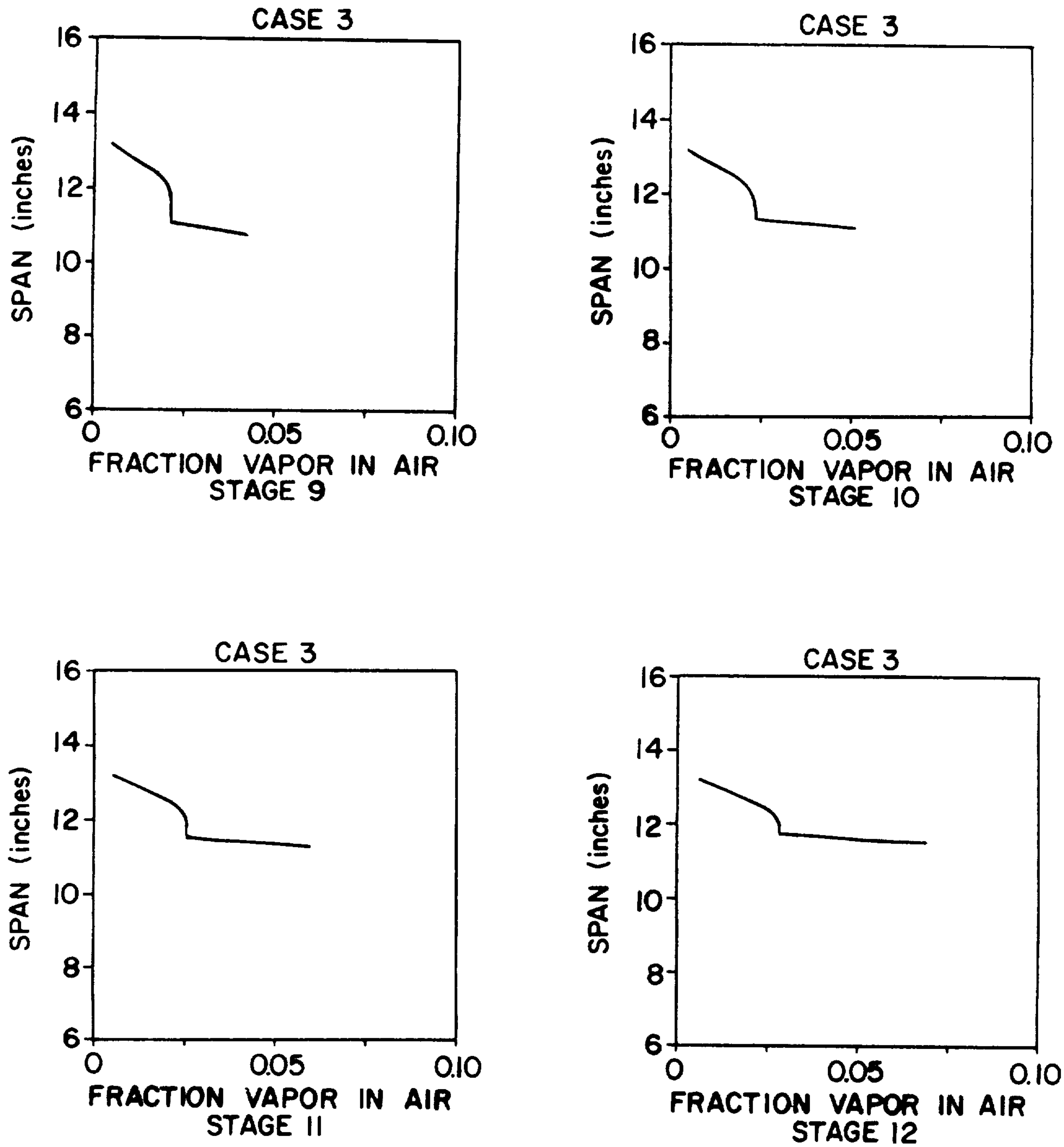

Figure 3.8 c) (3 of 4)

