OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

CORRELATION AND ANALYSIS OF ELEVON SEAL TEST RESULTS

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Final Report

Prepared for the
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July 1976 - September 1977
L. Roane Hunt, Technical Monitor
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INTRODUCTION

For shuttle-type reentry vehicles the boundary layer and surface temperatures generated will be very high, requiring extensive thermal protection systems. Ingestion of the hot boundary layer gas into the elevon-wing cove area is potentially destructive if leakage of this gas past the seal occurs, resulting in exposure of actuation and control mechanisms to high temperatures.

An experimental study investigating the effects of such leakage has been conducted by Scott et al. (ref. 1) in which a wing-elevon-seal model was exposed to high temperature gases in a small arc tunnel. At the NASA/Langley Research Center, a much larger model (fig. 1) was designed (41-inch elevon and seal width) and tested in the Langley 8-foot high Temperature Structures Tunnel [$M = 6.8$, $T_{total} = 3300°R$, and $Re = 0.5$ to $1.6\ (10^6)$ per ft]. A more complete description of the experimental program may be found in reference (2).

The initial objectives of the studies conducted under NASA grant NSG 1318 were (1) to correlate the heating rate and pressure distributions in and around the elevon cove, and (2) to develop an analytical approach incorporating such a correlation into a thermal-structural computer code in order to analyze the elevon seal and cove structure in flight.

During the actual course of the study, most of the initial emphasis was placed upon developing an analytical thermal model that could reasonably predict gas and wall temperatures in the

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[1] Associate Professor, Department of Mechanical Engineering and Mechanics, Old Dominion University, Norfolk, Virginia 23508.

cove area. After having developed such a computerized capability, emphasis was then placed upon comparing computed and measured results obtained from the extensive wind tunnel tests of the full-scale representation of the space shuttle wing-elevon juncture. Such a comparison was considered essential to validate the predictive capabilities of the simplified thermal model of the cove area before the computer model could be relied upon to predict temperatures for extended time periods characteristic of shuttle reentry trajectories (wind tunnel tests provided high temperature exposure times on the order of only 20 seconds).

The elevon cove area was modelled analytically by a parallel-plate flow channel, incorporating effects of axial wall conduction, axial and environmental radiant energy exchanges, and effects of laminar and turbulent convection entrance regions (fig. 2). A parametric study of these effects was made utilizing computer solutions of the governing integro-differential equations. An example is illustrated by figure 3, where wall conduction and energy storage effects upon transient wall and gas temperature distributions are shown.

The overall computational scheme devised permitted the determination of gas and wall temperature distributions for a variety of external flow conditions and a range of leak sizes. Actual test runs were thus modelled, permitting direct comparison of analytical results and experimental measurements. Upon specification of the leak size, pressure differential across the seal, and inlet gas temperature, the program calculates the (maximum) mass flow rate possible in the cove (choked flow conditions), categorizes flow as laminar or turbulent, employs appropriate entrance region heat transfer coefficients, and finally yields gas and wall temperature variations within the cove after a single time step. Calculations for additional time steps are modified to account for varying wall and gas properties due to the previously computed temperature changes.

Comparisons were made between computed and measured values of (1) cove wall temperatures, (2) local gas temperature within the cove, and (3) local wall heating rates. A comparison was also made between entrance region Nusselt numbers for flow in a parallel plate channel (ref. 3, for example) and those values calculated from the experimentally measured local values of heating rates and wall and gas temperatures.

Regarding comparisons of wall and gas temperatures, meaningful comparisons are not possible unless accurate inlet gas temperatures, modelling those existing throughout a given test run, may be specified as input to the computer calculations. Due to the quite complex flow conditions at the cove mouth, the inlet gas temperature is not known a priori and, furthermore, is time variant during a given test run. This is especially so during the early stages of a test run, when the high temperature gas loses energy to the relatively cool wing structure. Consequently, in the present analysis, after the mass rate of flow of gas was permitted by a seal leak of given size and with a pressure differential the same as that existing in a given test run, an iterative type procedure was used to determine an inlet gas temperature that resulted in the closest agreement between measured and predicted wall and gas temperatures within the cove.

Such an iterative type procedure is employed in both references 1 and 4. In reference 1, however, the cove wall heat flux distribution was iterated so as to match that measured in actual tests. In reference 4, the inlet Mach number is iteratively assumed until an appropriate downstream boundary condition is met. An example that illustrates how a given inlet gas temperature is observed to be more appropriate than another is shown in figure 4. A direct comparison of predicted and measured wall temperatures along the cove length is shown in figure 5.

