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SUPERSONIC LAMINAR FLOW CONTROL RESEARCH

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SEMI-ANNUAL
REPORT #4
July 1995 - December 1995

Dr. C.F. Lo, Principal Investigator
University of Tennessee Space Institute

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Title: Supersonic Laminar Flow Control Research

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Semi-Annual Report #4
July - December 1995

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Technical Objectives

The objective of this research is to understand supersonic laminar flow stability, transition and active control. Some prediction techniques will be developed or modified to analyze laminar flow stability. The effects of distributed heating and cooling as an active boundary layer control technique will be studied. The primary tasks of the research apply to the NASA/Ames PoC and LFSWT's nozzle design with laminar flow control and are listed as follows:

1. Predictions of supersonic laminar boundary layer stability and transition;

2. Effects of wall heating and cooling on supersonic laminar flow control;

3. Performance evaluation of the PoC and LFSWT nozzle designs with wall heating and cooling applied at different locations and various lengths, ~~and~~

4. Effects of a conducted -vs- pulse wall temperature distribution for the LFSWT.

Accomplishment of the First 18 Months (Refs. 1,2 & 3)

A. Prediction of Supersonic Laminar Boundary Layer and Stability

Two Computational Fluid Dynamics (CFD) codes which were used to conduct this study have been checked out successfully in the first half year. The first code is a boundary layer code developed by Harris at NASA (Ref. 4). This program solves the laminar, transitional, or turbulent compressible boundary layer equations for two dimensional or axisymmetric flows. The output of this code is used as input for the second CFD code developed by NASA contractor Malik (Ref. 5). This second program utilizes the compressible linear stability theory to predict the stability characteristics and the transition location of the boundary layer.

B. Temperature effects on the Stability of the Laminar Boundary Layer of a Flat Plate

The temperature effects on the stability of the laminar boundary layer was analyzed for a flat plate at M=1.6. The wall heating was applied to the leading ten percent of the flat plate and the rest of the plate remained at the adiabatic wall temperature. Three heating cases and an adiabatic case with wall temperatures 602°R, 702°R, 902°R and 502°R respectively were input into the boundary layer code. Each heating case increases the stability of the boundary layer with the N-factor getting smaller as the heating temperature increases. Details are reported in the Semi-Annual Report #1 (Ref. 1) as well as Lafrance's thesis (Ref. 6). These findings are consistent with theoretical results obtained for the subsonic flow in Ref 7.

C. Results for the PoC Nozzle with Local Strip Heating

Since the local strip heating can enhance the stability on the flat plate (i.e., without pressure gradient), it is reasonable to expect the same concept to apply to a nozzle configuration (i.e., with pressure gradient along the wall) in order to enhance the stability of the wall boundary layer.

One typical case is given here to illustrate the feasibility of searching for the optimal locations and increments of temperature for wall heating. Local heating and cooling strips are applied, in turn, at $2.86 \leq X \leq 3.73$ downstream of the nozzle entrance (station X=0.0) at 600°R and 400°R respectively. The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test section exit is 9.23 units. Results obtained from both the curvature criterion and N-factor theory are consistent with the conclusion that the heating strip stabilizes the boundary layer. Details of these results and other cases are given in Section 2.3 and 3.3 of Meredith's master thesis (Ref. 8).

D. Stability and Transition Prediction for the Laminar Flow Supersonic Wind Tunnel (LFSWT)

The Laminar Flow Supersonic Wind Tunnel (LFSWT) is 5.05 feet long, including the nozzle and test section. Five strip locations were used to investigate the effects of local heating and cooling on the laminar boundary layer stability; three upstream of the instability on-set (I.O.) point and two downstream of the same. Since removal of heat energy from the flow enhances the boundary layer stability, the location of the heating/cooling strips relative to the I.O. point is critical. To enhance the stability, in general, a heating strip should be applied upstream on the I.O. point or a cooling strip downstream of the same. Furthermore, application of two strips on the wall; a heating strip upstream of the I.O. point and a cooling strip downstream of the same, is expected to increase the stability (decrease the N-factor) over that of the single strip configuration. All results are given in Ref. 9.

The current findings indicate that stability is enhanced by localized heating upstream of the I.O. point and/or cooling downstream of the I.O. point. Localized cooling downstream of the I.O. point is more effective in stabilizing the laminar boundary layer than is heating upstream of the I.O. point.

Localized heating far upstream of the I.O. point introduces heat energy into the flow which creates a positive temperature gradient directed out into the flow stream normal to the wall. Since the wall temperature downstream is lower than that of the boundary layer stream, the thermal energy in the boundary layer flows into the wall. As a result, a cooling effect is established near the wall in the vicinity of the I.O. point. This cooling of the boundary layer enhances the boundary layer stability. When local cooling is employed upstream of the I.O. point, the stability is reduced since a heating effect is produced near the wall in the vicinity of the I.O. point. However, stability is increased when localized cooling is applied downstream of the I.O. point. The theoretical study by Masad & Nayfeh (Ref.7) and experimental evidence obtained by Demetriades (Ref.10) of laminar boundary layer control for a subsonic flat plate and supersonic nozzle respectively, provide similar trends to those described above. The application of strip heating and/or cooling to the quiet tunnel's wall seems feasible, especially since the heating and/or cooling is localized and limited to certain upstream and downstream regions of the wall.

Status of Progress

A. Stability and Transition Prediction with Conducted -vs- Pulse Wall Temperature Distribution for the LFSWT

The work done by Lo, et. al. (Ref.9) on laminar boundary layer control for quiet supersonic wind tunnels employed heating and/or cooling strips to alter the adiabatic wall temperature distribution. In the above work, the local wall temperature distributions created by the heating/cooling strips were modeled as pulse functions, $T_w(x)$, of constant temperature and widths equal to the respective heating/cooling strip lengths.

It is important to refine the model of the local wall temperature distribution to a realistic, "conducted", wall temperature distribution. The conducted wall temperature distribution was achieved by modeling the wind tunnel wall as a semi-infinite plane with one-dimensional heat transfer parallel to the wall, and the heating/cooling strips characterized as point sources of thermal energy (Ref 12). The effect of the "conducted" wall temperature distributions on the boundary layer stability are then studied and compared to the results of the pulse temperature distributions of Ref 9. Four cases are examined; two with heating/cooling strips upstream of the instability on-set (I.O.) point and two with the strips downstream of the same. The conducted wall temperature distributions used are considered reasonable, but not necessarily exact. The heating and cooling wall temperature distributions for the four cases are shown in Figures 1 through 8. The optimal overall wall temperature distribution (i.e. optimally placed heating and/or cooling strips producing "conducted" temperature distributions) is sought for as the guideline for the quiet supersonic wind tunnel experiment.

The N-factor that results from the adiabatic wall temperature case provides the baseline to which all subsequent heating/cooling cases are compared. Cases with N-factors less than the baseline N-factor (N_b) stabilize the boundary layer, whereas those with N-factors greater than N_b de-stabilize the boundary layer. The results are examined by comparing the maximum N-factors and the I.O. locations for four cases (same as Case I,II,IV and V of Ref. 9). The table below summarizes the N-factor results for the four cases for both the pulse and conducted temperature distributions.