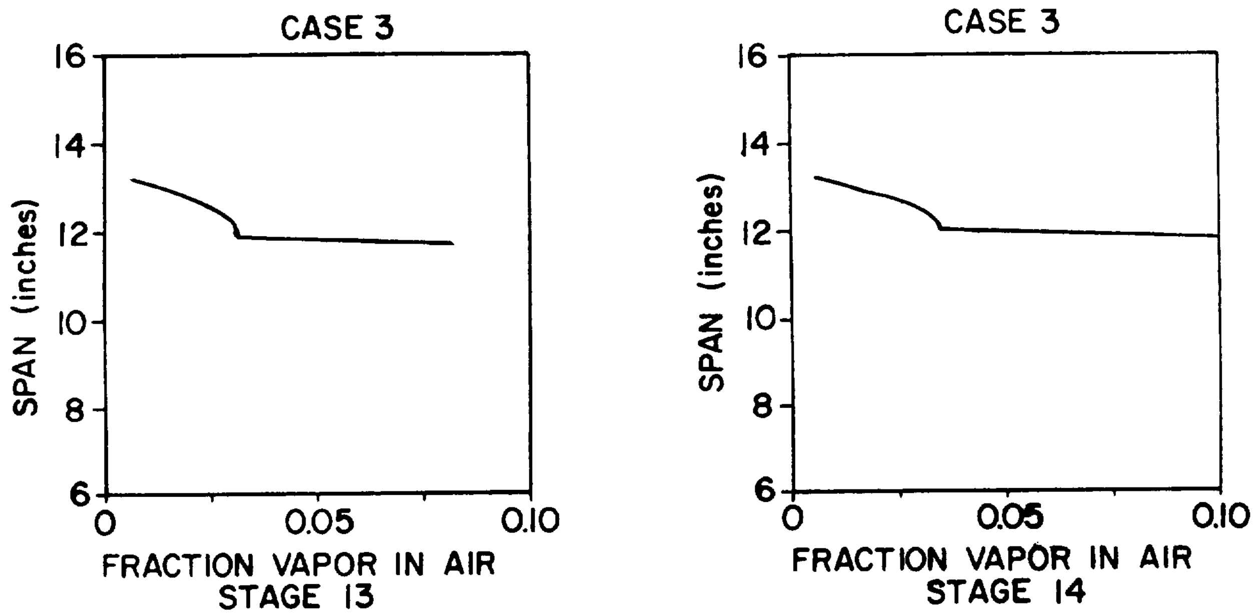

Figure 3.8 c) (4 of 4)