It was initially hoped that direct comparisons could also be made between calculated and measured local gas temperatures in the cove (gas temperatures were measured only at two axial locations in the cove). Upon measuring the time constants of the thermocouples actually employed in obtaining these measurements it was found that the smallest time constant was 1.3 seconds (i.e., after being subjected to a step change in temperature, the thermocouple would attain 0.632 of the final temperature in 1.3 seconds). In view of these large time constants, together with the probable time varying inlet gas temperatures, the gas temperatures measured (or indicated) were judged to be sufficiently inaccurate to prevent meaningful comparisons with the values computed from the analytical model.

Similarly, attempts were made to compare local heat transfer coefficients developed for laminar flow in parallel-plane channels with those coefficients calculated from measured heating rates and gas and wall temperatures. Reasonable agreement was not obtained, again apparently because of significantly large inaccuracies in gas temperature measurements. Initially it appeared that actual heat transfer coefficient values were as much as three times larger than those predicted by theory (see fig. 6, for example). Close examination of wall and gas temperature measurements, i.e., the magnitude of possible errors associated with each, has shown that such large disagreement may quite reasonably be attributable to the inaccuracies in these measurements.

Transient temperatures of the seal and rub-plate were also calculated, using the MITAS computer code (lumped parameter approximation) and were found to be in reasonable agreement with measured values. Using the previously discussed modified "h" values and the transient cove entrance gas temperature, exit gas temperatures were obtained and used as input values to the MITAS program. Calculated values of the rub plate temperature were in reasonably good agreement with those measured. The rub plate temperatures are lower than the wall temperatures calculated by the previously discussed model and procedures near the channel (cove) exit. This is so because the thin wall section to which the thermocouples are attached in the rub-plate are surrounded by the relatively massive thick-wall portions of the rub plate. The MITAS model thus accounts for heat-sink effects, in contrast to the previously discussed finite difference model, which considers only a uniform channel wall thickness. The uniform wall thickness (0.03125 in.) chosen models the thickness of wall to which the thermocouples are attached and, by contrast, does not consider any heat-sink effects.

The computer program and thermal model developed is, to be sure, a simplified representation of an actual wing-elevon cove. The model cannot simulate a multi-layer wall with irregular cove geometry. If, however, the model can predict temperatures reasonably well, and on the conservative side, the simplicity of the model and the ease with which a parametric study can be conducted may be well worth the simplicity. While some parametric-type calculations have been explored (fig. 3, for example), a full parametric study was not conducted, in deference to establishing its basic validity by comparison with a single geometry and a limited range of flow conditions (i.e., with the single test model and tunnel conditions).

PRINCIPAL CONCLUSIONS

The principal conclusions that appear to be justified by the results obtained to date are as follows:

1. The analytical model and computational methods developed and employed appear to offer reasonable predictive capabilities of wall temperatures and heating rates, provided that accurate inlet gas temperatures may be specified.

2. Maximum temperatures calculated in the seal and rub-plate, using a gas temperature equal to the exit gas temperature from the cove analysis, is always lower than the cove wall temperature preceding the rub plate.

This is so because the heat-sink effects in the rub-plate area are accounted for in the MITAS analysis. These effects are not accounted for in the cove analytical model; consequently, the cove wall temperatures calculated are conservatively high. Some evidence exists that the rub-plate leading edge initiates a new boundary layer, and thus generates a high heat transfer coefficient over the rub-plate and seal areas. The consequences of this occurrence remain to be investigated in the MITAS analysis.)

3. The validity of the concept of entrance region flow in the cove, e.g. characteristically high Nusselt number variations in the entrance region, is neither proved nor disproved by actual Nusselt number variations calculated from measured heating rates, gas, and wall temperatures. There is some indication that high heat transfer coefficients, characteristic for a reinitiated boundary layer, occur beyond the reverse bend in the cove and at the rub-plate. Large uncertainties in the gas temperature measurements, however, prevent a definitive conclusion in that regard.

4. Wall conduction effects are quite small for the short exposure times considered (5 seconds). That is, the overall temperature distribution in the wall is little affected by axial energy transfer within the walls.