B. Discussion of Results

The present results reveal that the effects of a conducted wall temperature distribution, imposed by heating or cooling strips, on the boundary layer stability follow the same trend shown in Ref. 9 for a pulse temperature distribution. However, it is shown that for heating upstream of the I.O. point, the conducted temperature distribution produces more stable (lower N-factors) results than do the corresponding pulse temperature distributions as shown in Figures 9 and 10. The same is true for cooling downstream of the I.O. point, see Figures 11 and 12. In both heating upstream or cooling downstream of the I.O. point, if the imposed temperature distribution extends over the I.O. point, significant shifts in the I.O. point can occur along with increased uncertainty.

A conducted wall temperature distribution produces increased boundary layer stability compared to a pulse temperature distribution if properly placed relative to the I.O. point. Greater care must be taken in the placement of the heating /cooling strips relative to the I.O. point since the conducted temperature distribution influences more flow area. This work will be beneficial to the optimization of the heating/cooling locations.

Publications

Results of the first year's study are summarized in a journal paper entitled **"Wall Temperature Effects on the Stability of Laminar Boundary Layers"** published in the *AIAA Journal of Aircraft* (Ref. 11).

Future Plan

- Apply the Neural Network Analysis to find heating/cooling strip configurations that will optimize the boundary layer stability and delay transition.

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Table - N-factor Summary

	N_b	N-factor (Conducted T_w)	N-factor (Pulse T_w)
Case I - Ht	6.17	5.20	5.81
Case I - Cl	6.17	7.72	6.67
Case II - Ht	6.17	4.14	5.52
Case II _ Cl	6.17	8.93	6.91
Case IV - Ht	6.17	7.91	6.63
Case IV - Cl	6.17	4.07	1.29
Case V - Ht	6.17	9.61	7.88
Case V _ Cl	6.17	1.36	3.13

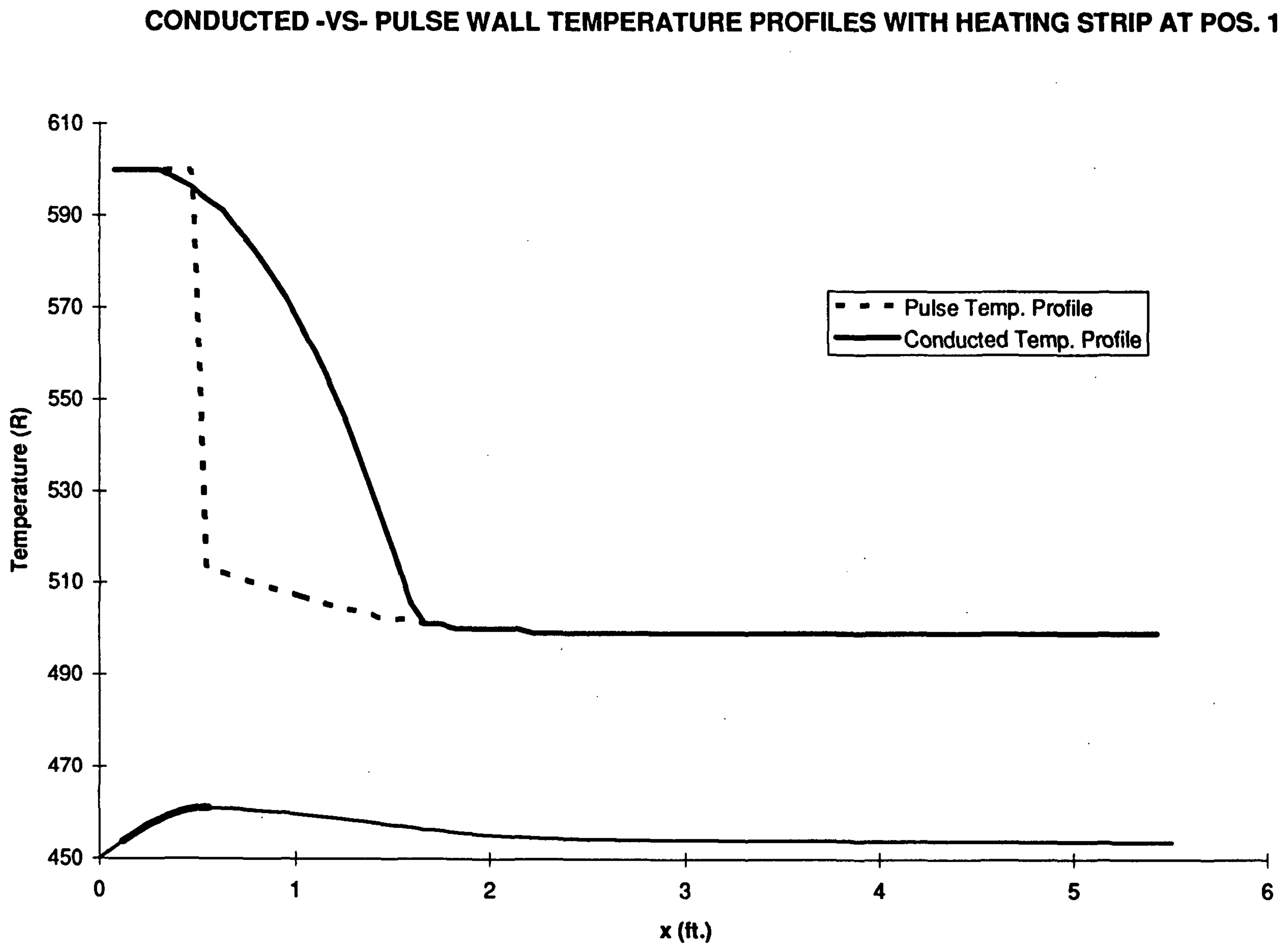

Figure 1. Conducted and pulse wall temperature distributions for Localized Heating at Location #1 on the LFSWT.