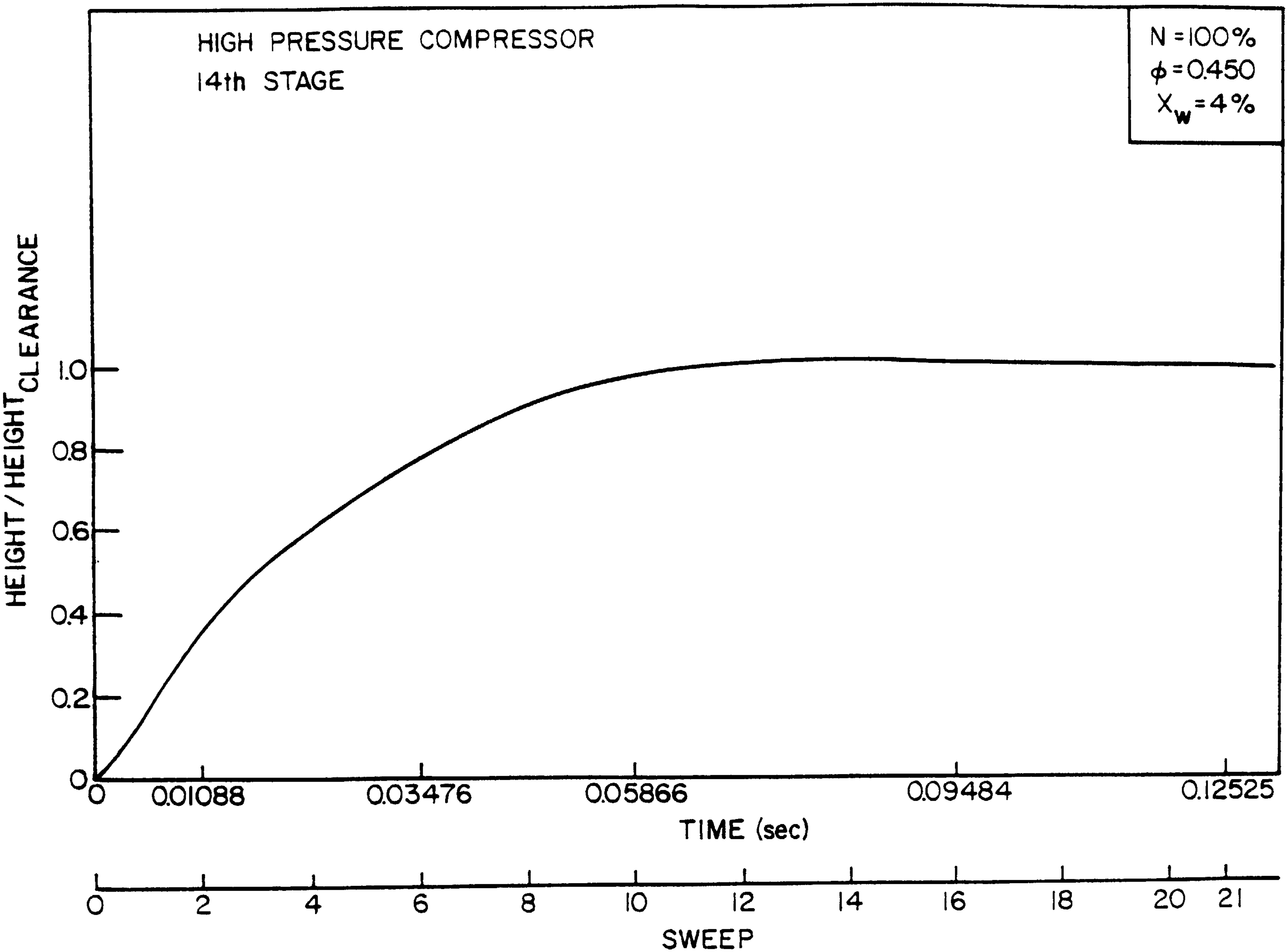

Figure 3.9 a) Growth of film in clearance vs. no. of sweeps/clock time

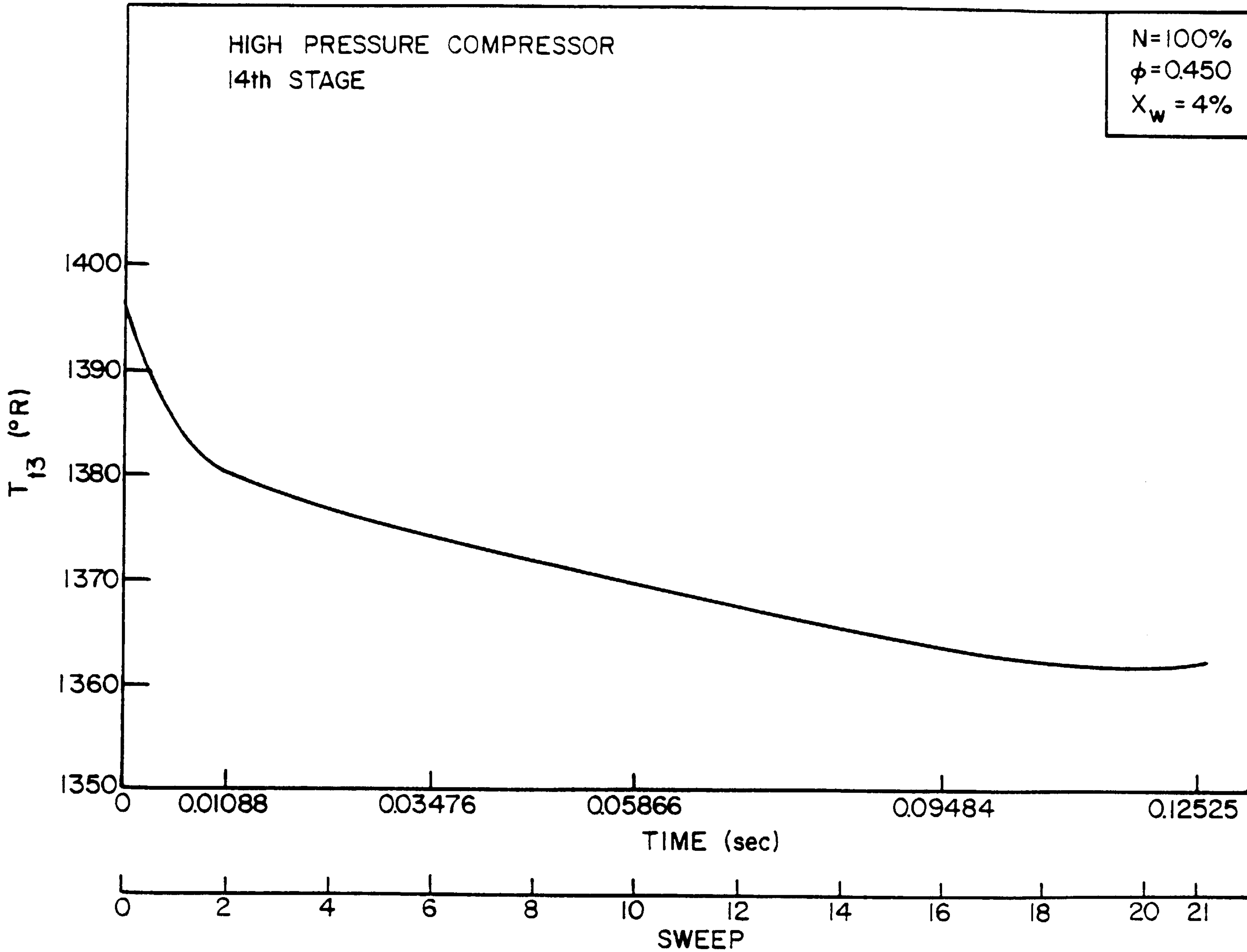

Figure 3.9 b) HPC outlet temperature vs. no. of sweeps/clock time

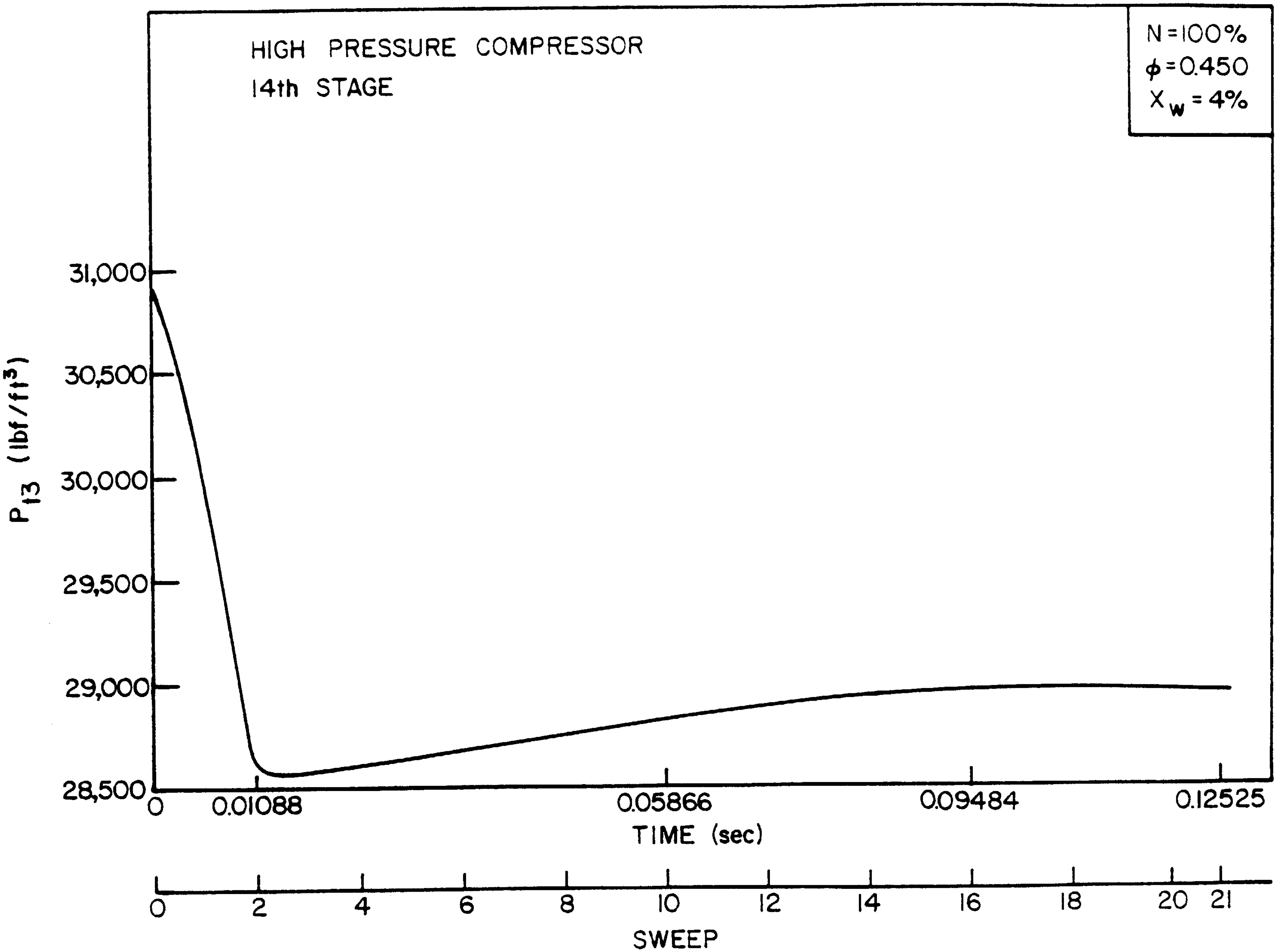

Figure 3.9 c) HPC outlet pressure vs. no. of sweep/clock time

APPENDIX I

Modifications to the WINCOF code to generate the WINCOF-I code.

SUBROUTINE WICHET

1. Description:

Subroutine WICHET is called at end of stage to perform the heat transfer calculation between water droplet and gaseous phase. The heat transfer rate can be determined from the following equation:

$$\frac{dh}{dt} = h_h A(T_g - T_w)$$

where h_h is the heat transfer coefficient, A, the droplet surface area, T_w, the droplet surface temperature, and T_g, the temperature of the surrounding gas. The heat transfer coefficient can be expressed as follows:

$$h_h = \frac{k_a}{D_d} \cdot Nu$$

where k_a is the thermal conductivity of air, and Nu, the Nusselt number. The Nusselt number can be expressed in terms of the dimensionless groups as follows (Ref. 16):

$$Nu = 2.0 + 0.6\,(Re)^{0.50}\,(Pr)^{0.33}$$

where Re is the Reynolds number based on the relative velocity between the droplet and the surrounding air, and Pr is the Prandtl number.