5. Radiation effects are similarly quite small for the short exposure times (5 seconds). It would be expected that for longer test times (higher temperature levels) a significant redistribution in the wall temperature would be seen.

RECOMMENDATIONS

Analysis

1. Investigate and recommend orifice coefficients for flow through seal passageways over a range of flow conditions, including rarefield gas flows (see refs. 5-6 for example). This will permit extension of the analysis to cover typical flight reentry conditions.

2. Extend the two-dimensional capability of the analytical model (presently considers only one-dimensional conduction within the channel walls) by introducing the "penetration-depth" concept (see ref. 7) into the computational scheme. This concept will, in essence, permit only the thickness of wall actually "sensing"

the high temperature gas flow to be considered at each time step. As successive time steps are traversed, larger and larger wall thicknesses would be included in the model, and which thicknesses would be equal to the penetration depth or some physically appropriate fraction thereof.

Analyze the "inverse" problem with respect to the actual gas temperatures being experienced by thermocouples inserted into the gas stream. The actual gas temperatures would be determined by the transient temperatures indicated by the thermocouples, the thermocouple physical response characteristics, and heat transfer coefficients existing at the thermocouple surface itself.

4. Improve the predictive capabilities of the inlet gas temperature to the cove by analyzing the boundary layer on the wing surface and considering a portion of the bottom of the boundary layer to be "skimmed off" and directed into the cove, in accordance with the maximum mass flow rate permitted by the known size of the seal leak (and accompanying pressure differential across the seal).

5. Investigate methods of establishing (predicting) the pressure differential across the seal (Δp_{ℓ}) without utilizing actual test measurements for a given test run. That is, attempt to develop the capability of predicting Δp_{ℓ}, given the flow conditions external to the cove.

6. Investigate and modify heat transfer coefficients in the analytical cove-flow model for slip, transition, and free molecule flow regions in order to permit modelling actual flight reentry conditons.

Experiment

1. Accurately measure characteristic time responses of all thermocouples used to measure gas temperatures. Similar information should also be available for typical wall thermocouple installations.

2. Conduct at least one test with 1-inch or 12-inch leakage slot considerably offset. Comparing gas temperatures, wall temperatures and heat rates with those of the centered slots will be informative relative to the nature of flow (and flow redistribution) within the cove.

3. Conduct flow visualization tests of flow within the cove by using the pilot tunnel facility and a suitably sized scale model of the wing-elevon system.

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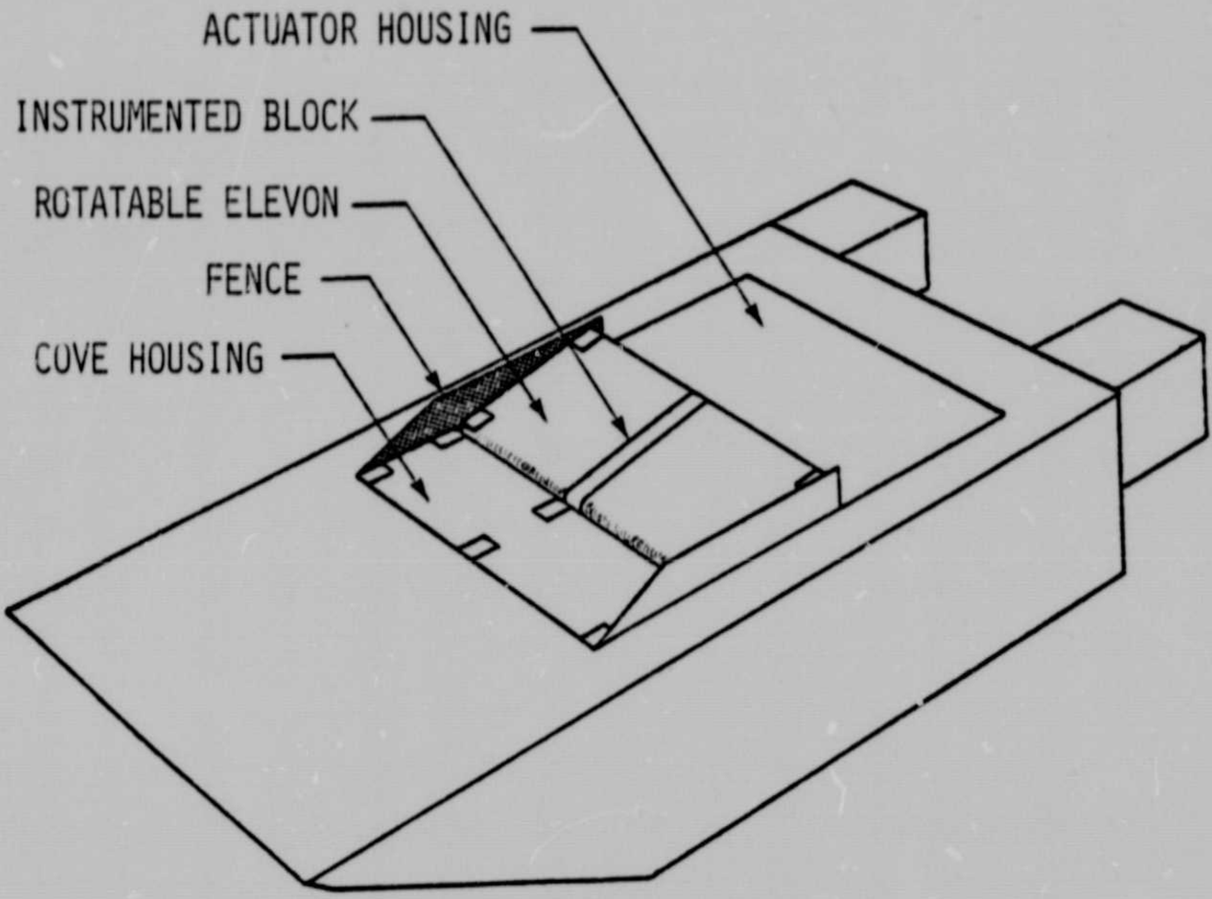

