SOLIDIFICATION IN THE MOLD OF A CONTINUOUS BILLET CASTER

by

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Abstract

Billet samples obtained from a large number of heats were examined to study different aspects of solidification in the mould; columnar-equiaxed transition, segregation bands, off-corner cracks, rhomboidity, sub-surface structure and oscillation marks. With the aid of two mathematical models the influence of heat extraction on early solidification and billet quality has been elucidated.

In the carbon range 0.13-0.36%, increasing carbon and phosphorous (0.020-0.060%) were seen to cause an early columnar-equiaxed transition. Higher heat transfer rates as carbon is increased from 0.13 to 0.36% were seen to promote the growth of equiaxed zone. A steep rise in the length of columnar zone in steels with carbon content more than 0.38% was observed for the first time in billet casting inspite of high heat transfer rates.

Examination of macroetches revealed that there exist two distinct bands within 10-11 mm off the edge of the billets. These were found to delineate the shell profile at an instant of time. With the help of the one-dimensional model it was shown that the white band which is closer to the surface forms 450-550 mm below the meniscus where the solidifying shell is subjected to a constant cooling rate and the solidification front proceeds at a minimal speed. The shell thickness corresponding to the second band which was dark or deeply etched was found to have developed at the midface very close to the bottom of the mould.
Based on the pool profile exhibited by these bands in the transverse sections it has been concluded that while solidification proceeds slowly at the midface after the formation of the white band 450-550 mm below the meniscus it appears to have virtually stopped at the off-corner/corner area. Thin white bands at the obtuse angle corners of the billets which are a result of improper heat extraction could lead to rhomboid billets in the sub-mould regions because of differential contraction of adjacent faces.

Study of these bands has shown that in the majority of the billets heat transfer on the four faces is not identical indicating that the mould billet gap is different on the four sides. When one of the mould walls was constrained, rhomoidity was found to be minimum showing that wall movement gives rise to different cooling capacities of curved and straight walls.

Off-corner cracking was seen to be aggravated by mould water velocities of 6.5-7.2 m/s and Mn/S ratios lower than 22-25. Absence of secondary cooling water was found to accentuate cracking at the off-corners. It was suggested that these cracks would form when the midface bulges in the lower parts of the mould or immediately after the billet's exit from the mould wherein according to the one-dimensional unsteady state model the surface was found to undergo extensive amount of reheating.

A two-dimensional unsteady-state mathematical model was developed to study the possibility of meniscus solidification observed in the the structure around the oscillation marks on the billet surfaces. It was found that the heat flux necessary
to allow growth of solid over the meniscus has to be much larger than those obtained from experiments conducted in a separate study. A new mechanism has been formulated to explain meniscus solidification and the formation of oscillation marks in billet casting. The negative taper in billet moulds constrained only at the top was thought to be the potential cause of these periodic depressions.
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I. INTRODUCTION

As an alternative to the conventional ingot casting-soaking pit- blooming mill route, continuous casting has emerged as a far more economical and efficient process to produce semi-finished shapes from liquid steel. It offers improved product quality and homogeneity and is being extensively employed by both the mini-mills and the major integrated steel works to cast billets, blooms and slabs.

Continuous casting yields greatest economic benefits when section sizes closest to the shape of finished product are cast, eliminating the need for several processing and reduction stages. For rod and bar production, billet casting with which this thesis is concerned, is gaining momentum beyond its already widespread use in mini-mills. But lower reduction ratios, higher casting speeds and the recent application of in-line reduction have brought about stringent quality requirements in billet casting. Various machine design criteria and operating practices are under scrutiny to obtain a better understanding of billet casting and the problems involved.

The heart of the continuous casting installation is the water-cooled copper mould which gives shape to the liquid steel issuing from the ladle through an intermediate vessel, the tundish. Rapid heat extraction in the mould and easy withdrawal from it, facilitated by oscillation of the mould coupled with lubrication, are features that make the continuous casting process physically viable. A 9-12mm shell develops in the
mould; growth of the shell is dependent on heat flow across the gap to the mould wall which in turn is affected by steel composition, mould distortion, etc. Characteristics of the primary shell formed have a profound influence on the quality of the billets cast: mould-related defects include, rhomboidity, longitudinal corner cracks, midface cracks as shown in Fig 1.

An attempt is made in the present study to understand the nature of some of the mould-related problems viz, off-corner cracks, and rhomboidity and the mechanisms involved. Emphasis is placed on the relationship between heat transfer in the mould and the quality of the billets. Mould heat flux data obtained from in-plant mould temperature measurements, together with billet samples from corresponding heats are utilised to eludicate the effect of casting variables such as steel composition, superheat and mould water velocity on the incidence and severity of some of the mould related defects.