After calculating the temperature rise of the water and gas phase due to the work done by the rotor, the heat transfer calculation is carried out as follows:

i. Calculate the average droplet diameter, D_d.

ii. Calculate the number of droplets, N_d.

$$N_d = \frac{m_w}{\rho_w \frac{4}{3} \pi (D_d/2)^3} \cdot t_m$$

where m_w is the mass flow rate of water phase, ρ_w, the density of water, and t_m, the total time of residence of an average droplet in the stage.

iii. Calculate the droplet surface area, A.

iv. Calculate the Nusselt number, Nu.

v. Calculate the heat transfer coefficient, h_h.

vi. Calculate the stage outlet temperature for droplet and gas without heat transfer, that is

$$T_{g_2} = T_{g_1} + (\Delta T_g)_{wk}$$

$$T_{w_2} = T_{w_1} + (\Delta T_w)_{wk}$$

where $(\Delta T_g)_{wk}$ and $(\Delta T_w)_{wk}$ are the temperature rise of the gas and water due to work done by rotor.

vii. Calculate the amount of heat transferred from the gas to the droplet.

$$\Delta H = h_h A(T_{g2} - T_{w2})$$

viii. Calculate the temperatures rise of the droplet and the temperature drop of the surrounding gas.

$$(\Delta H_g)_{ht} = H/m_g C_s$$

$$(\Delta H_w)_{ht} = H/m_w C_w$$

where C_w is the specific heat for water and C_s is the specific heat for air-water mixture.

ix. Calculate the stage outlet temperature for droplet and gas.

$$T_{g_2} = T_{g_1} + (\Delta T_g)_{wk}$$

$$T_{w_2} = T_{w_1} + (\Delta T_w)_{wk}$$

x. **Using the temperature calculated in step (ix), repeat the steps (vii) to (ix) until a desired accuracy is obtained.**

2. Input Variables:

TG1	temperature of gaseous phase at stage inlet
TG3	temperature of gaseous phase at stage outlet
TW1	temperature of droplet at stage inlet
TW3	temperature of droplet at stage outlet
DAVEN2	droplet nominal diameter at stage inlet
DAVEN	droplet nominal diameter at stage outlet
DELZI	length of stage
VZ	axial velocity
TTIME	time of residence of average droplet
WMASS1	mass flow of water
VMASS1	mass flow of vapor
AMASS	mass flow rate of dry air
CHMASS	mass flow rate of methane
CPG	specific heat constant pressure to gaseous phase
CPW	specific heat of water
RE	Reynolds number based on relative velocity between droplet and gaseous phase

3. Output Variables:

DELTGH temperature drop in gaseous phase due to heat transfer between water droplet and gaseous phase

DELTWH temperature rise in droplet due to heat transfer between water droplet and gaseous phase

4. Usage:

CALL WICHET (TG1, TG3, TW3, DAVEN2, DAVEN, DELZI, VZ, WMASS1, VMASS1, AMASS, CHMASS, CPG, CPW, DELTGH, DELTWH, RE)

FUNCTION WICMTR

1. Description:

   Function WICMTR is called in Subroutine WICMAS and calculates the mass transfer rate.

2. Input Variables:

TTG	temperature of gaseous phase at stage inlet
TTW	temperature of gaseous phase at stage outlet
PPP	pressure of gaseous phase
DAVW	droplet nominal diameter
TTIME	residence time of droplet in stage
VZ	axial velocity
DZ	length of stage
MMASS	mass flow rate of mixture
PW	vapor pressure
RE	Reynolds number based on relative velocity between droplet and gaseous phase

3. Output Variable:

DMDT	mass transfer rate

4. Usage:

   WICMTR (TTG, TTW, PPP, DAVE, VZ, DZ, MMASS, PW, RE)

SUBROUTINE WICRGN

1. Description:

   Subroutine WICRGN is called at end of rotor calculations to perform the centrifugal calculations for all 10 streamtubes.

   WICDML and WICCEN are called for individual streamtubes, and water is added and subtracted from each streamtube accordingly.