Figure 1. Schematic of test apparatus modelling shuttle wing-elevon-cove system.

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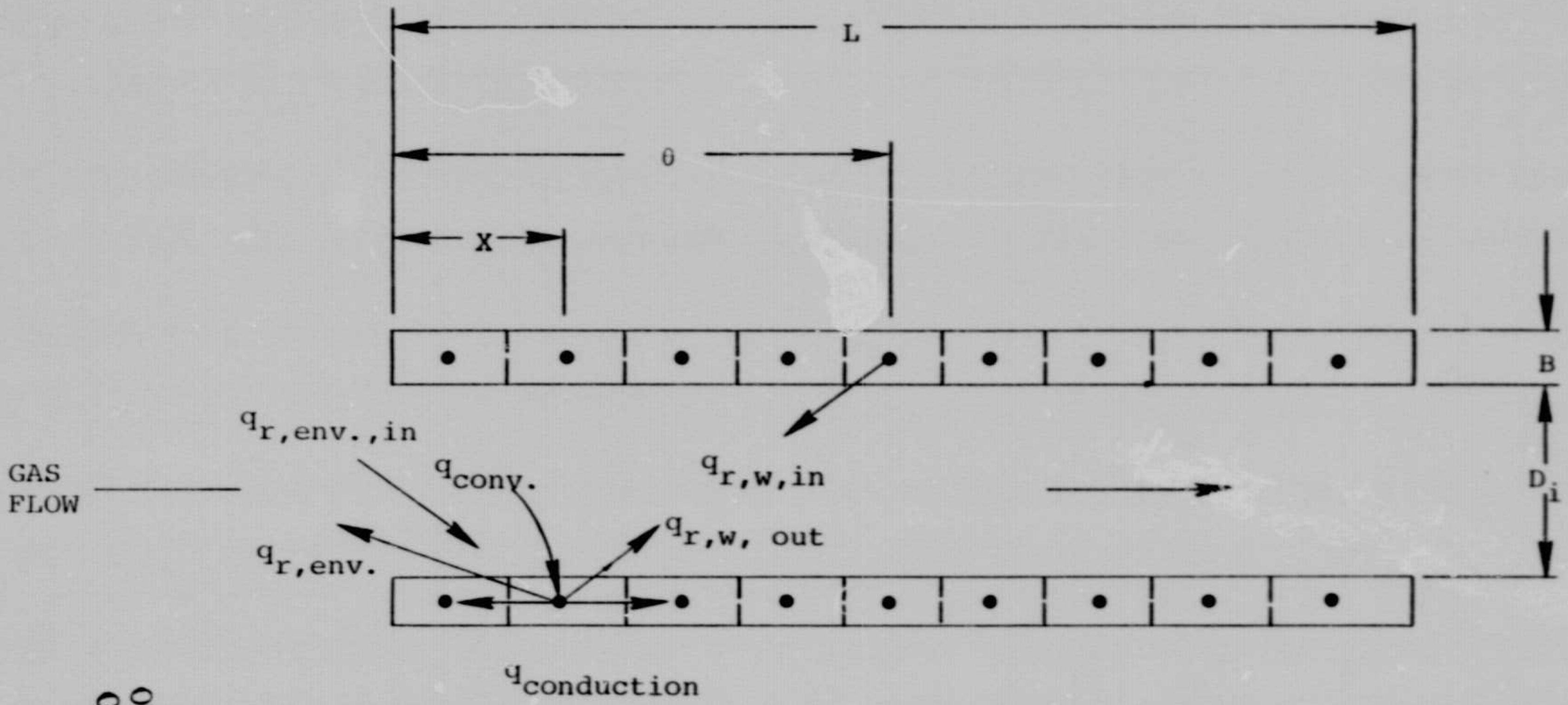


