Engineering Foundation Report, presented in Research in Progress session, 29th Mechanical Working and Steel Processing Conference (ISS/AIME), Toronto, Canada, Oct. 21-23, 1987

Application of Mathematical Models to Investigate Defect Formation during the Direct Charging of Continuously Cast Steel Slabs

prepared by

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As the domestic steel industry moves away from ingot casting, the process of continuous slab casting has emerged as the premier process for economic large scale production of quality steel. To further increase their productivity and competitiveness, many companies are implementing or considering the direct charging of continuous cast products into reheating furnaces immediately after leaving the casting machine. It is essential that quality be improved by increasing control and understanding of this relatively new process. As control of the direct charging improves, there is a growing need to find optimum operating conditions and improved understanding of their relationship to product quality.

Unfortunately, the continuously-cast strand is subject to a variety of defects, ranging from cracks and depressions that arise in the mold region to defects that initiate much later in the process. These defects arise through a combination of reduced hot ductility and tensile stresses in the solidifying shell. Although the metallurgical aspects of reduced high temperature ductility just below the melting point of steel have been the subject of many recent studies, the generation of stresses in the steel shell has received relatively less attention. This lack of attention is not due to a failure to recognize the importance of the stresses but is an indication of the complexity of the problem. Only with the advent of recent sophistication of finite-element methods and the existence of large computational facilities is the problem now feasible to tackle realistically.

This project is directed toward understanding defect formation during the direct charging of steel slabs. This is accomplished by using mathematical models which predict temperature, strain, and stress within the steel strand from the onset of solidification in the mold continuing through all processing stages until the start of hot rolling (including solidification in the mold, spray chamber cooling, transfer, and reheating). This paper details the progress of this research to date, presents preliminary findings based on simulations of the Inland Steel #1 slab caster and discusses areas of further work.

DEVELOPMENT OF MATHEMATICAL MODELS

A two-dimensional, finite element model has been developed which simulates the heat transfer and stress development in a continuously cast strand. The model simulates the complete processing stages from solidification of the shell in the mold, cooling of the strand in the secondary spray zones, air cooling on the runout table and in the transfer car, and finally, reheating of the strand in the reheat furnace prior to rolling. (fig. 1) A two-dimensional, transverse slice through the strand is analyzed. The heat transfer and stress models have been coupled, allowing for convergence parameters to be checked, and if necessary, the model may resolve the time step in question. A flow chart for the coupled model is shown in figure 2. The models are capable of handling the variation in both thermal and mechanical properties that exist over a wide temperature range. Details of these models are described elsewhere.[1,2]

The simulation is divided into four regions: mold, spray zones, transfer, and reheat. The model is set up such that the output from on region can be used as an input to the next region. In this way, many different combinations of casting practices may be analyzed without having to redo the entire simulation. Each region has unique aspects, which will now be discussed in turn. The simulation conditions used for this report are shown in table 1.

MOLD

The heat flow model determines the heat flux across the mold/shell interface based on the air gap thicknesses calculated by the stress model. The output from a more complex, detailed mold simulation is used as an initial temperature and stress field.[3] In this paper, the heat flux into the mold is described by the following equation of Savage and Pritchard[4] for billet casters:

$$q_s = 2680 - 335 \sqrt{z/u} \quad \text{kW/m}^2$$

This simple relationship generates heat flux curves that are similar to those from the more complex mold model[3], and compare favorably with experimental heat flux measurements for slab molds.

The stress model uses a transient, elasto-viscoplastic formulation and is capable of handling any desired variation in material properties and constitutive relation including composition and temperature dependent thermo-mechanical properties and temperature, strain-rate and structure dependent plastic flow. In addition, the model incorporates arbitrary expansion-contraction behavior including volume changes due to phase transformations and non-equilibrium effects related to kinetics. This complete version of the model has not yet been used to simulate stresses completely through the caster, however.

SPRAY ZONE

To provide a more realistic simulation, the spray zone configuration for an operating slab caster (Inland Steel #1 slab caster) was used. This caster has five zones of spray cooling, each with varying roller radii and water fluxes. The spray water heat transfer was handled using a convection boundary condition. As shown in figure 3, the convection coefficient was calculated using the equation of Nozaki et al.[5] Also included was the critical Leidenfrost temperature, around 550 ^{o}C, where the heat transfer mechanism changes from film boiling to transition boiling, accompanied by a considerable increase in heat removal. The effect of the rollers on the heat flow is characterized by the heat transfer coefficient, the film temperature, the water flux and by varying the contact time of each support roller. Because these parameters highly affect the thermal cycling of the strand surface and the resulting stress, much effort was put into modeling the differences in heat removal by the roller and the sprays. The heat transfer coefficient is scaled appropriately to reflect these differences. These percentages are listed in table 1 and are taken from Hibbins.[6] Complete control over the thermal effect of the rollers is achieved by varying both the fraction of heat removed by the rolls, and by varying the roll contact time. This contact time (length) has been found to greatly affect the temperature variations predicted on the surface, and thus the local stress state on the surface. The narrow face is cooled by the water spray in only zones 1 and 2, and by radiation in all zones.