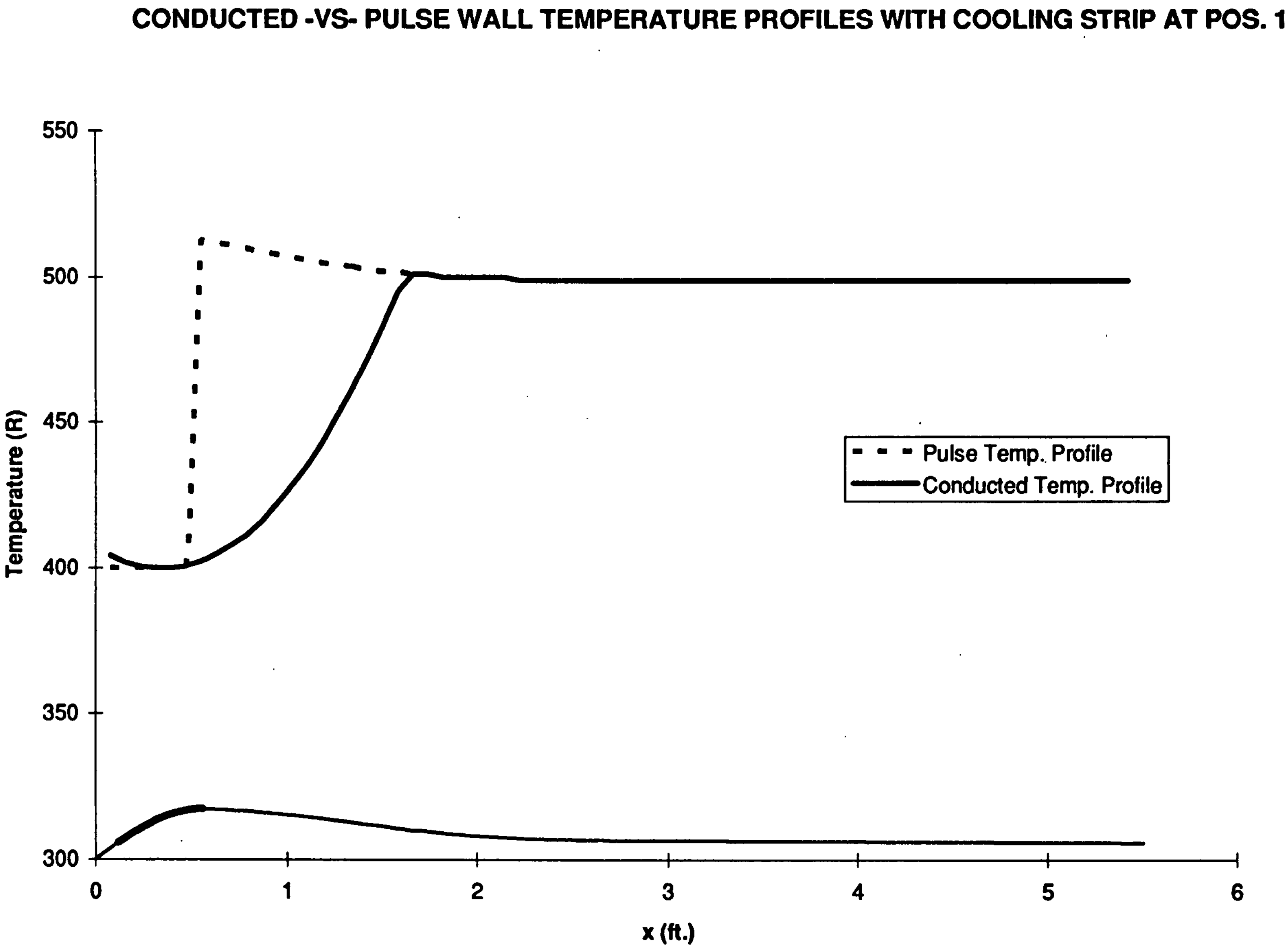

Figure 2. Conducted and pulse wall temperature distributions for Localized Cooling at Location #1 on the LFSWT.

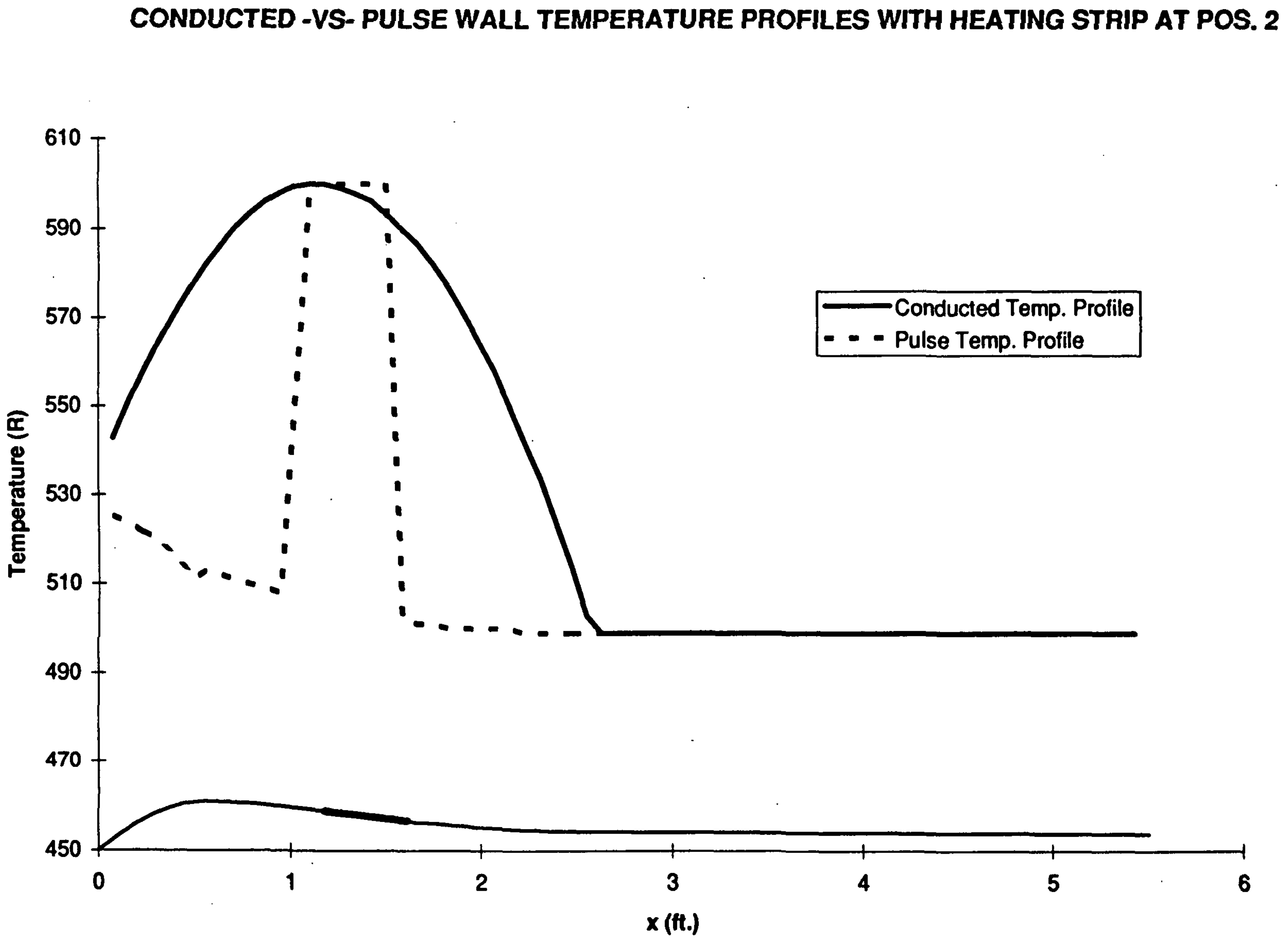

Figure 3. Conducted and pulse wall temperature distributions for Localized Heating at Locaction #2 on the LFSWT.