Figure 2. Simplified thermal model of gas flow in cove.

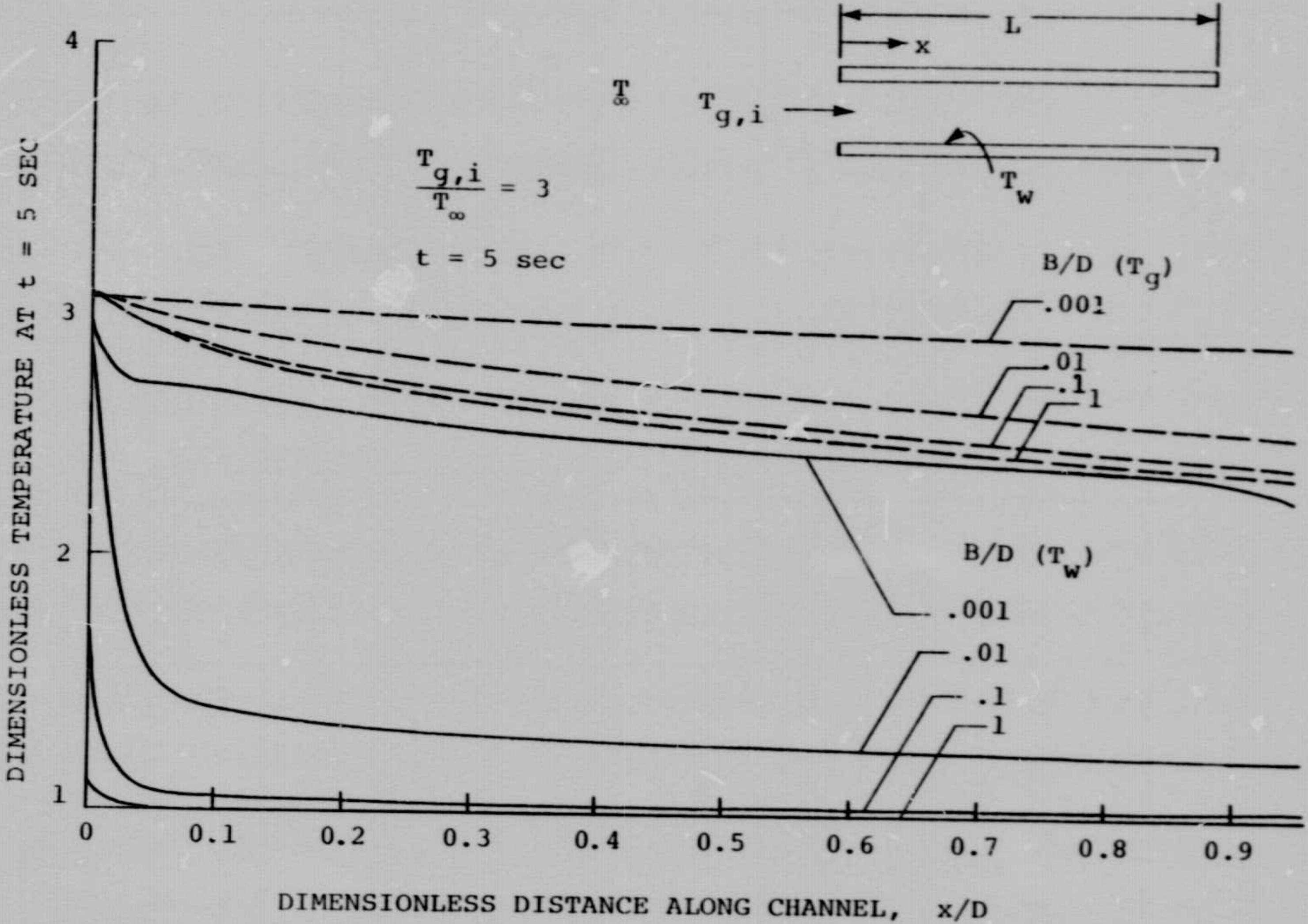


Figure 3. Wall and gas temperature distributions after 5 seconds, for various B/D ratios.