Currently, only the stresses arising from the resulting temperature are analyzed. The combined effect of ferrostatic pressure and roll forces are ignored at this time, (thus assuming that they approximately cancel). Also ignored are the out of plane stresses arising from unbending of the strand. The simulation detailed in this paper assumes an elastic behavior.

TRANSFER AND REHEATING

After exiting the spray zone, both the transfer cooling stage and reheating stage assume heat transfer based on radiation and free convection alone, as shown in figure 3.

RESULTS AND DISCUSSION

Figure 4 shows the temperature history of the mid-wide face surface, corner, and center nodes through the secondary cooling zone. The center temperature decreases as expected, with the strand fully becoming fully solidified at 21.6 meters (71 ft.), This calculated metallurgical length agrees approximately with the experience of Inland Steel for the simulated conditions on this caster. At the end of the second spray zone, both the corner and the mid-narrow face show noticeable reheating, caused by the elimination of cooling sprays on the narrow face at that time. Both faces exhibit large temperature swings on the surface, but subsurface variations are not as extreme, the depth of these noticeable variations being approximately 15 mm. The mid-wide face temperature follows the mid-narrow face, but does not experience any reheating. Each of the 5 spray zones can be clearly distinguished on the graphs.

Figure 5 shows the hydrostatic stress state corresponding to the temperature history previously discussed. (The hydrostatic stress is important to crack formation based on a creep deformation mechanism) An elastic stress state was assumed for this example simulation, which accounts for the high stresses predicted. The high fluctuations in surface stress are a direct result of the large temperature variations discussed above. Of interest is the stress reversal that occurs at the center of the strand once complete solidification is achieved.

Figure 6 shows the temperature and stress state at the exit of the casting machine. The removal of water cooling from the narrow face is evident, as the temperature contours only slightly bend away from the wide face on that side. The stress state shows subsurface layers of tension, with quite rapid changes of stress near the corner. Had plasticity been utilized, the stresses would have been substantially reduced, particularly in the interior, due to high temperature creep. Lastly, the fraction of steel that has been transformed to ferrite (α) is plotted. For the conditions simulated, most of the slab is seen to be in the austenite phase at this time, exiting the caster.

Finally, figure 7 shows a complete thermal history for the mid-wide face surface. Substantial reheat is noted at the caster exit while the slab is being transferred to the reheat furnace. This reflects the substantial decrease in surface heat extraction once water sprays are no longer present.

CONCLUSIONS

Results so far have shown that the models are capable of predicting reasonable temperature distributions in the slab section. They also show that the narrow faces play an important role in determining both the total heat transfer from the slab, and the relative temperature distributions which are important to the subsequent stress analysis. Finally, the dramatic reheating observed after exiting the spray zones is indicative of the redistribution of heat within the slab, which has at least two important consequences to defect formation during direct charging processes. The first is that the surface temperature may be sustained above the critical embrittlement temperature zone (between about 700 and 900 ^{o}C) for a considerable length of time, allowing time for transfer to reheat furnace even without an insulated transfer car. The second consequence, which has not yet been fully examined, is that the temperature redistribution produces considerable stress, that may be important to subsequent defect formation, if the slab is allowed to fall below 900 ^{o}C into the low ductility zone.

CURRENT WORK

Currently, problems with convergence of the coupled models and the presence of plasticity are being corrected. The plasticity portion of the model has been verified by comparison to a thermally loaded beam problem for which the analytical solution is known. Much effort has been put into reducing the long execution times associated with plasticity simulations. Preliminary results using a one-dimensional slice show favorable predictions of the resulting stress states. This simplified model has run through the mold and spray regions. Using this smaller problem gives insight into the effect of various convergence parameters without involving the long execution times. Soon, the two-dimensional model will be run completely through the spray zones, transfer, and reheating stages, including plasticity.