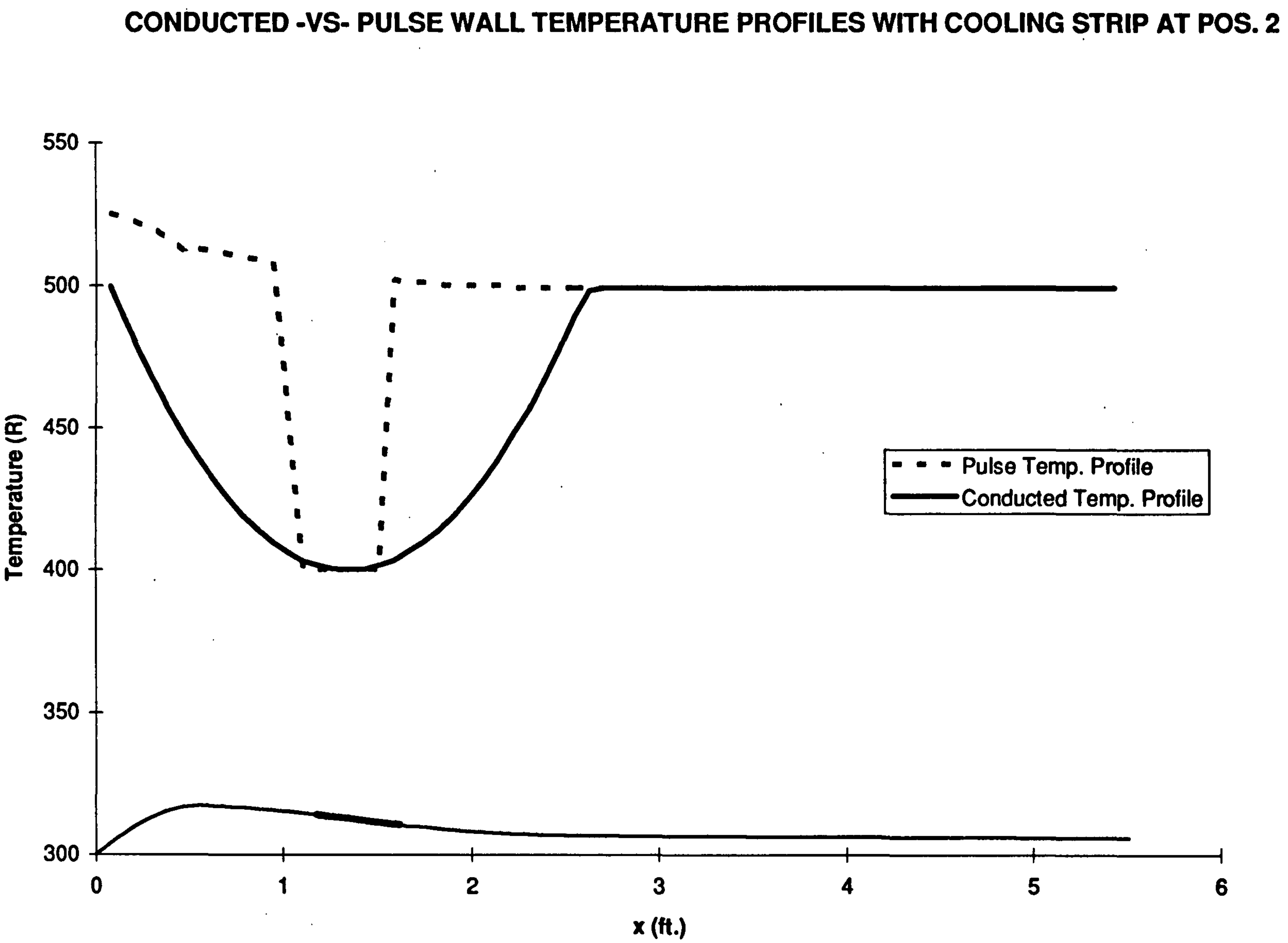
CONDUCTED -VS- PULSE WALL TEMPERATURE PROFILES WITH COOLING STRIP AT POS. 2

Figure 4. Conducted and pulse wall temperature distributions for Localized Cooling at Location #2 on the LFSWT.

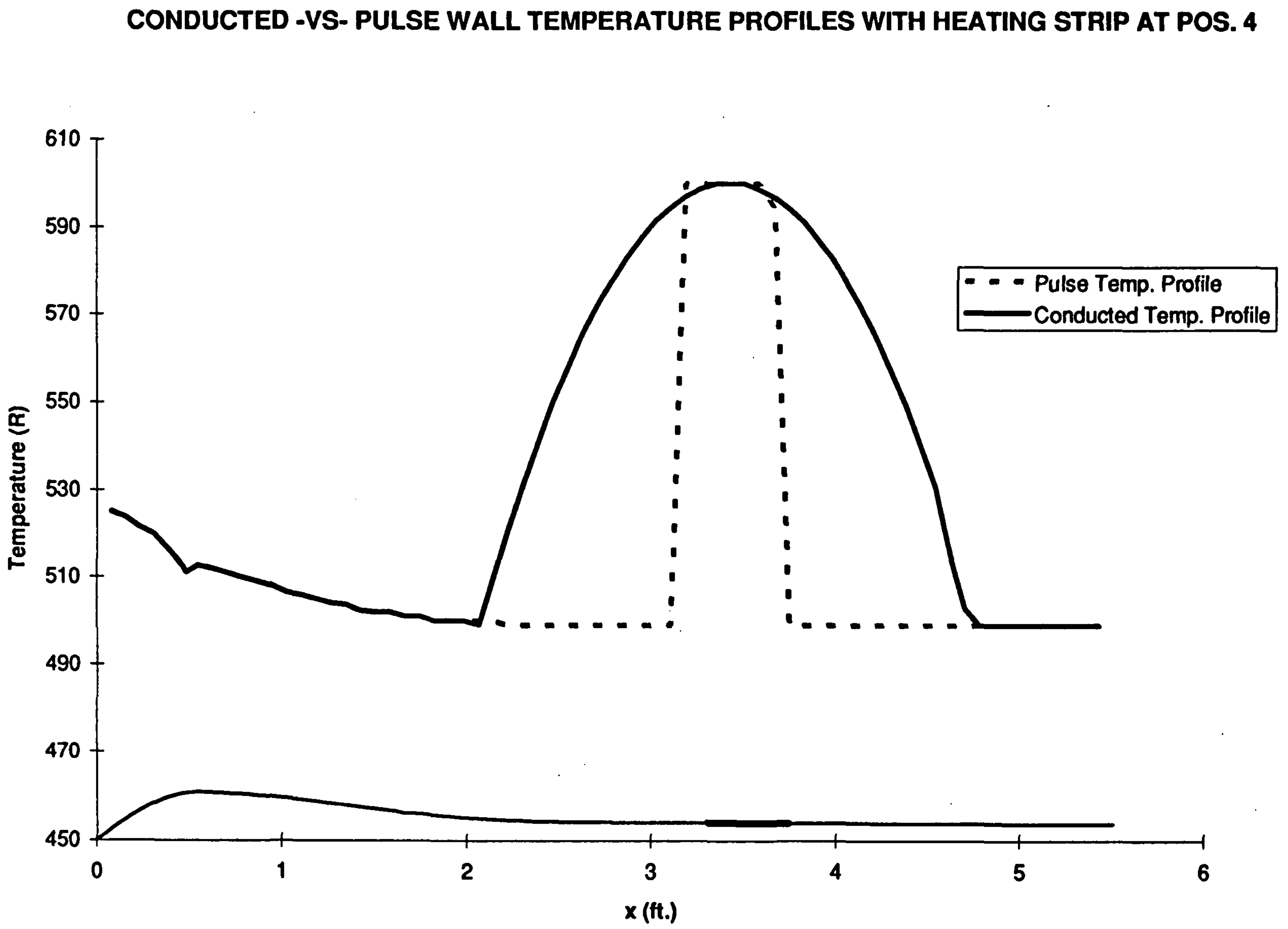

Figure 5. Conducted and pulse wall temperature distributions for Localized Heating at Location #4 on the LFSWT.