2. Input Variables:

   WATRGN mass of water in streamtubes

   NREGON number of streamlines (10)

   ISTAGE current stage number

   RT radius of blade at tip

   RRHUB radius of blade at hub

   FMMASS mass of water in casing coming from previous stage

3. Output Variable:

   WATRGN mass of water in streamtubes

4. Usage:

   CALL WICRGN (WATRGN, NREGON, ISTAGE, RRTIP, RRHUB, FMMASS)

SUBROUTINE WICRGV

1. Description:

   Subroutine WICRGV is called at end of rotor calculations to perform the centrifugal calculations for all 10 streamtubes.

   WICDMV and WICCEN are called for individual streamtubes, and vapor is added and subtracted from each streamtube accordingly.

2. Input Variables:

VAPRGN	mass of vapor in streamtubes
NREGON	number of streamlines (10)
ISTAGE	current stage number
RT	radius of blade at tip
RRHUB	radius of blade at hub
CSTAREA	area of casing streamtube
NS	number of stages

3. Output Variable:

VAPRGN	mass of vapor in streamtubes

4. Usage:

   CALL WICRGV (VAPRGN, NREGON, ISTAGE, RRTIP, RRHUB, CSTAREA, NS)

SUBROUTINE WICFLM

1. Description:

Subroutine WICFLM is called after WICRGN and calculates a mean velocity of the casing water given the incoming mass of centrifuged water. This film of water is assumed to have a quadratic velocity profile:

$$\frac{U}{U_i} = C_2$$

where U is the velocity at any point in the film, U_i is the film-gas interface velocity, δ_w is the film thickness, and C_2, C_4 are constants:

$$C_2 = \frac{3}{2} - \delta w \frac{\tau_o}{2} \mu_w U_i$$

$$C_4 = \frac{1}{2} \cdot -1 + \delta w \frac{\tau_o}{\mu_w} U_i$$

The gas boundary layer is assumed to have a profile:

$$\frac{U}{U_\infty} = C \left(\frac{y}{\delta}\right)^{\frac{1}{7}}$$

y/del**1/7 profile. The momentum lost by the gas in each stage is transferred to the water in the film, and an equilibrium interace velocity is calculated. From the momentum and mass of the film, a mean velocity is calculated.

2. Input Variables:

VZ	axial velocity
FMMASS	mass of water in casing entering stage
XWT	percentage of water in streamtube
CLEAR	casing clearance
RCASE	radial distance of casing
NRADS	flag for redistributed water

REDMAS	amount of redistributed water
RHOM	density of water
RT	radius of blade at tip
WTMASS	mass of water in streamtube
HTOTL	thickness of casing film
WATRGN	mass of water in individual streamtube
RRHUB	radius of blade at hub
NREGON	number of streamlines
MMASS	mass of gas in streamtube
UMLAST	mean velocity of film coming from last stage
CSTAREA	casing area
FILMM	momentum of casing water
NS	number of stages
DELZZ	length of stage

3. Output Variables:

UIF	film-gas interface velocity

4. Usage:

CALL WICFLM (VZ, FMMASS XWT, CLEAR, RCASE, NRADS, REDMAS,
RHOM, RT, WTMASS, HTOTL, WATRGN, RRHUB, NREGON,
MMASS, UMLAST,CSTAREA, FILMM, UIF, NS, DELZZ)

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16. Abstract

The PURDUE-WINCOF code, which provides a numerical method of obtaining the performance of a fan-compressor unit of a jet engine with water ingestion into the inlet, has been modified to take into account (1) the scoop factor, (2) the time required for the setting-in of a quasi-steady distribution of water and (3) the heat and mass transfer processes over the time calculated under (2). The modified code, named WINCOF-I, has been utilized to obtain the performance of a fan-compressor unit of a generic jet engine. The results illustrate the manner in which (i) quasi-equilibrium conditions become established in the machine and (ii) the redistribution of ingested water in various stages in the form of (a) film out the casing wall, (b) droplets across the span and (c) vapor due to mass transfer.

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