FUTURE WORK

Once the stress state is determined and verified at the caster exit, these conditions will be used as initial conditions to various combinations of transfer cooling and reheating practices. Because ductility loss at high temperature is of great importance in predicting defect formation, three classes of simulations will be examined. First, a "fast" run through the caster will be followed by a short transfer time, and then reheat. This will attempt to keep the strand above 700-900 ^{o}C where ductility loss is evident. Next, a simulation will be run where the strand is allowed to cool past the loss of ductility zone and then reheated. The last simulation will involve reheating the strand while it is in the ductility zone. As noted from figure 7, the high rebound at the caster exit is likely to have a substantial effect on the stress distribution in the strand. Examining various transfer and reheating cases will allow a better understanding of the effect of transfer times, caster speeds, and reheat times on the temperature and stress distribution in the slab. This, in turn, will shed insight on defect formation (such as surface cracks) that may arise during direct charging.

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CONTINUOUS CASTING AND DIRECT CHARGING PROCESS

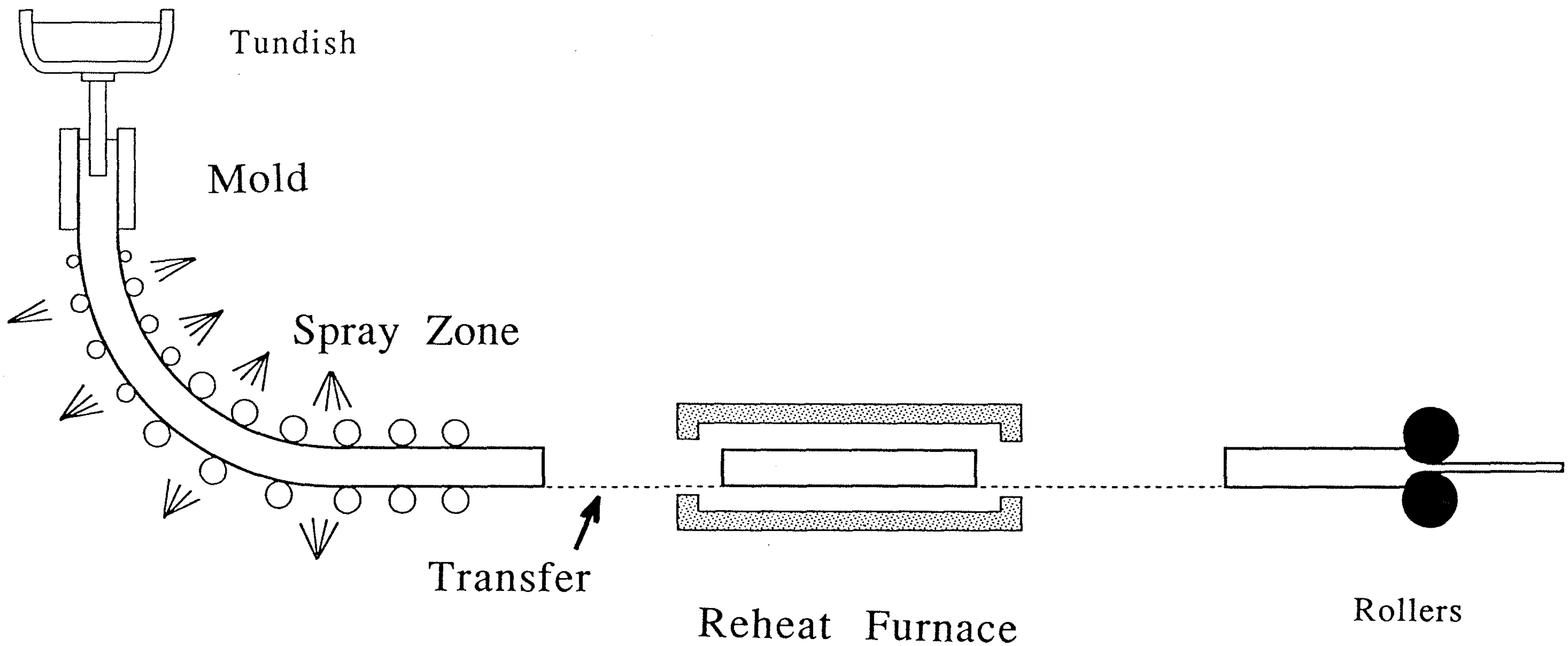

Figure 1.