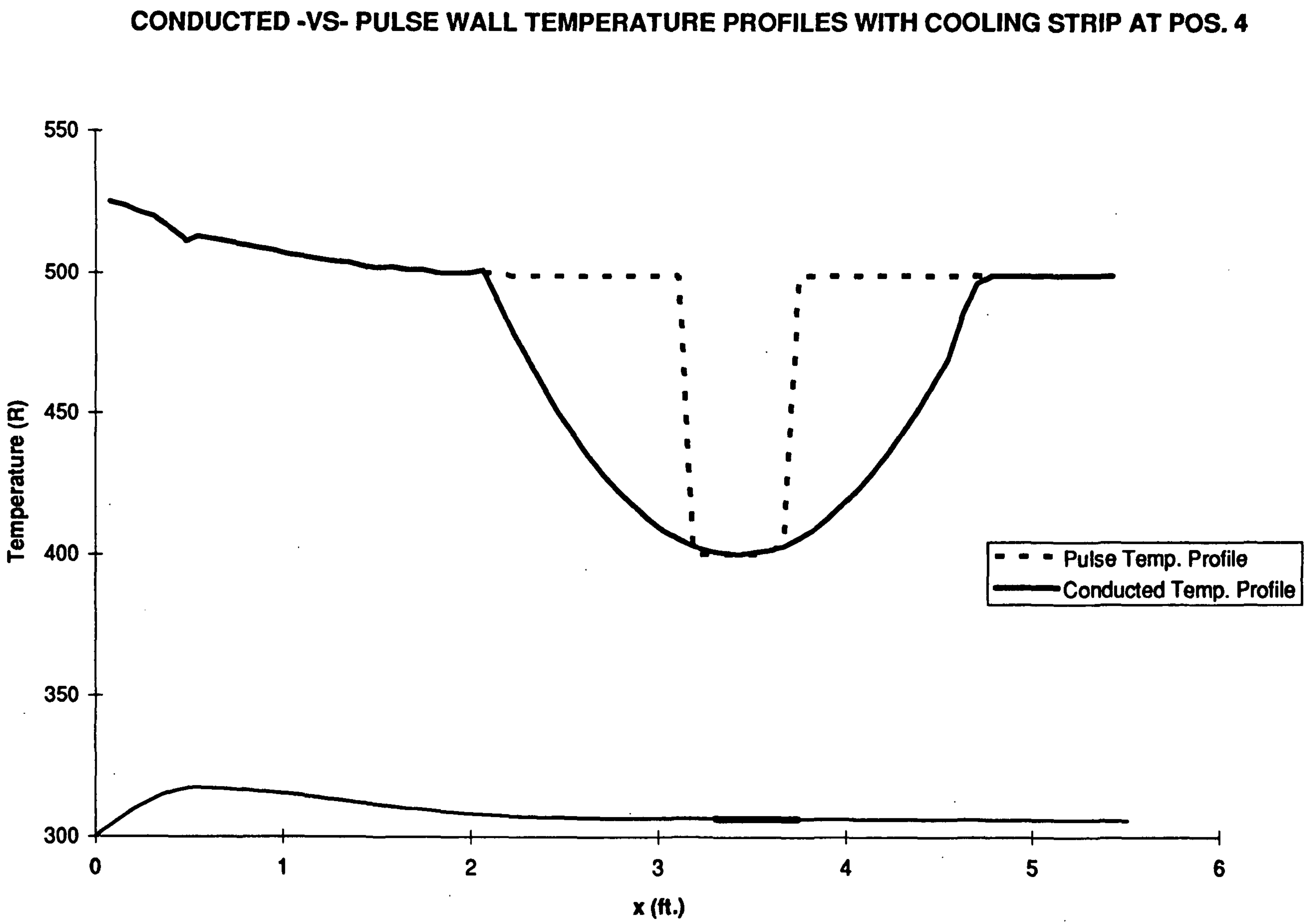

Figure 6. Conducted and pulse wall temperature distributions for Localized Cooling at Location #4 on the LFSWT.