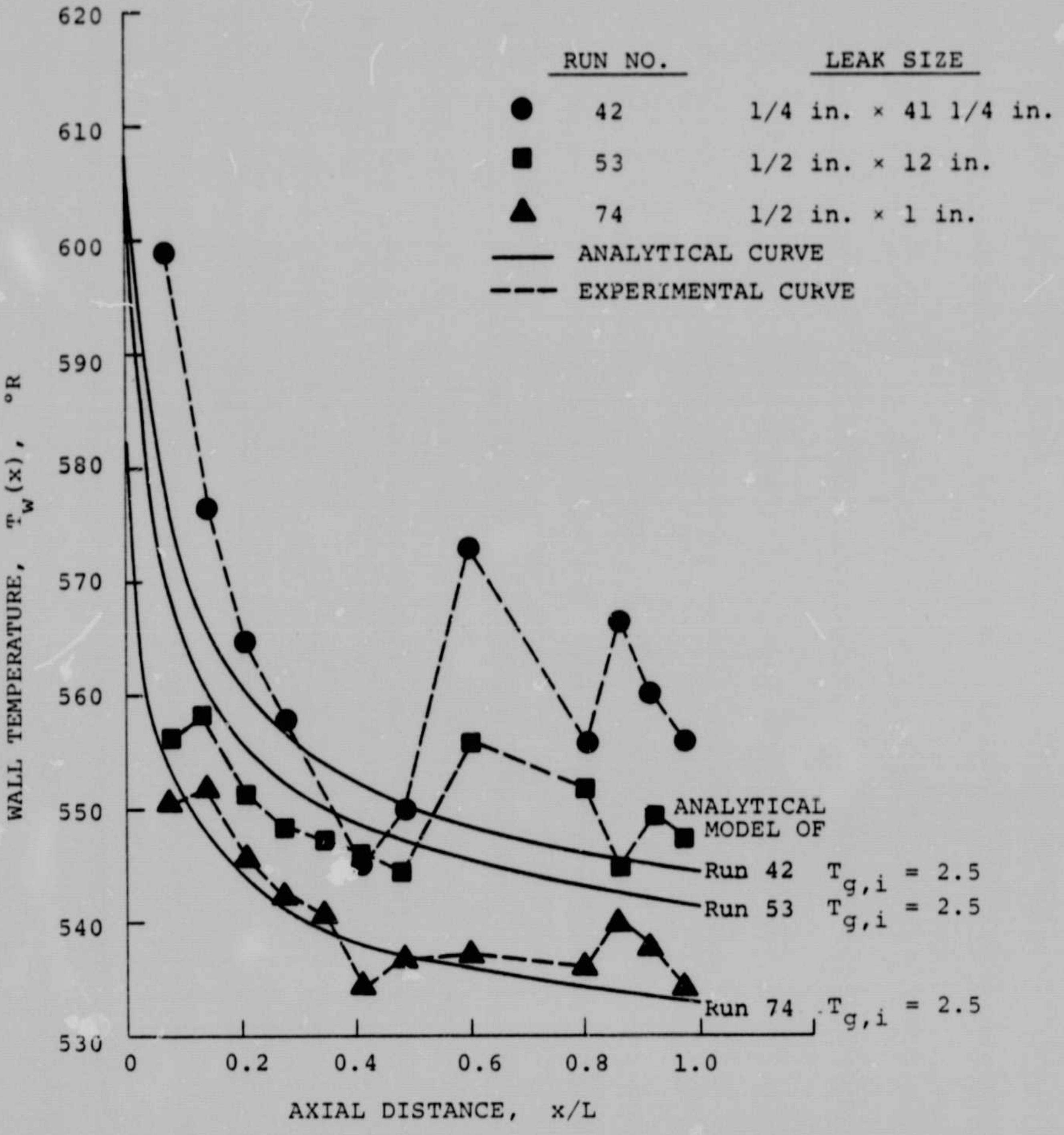


Figure 4. Comparison of axial wall temperature distributions--parallel plate flow model computer results vs. experimentally measured values (both after 5 seconds).