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Figure 2

Flow Chart for Coupled Heat Flow/Stress Model

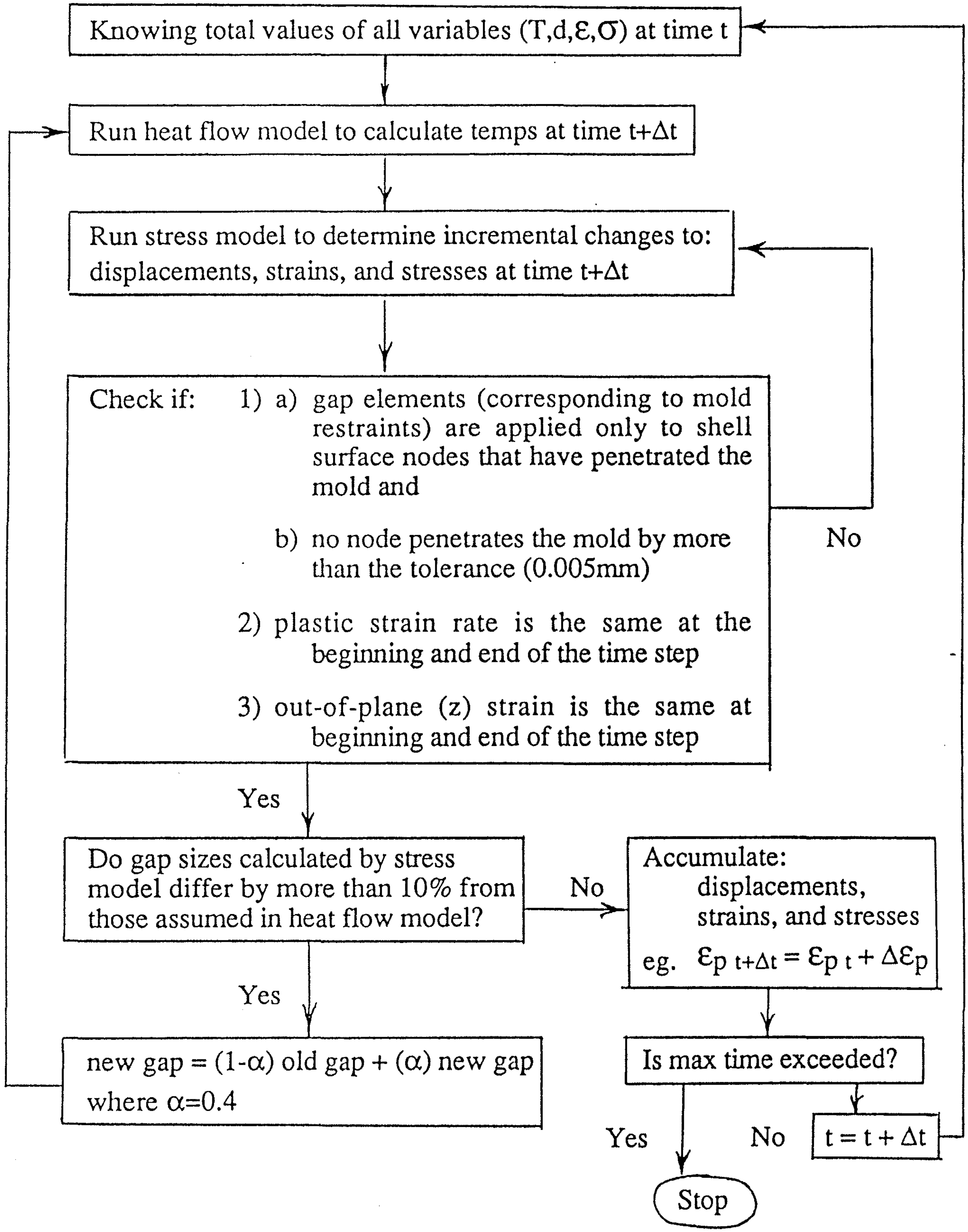


Table 1

Simulation Conditions

Mold Dimensions:

Slab width	914 mm	(36")
Slab thickness	235 mm	(9.25")
Length	700 mm	(27.6")

Material Properties:

Grade	Low Carbon Steel (.15% C, 1.5%Mn)
Liquidus temperature	1513 °C
Solidus temperature	1487 °C

Casting Conditions:

Initial temperature	1523 °C
Meniscus Position	100 mm below top of mold
Casting speed	16 mm/s (37.8 in/min)
Ambient Temperature	35 °C (spray and transfer)
Reheat Temperature	1200 °C
Radiative Emissivity	0.8