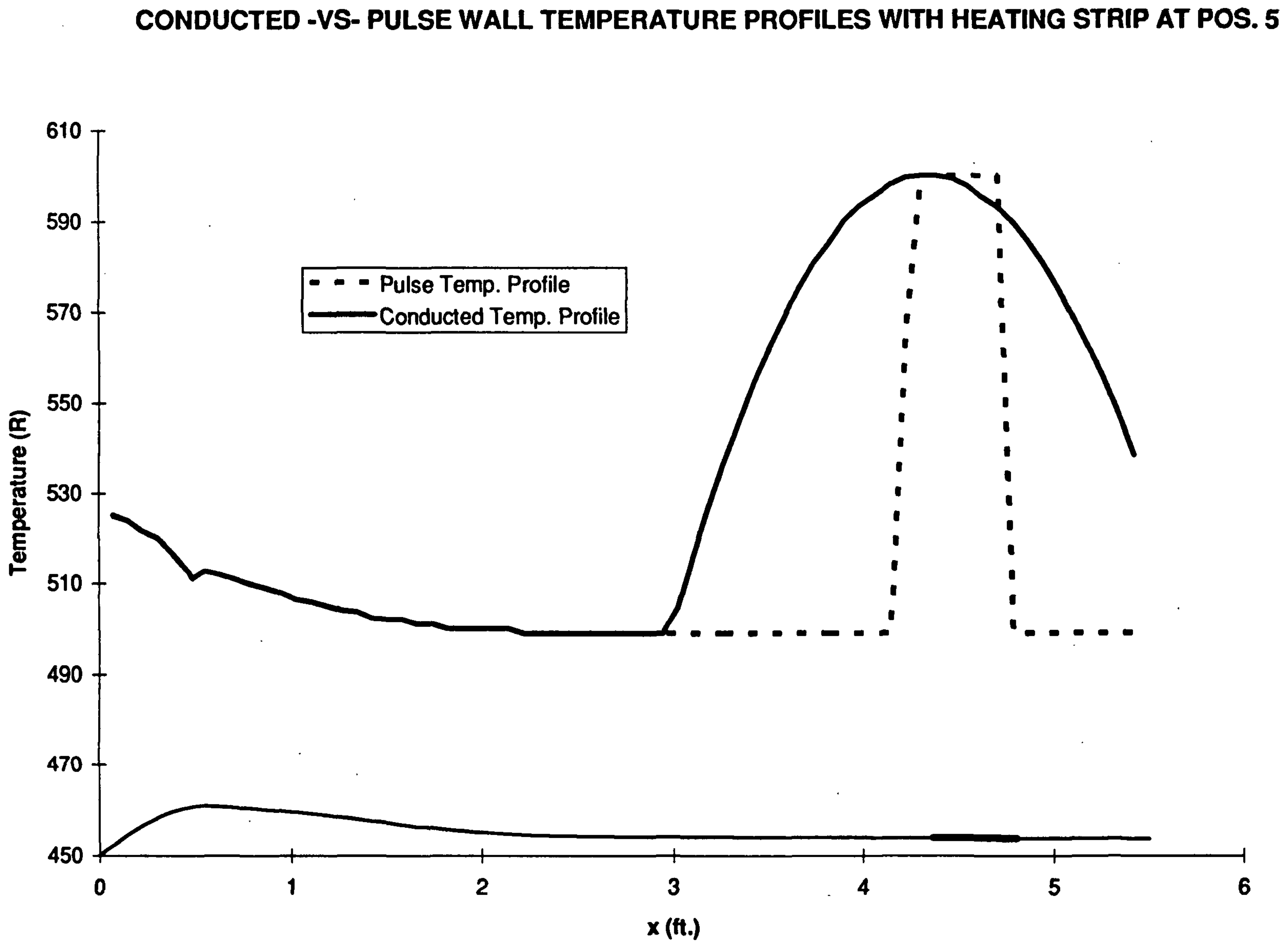

Figure 7. Conducted and pulse wall temperature distributions for Localized Heating at Location #5 on the LFSWT.

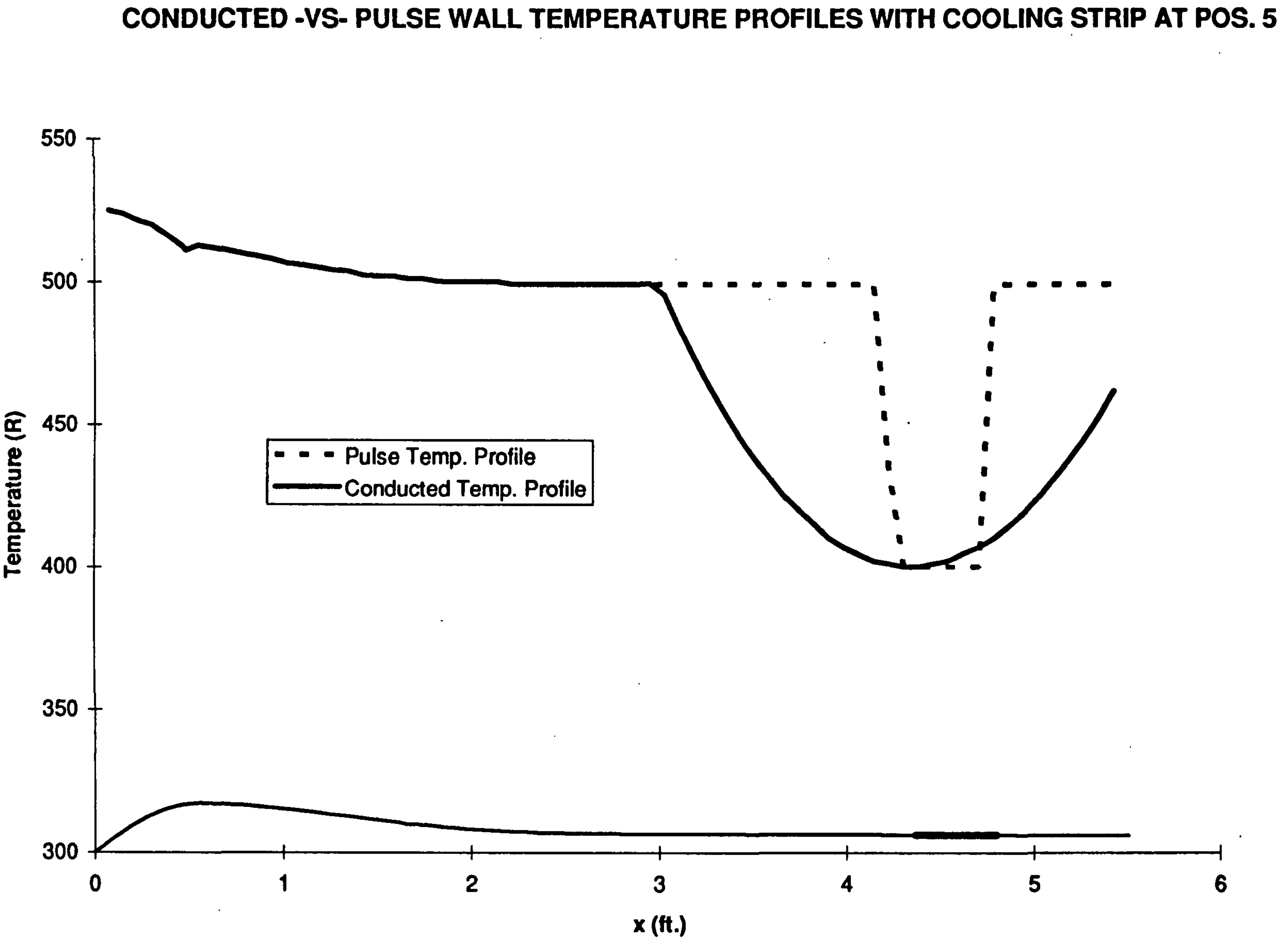
CONDUCTED -VS- PULSE WALL TEMPERATURE PROFILES WITH COOLING STRIP AT POS. 5

Figure 8. Conducted and pulse wall temperature distributions for Localized Cooling at Location #5 on the LFSWT.