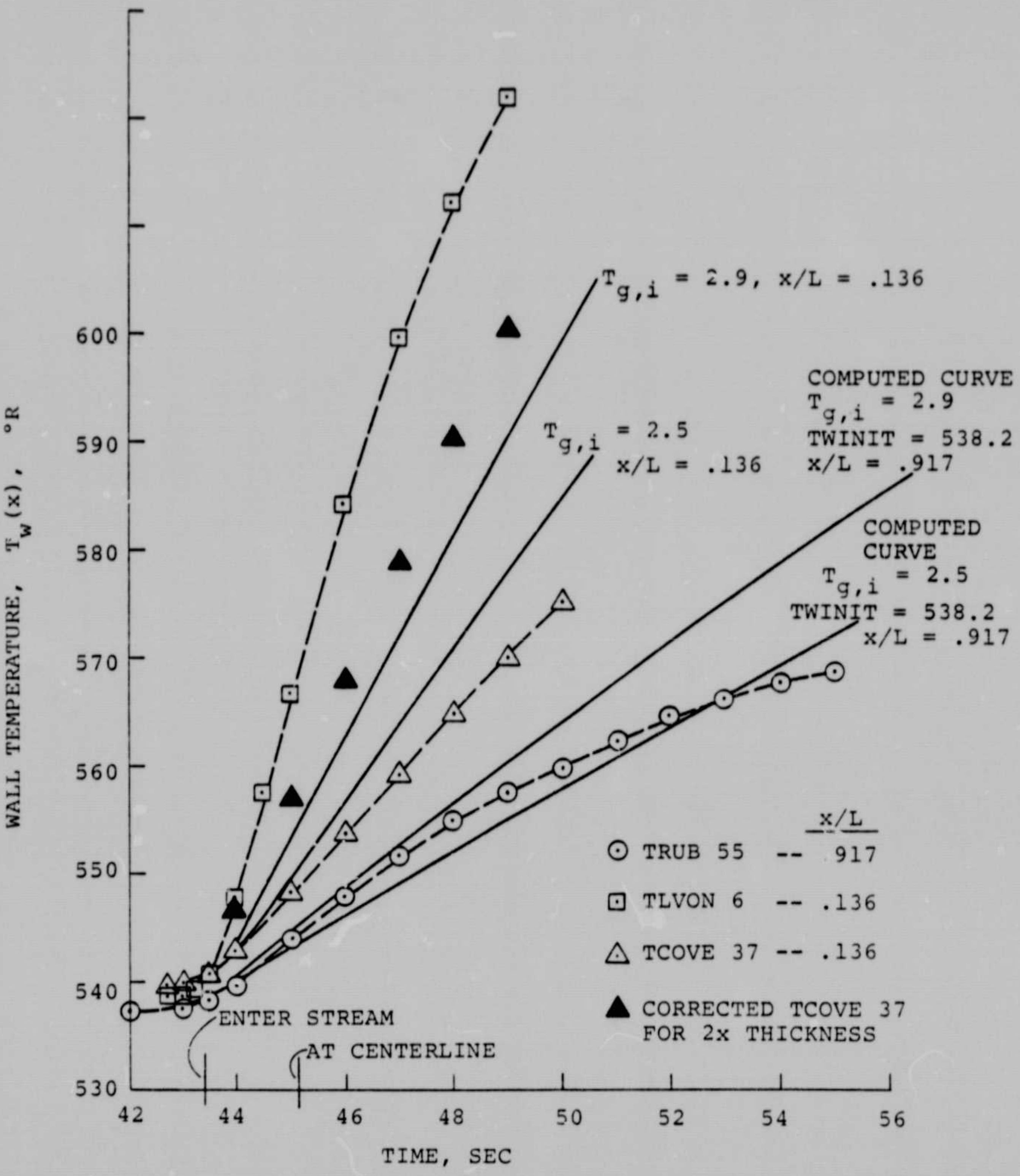
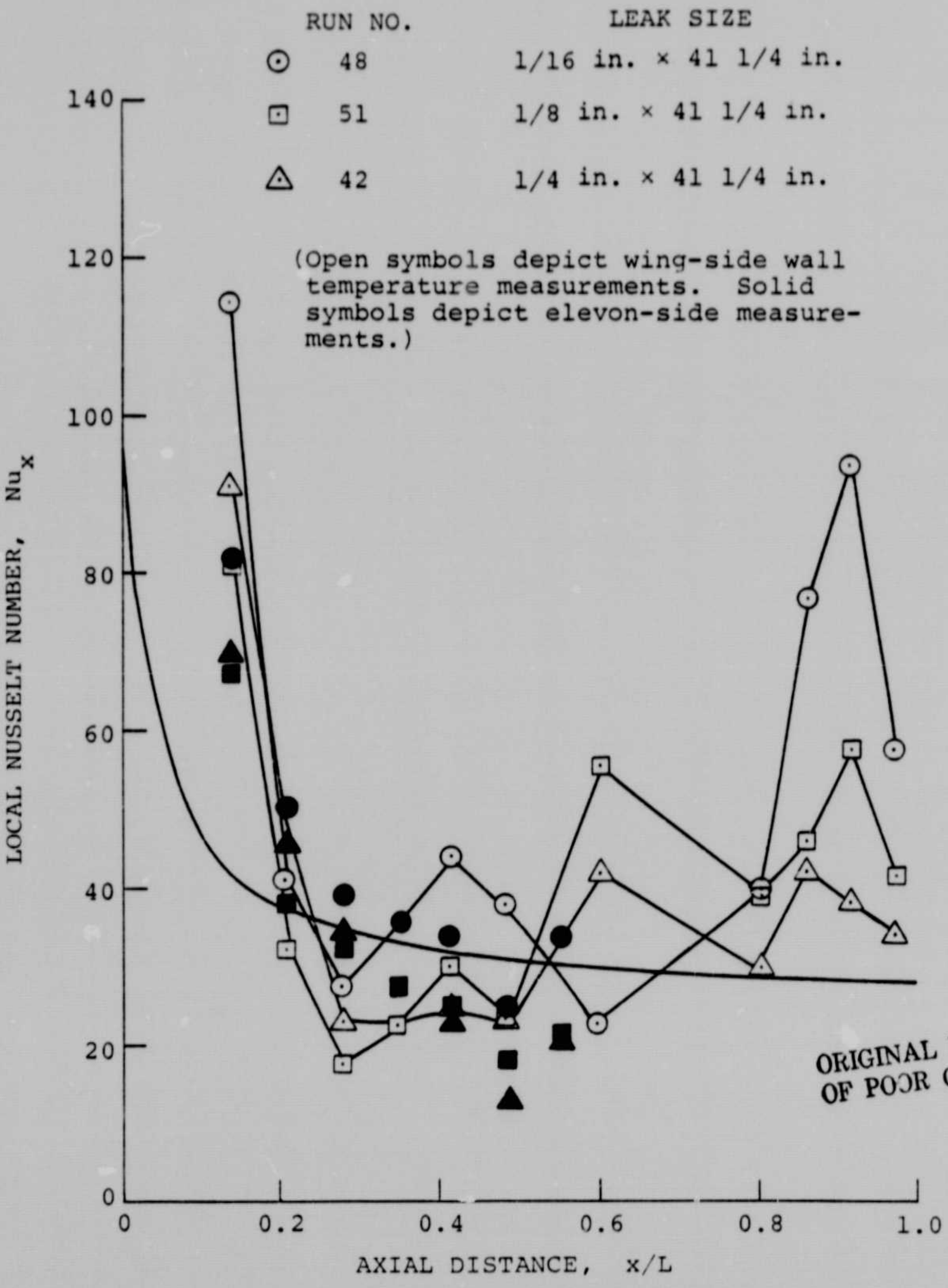


Figure 5. Comparison of temperature-time histories for three wall positions in cove--calculated computer model results compared with measured results.



(Open symbols depict wing-side wall temperature measurements. Solid symbols depict elevon-side measurements.)

Figure 6. Local Nusselt numbers calculated from measured wall and gas temperatures in cove ("cold-wall" conditions) compared with computer model predictions based on laminar flow entrance conditions. $T_{g,i} = 2.5$.