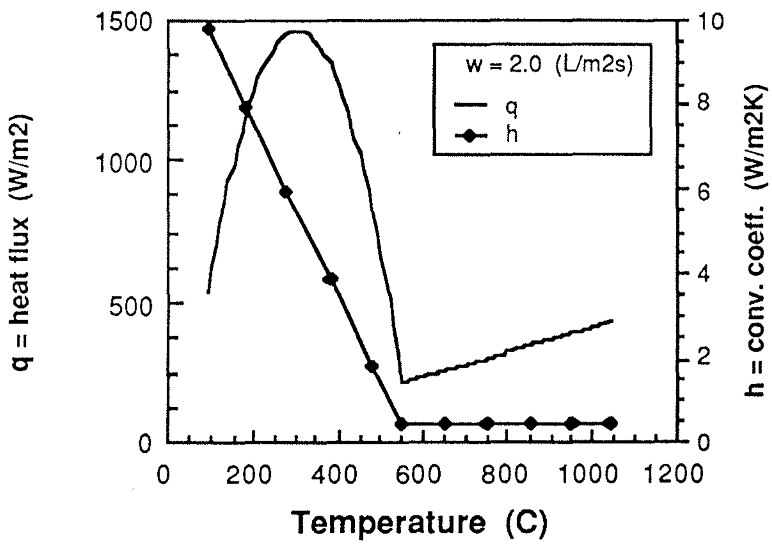
Spray Zone	Distance below Meniscus	Water Flux (L/m^2s)	% Heat withdrawn by rolls
Zone 1	0.60m	8.0	1
Zone 2	0.94m	4.0	8
Zone 3	2.71m	1.75	22
Zone 4	8.70m	1.5	20
Zone 5	13.64m	1.0	36

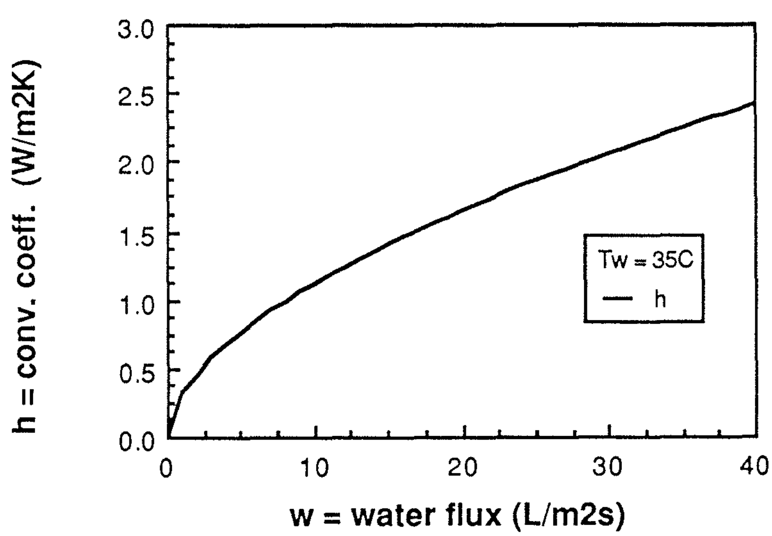
Modeling Conditions: 2D, Elastic, Plane Stress

Heat Transfer Model Boundary Conditions

Spray Zone

$$h = 1.57\ W^{0.55} (1\text{-}0.0075\ T_w) / 4.0$$ from Nozaki et al. 1978





Transfer and Reheating

$$h = \sigma\, \varepsilon\, (T_s + T_w)(T_s^2 + T_w^2) + Nu_L\, (k_f / L_c)$$

(Radiation) (Free Convection)