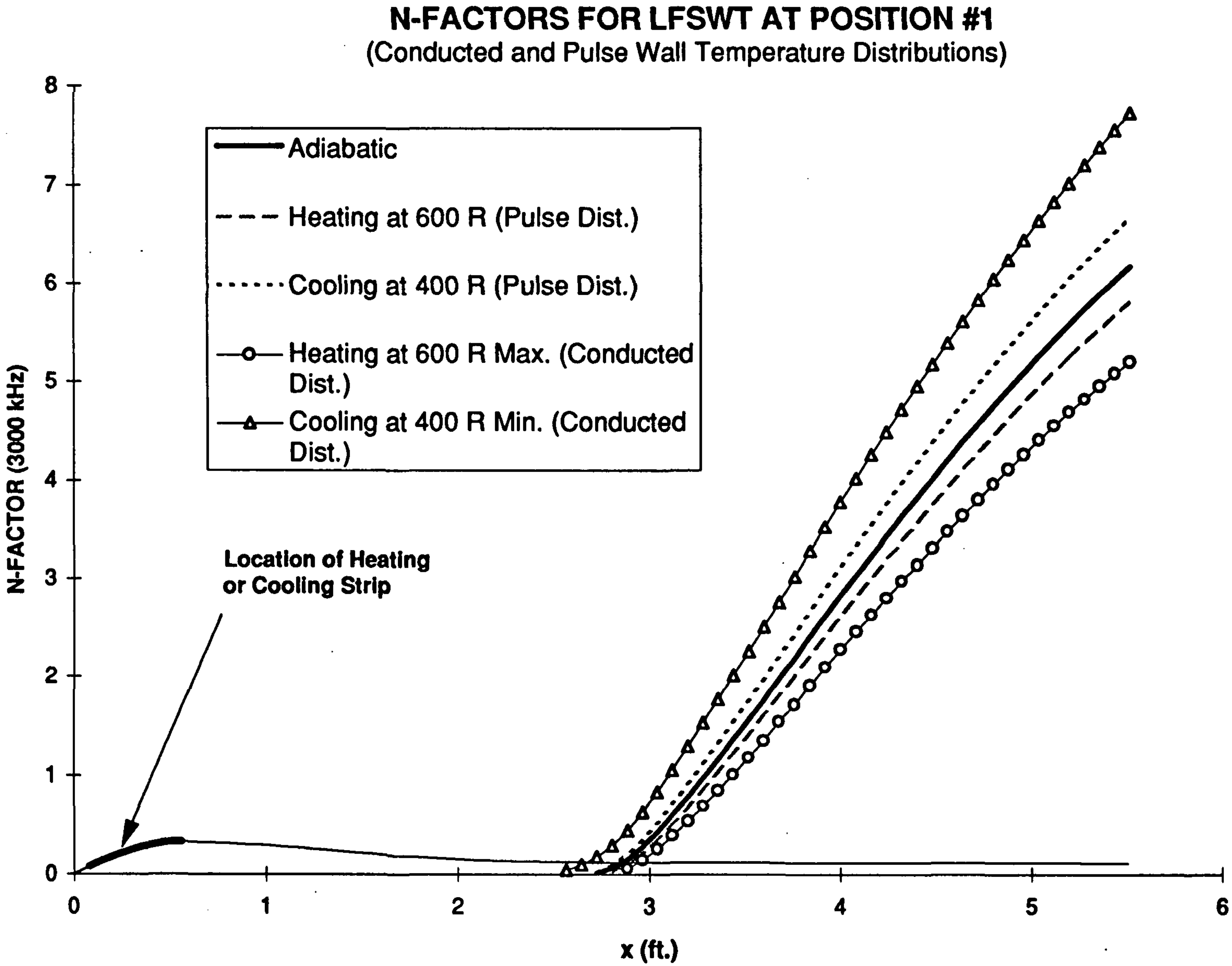

Figure 9. Streamwise N-factor profiles for the adiabatic case and local heating and cooling cases for both Conducted and Pulse wall temperature distributions at Location #1 on the LFSWT.

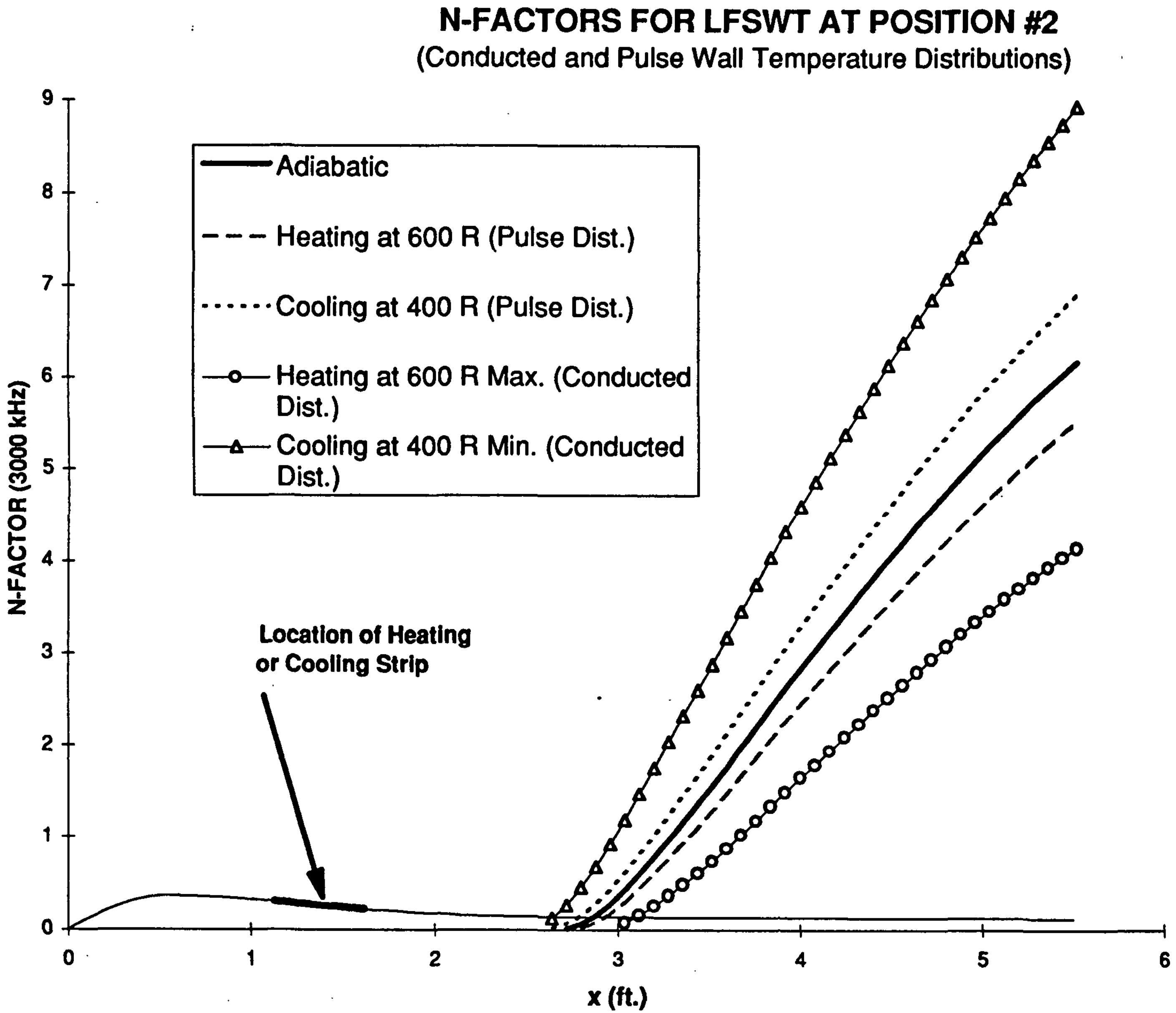

Figure 10. Streamwise N-factor pofiles for the adiabatic case and local heating and cooling cases for both Conducted and Pulse wall temperature distributions at Location # 2 on the LFSWT.

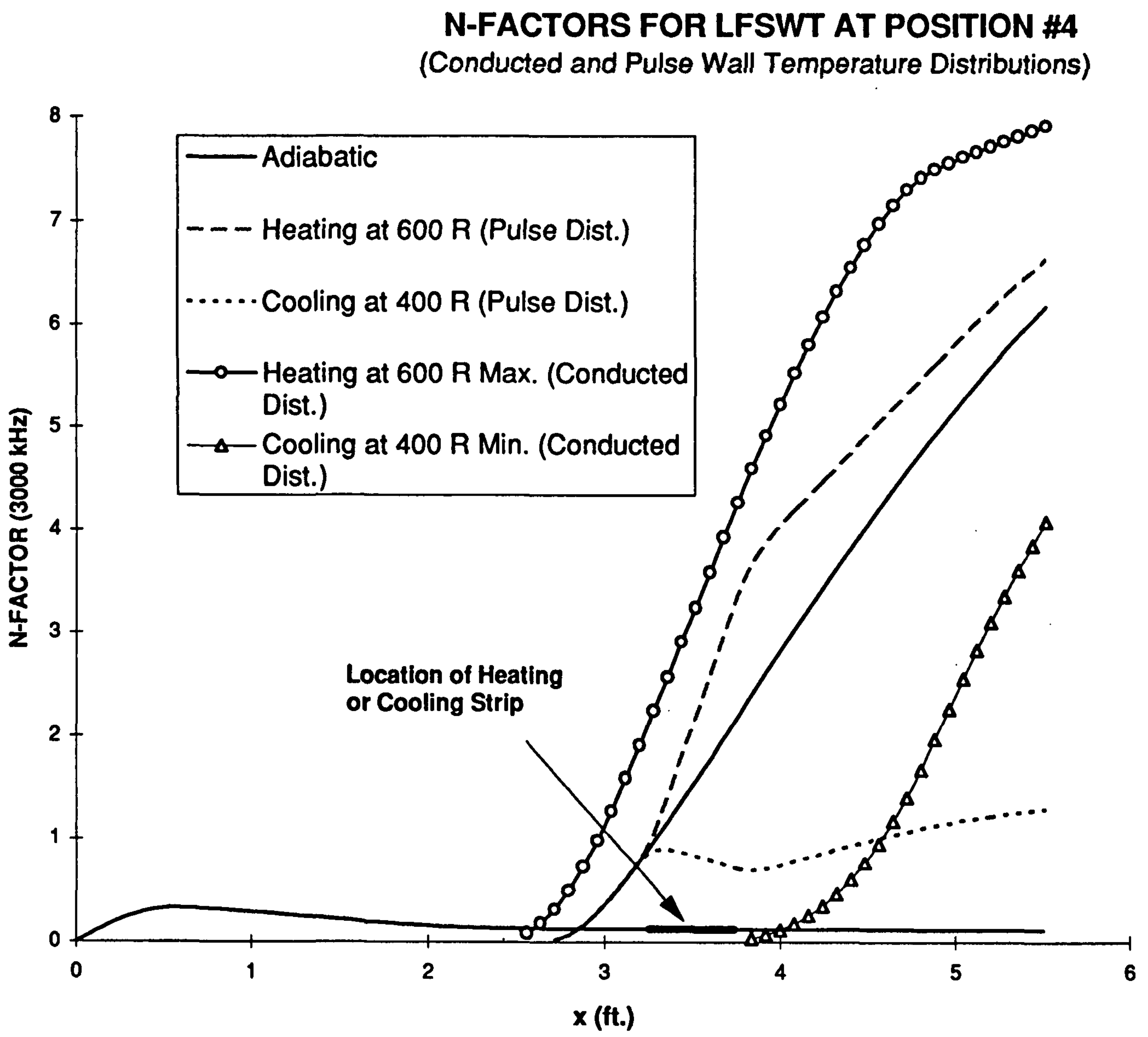

Figure 11. Streamwise N-factor profiles for the adiabatic case and local heating and cooling cases for both Conducted and Pulse wall temperature distributions at Location #4 on the LFSWT.

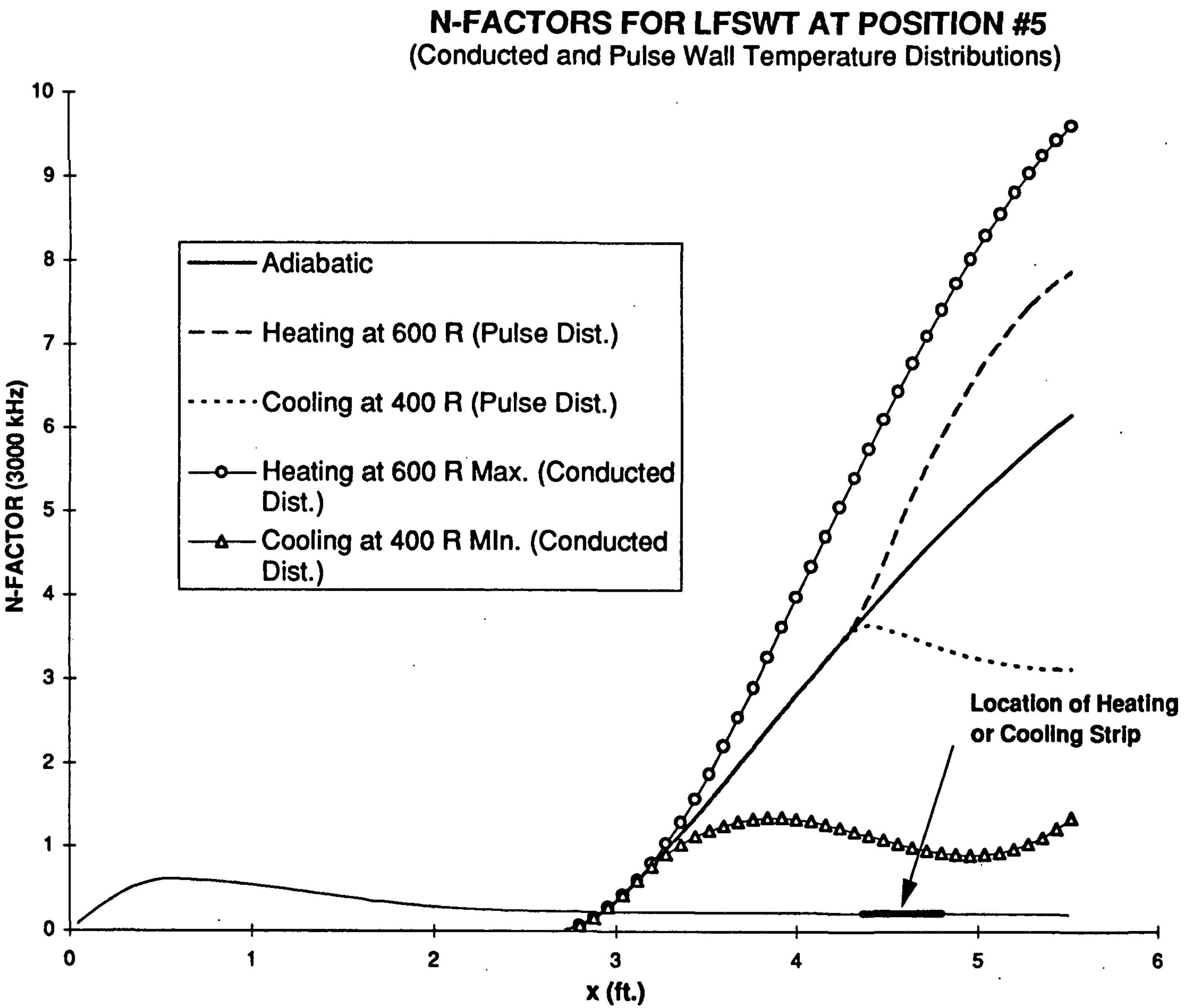

Figure 12. Streamwise N-factor profiles for the adiabatic case and local heating and cooling cases for both Conducted and Pulse wall temperature distributions at Location #5 on the LFSWT.