Figure 3

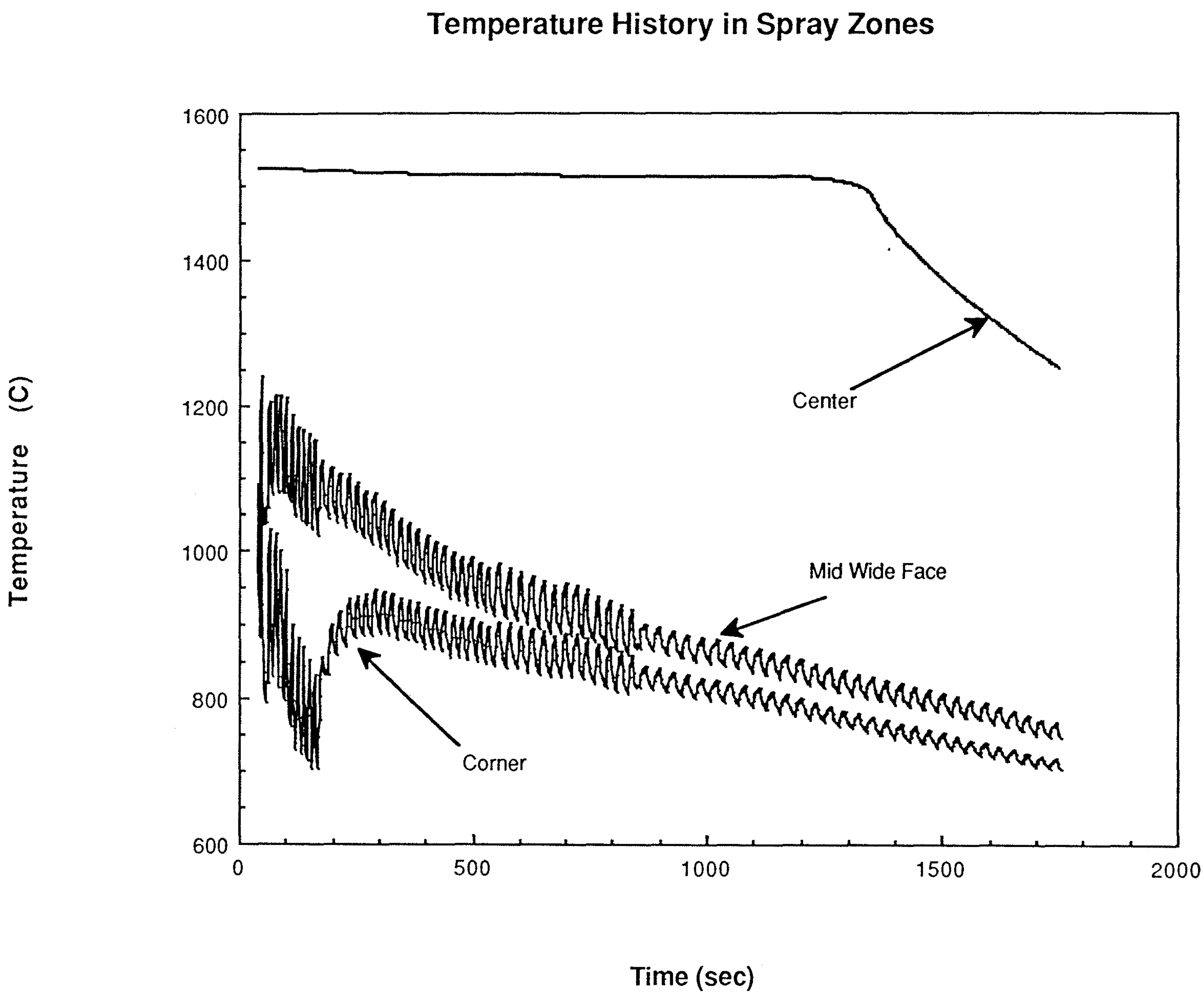

Temperature History in Spray Zones
1600
1400
1200
1000
800
600
0
500
1000
1500
2000
Temperature (C)
Time (sec)
Center
Mid Wide Face
Corner

Figure 4

Stress History in Spray Zones

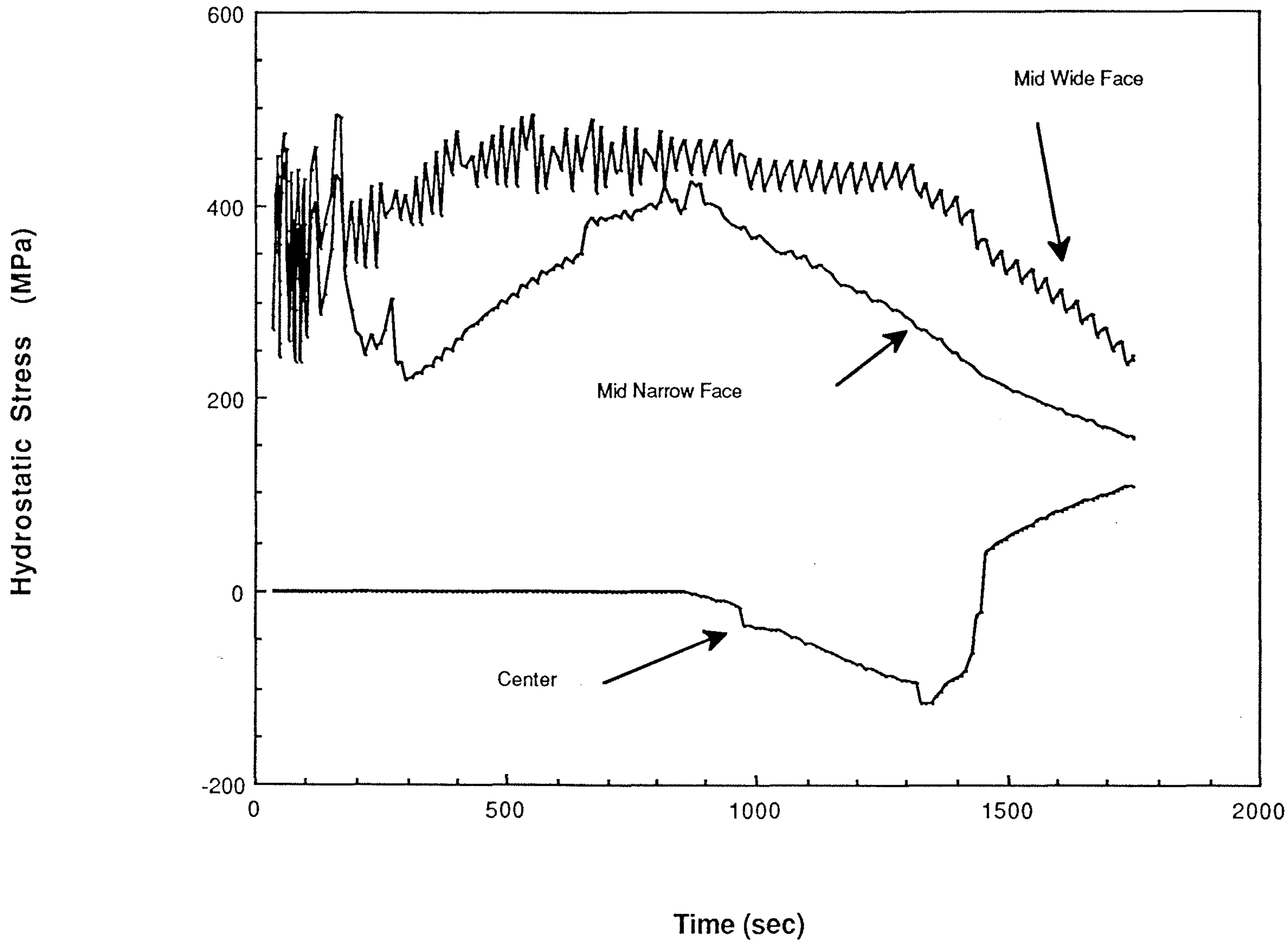


Figure 5

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Temperature and Stress State at Exit from Spray Zones

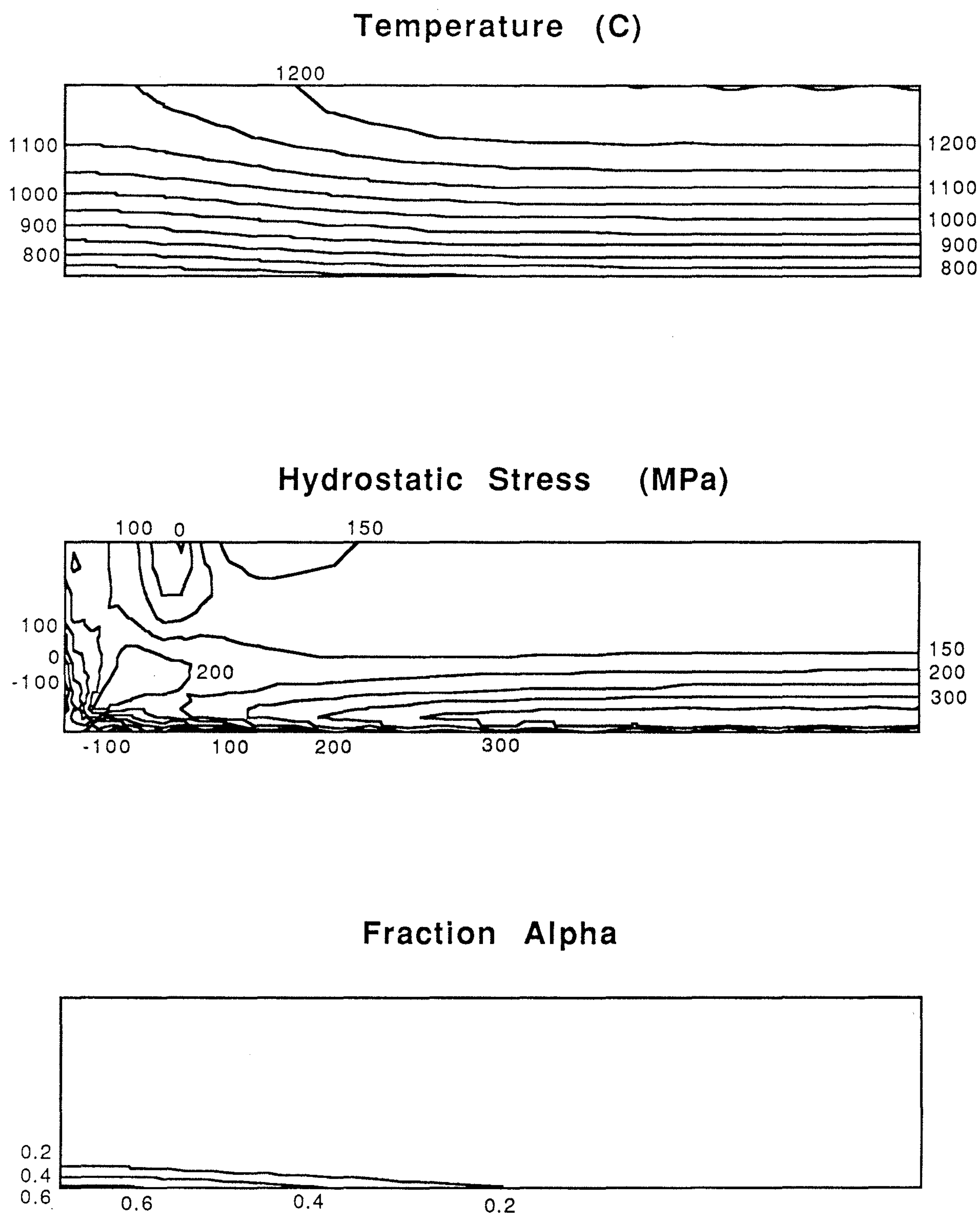

Figure 6

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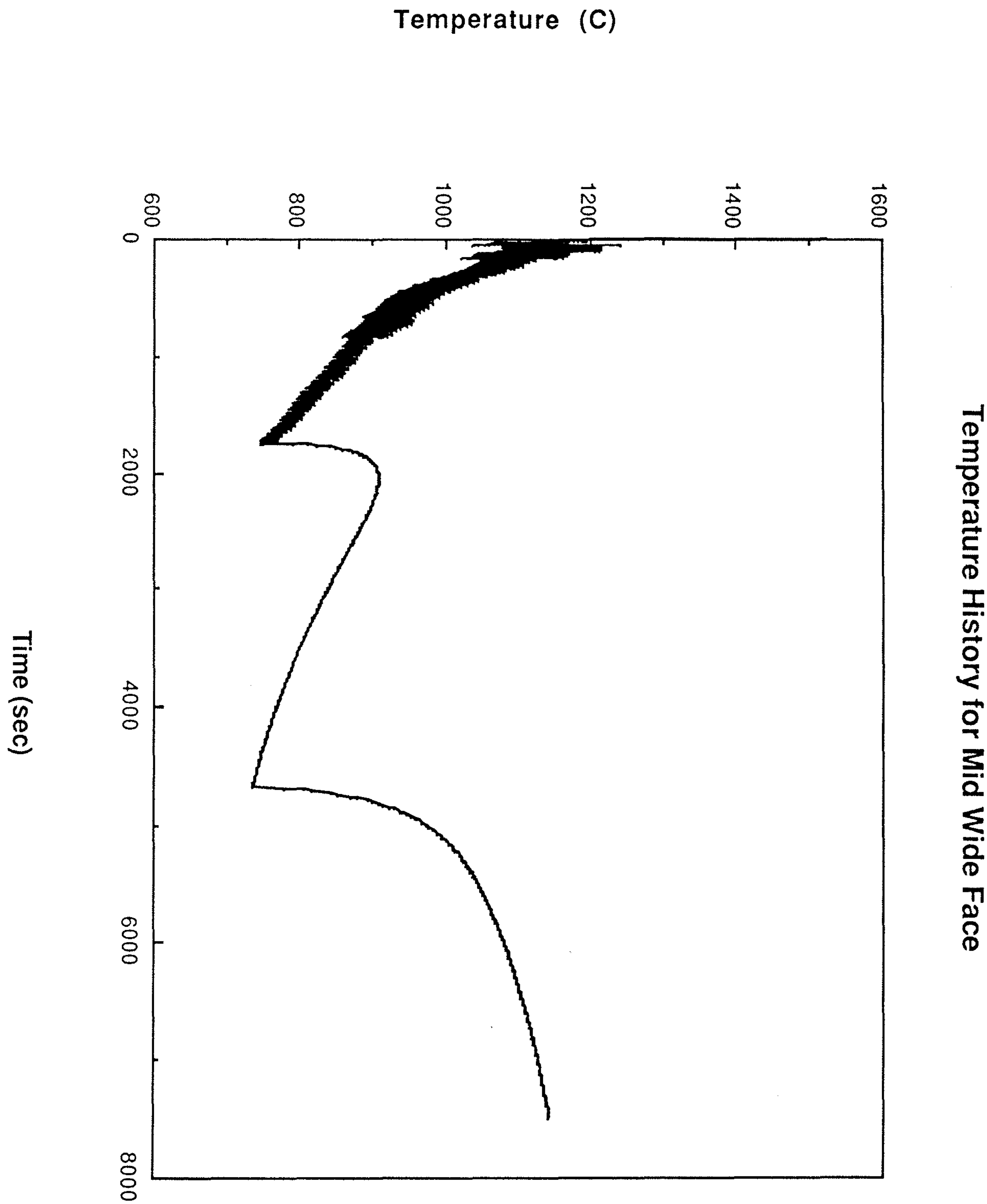

Figure 7