The present study has also been aimed at explaining some of the basic features of the billets cast through oscillating copper moulds. Mould related phenomena like oscillation marks and solidification band formation have been analysed. A fresh look was taken at the macrostructural features of a population of billets in order to estimate the influence of heat transfer as well as of steel composition.
1 Rhomboidity
2 Off-corner cracks (internal)
3 Mid-face cracks
4 Internal corner cracks
5 Longitudinal corner cracks
6 Surface cracks
7 Transverse corner cracks

Figure 1 - Mould related defects in Billet casting
II. LITERATURE SURVEY

The initial seconds when liquid steel passes through the billet mould and acquires a thin shell are of great importance, because it is during this time that cracks of the off-corner, midface, diagonal and longitudinal corner type initiate (Fig 1). Also, as the mould is oscillated sinusoidally to facilitate withdrawal of the billet depressions on the surface are formed periodically. Before the study of the relation between these phenomena and heat transfer in the mould is presented, it is considered apt to give a brief description of the billet moulds and the heat transport processes involved along with the variables which are known to affect the latter in a significant way. A review of the literature published regarding the mould-related defects and oscillation marks is presented thereafter.

2.1 General Description of Billet Moulds

Billet moulds are made up of 9-12mm, thick copper tube, usually of square cross-section with round corners. Fig 2 shows a typical billet mould assembly. The mould tube is held in a steel liner and is constrained either at both ends or only at the top. Constraints may be on all four sides or only on two opposite faces. Cooling water flows normally in an upward direction, through the annulus between the tube and the liner. A back pressure of about 240KPa is also applied in combination
Figure 2 - Typical mould assembly for a billet caster
with the upward flow to ensure that the annulus is full of water. An array of steel spacers welded to the mould liner are used to ensure that the mould is mounted concentrically and the water gap is uniform around the periphery of the mould. Water velocities range from as low as 5m/s to 14m/s.

Usually 60-80 cm long, billet moulds are tapered to compensate for shrinkage of the solidifying shell. Tapers vary from a single straight taper of 0.7-0.8%/m that extends over the entire mould length to double tapers that change down the mould.

Deoxidised copper is most commonly employed of the mould materials owing to its high thermal conductivity. In some instances silver-bearing coppers have been used as well. These mould coppers do have a tendency to distort and this has led to the development of a whole new range of high strength low ductility copper-alloys. The inside surface of the moulds is usually chrome plated to improve wear resistance.

Lubricating oils such as rapeseed oil and other vegetable oils are most commonly used in billet moulds. Oil is pumped to a splitter that distributes it to channels in an oiling plate from which it is transmitted uniformly around the mould wall.

The mould is oscillated to prevent sticking because early in the development of continuous casting the rapid withdrawal of the ingot from the fixed mould caused an immediate rupture of ingot skin in the mould leading to a breakout. mould oscillation was introduced by Junghans; the oscillation consisted of a downstroke at a rate equal to the strand withdrawal speed followed by a high speed upward stroke. But it
was found that the billet was stuck to the mould during the downstroke and was torn on the upstroke. In order to eliminate this potential source of trouble BISRA proposed a slight overtaking action of the mould relative to the ingot surface during the downstroke. This technique of moving the mould downward at faster speeds than the strand is called 'Negative strip'. Not only does it prevent sticking, in the downward stroke, it is claimed that if sticking occurs it releases the attached billet compressively. Compressive forces exerted on the solidifying shell seem to be very beneficial to the smooth operation of casters. These forces prevent formation of cracks on the billet surface in the downstroke. If any cracks do form by drag during the upward stroke of the mould, it is claimed they are closed on the downstroke by pressing into still softer parts of the strand shell. Based on this particular feature of negative strip, U.S.Steel developed an oscillation cycle to provide a downstroke time that is greater than the time required for the upstroke whereby the skin is subjected to the desirable compressive stresses for a longer time than can be obtained with regular sinusoidal cams. However, mould oscillation that follows a sine curve is being extensively used in many of the modern installations and usually the motion is electrically synchronised with the casting speed. For oscillation using a sine wave principle, the negative strip time, i.e., the time for which the mould has an overtaking action over the billet in the down
stroke is given by the following equation.

\[ t_n = \frac{1}{f} - \left[ \frac{1}{\pi f} \cos^{-1} \left( \frac{-v}{2\pi fa} \right) \right] \]  

where

- \( f \) = frequency of oscillations
- \( v \) = casting speed
- \( 2a \) = stroke length

2.2 Billet Mould-heat Transfer

Although simple in design, the billet mould is very complex from the standpoint of heat transfer. Heat is transferred from the strand surface to the mould cooling water via a series of thermal resistances, viz;

i. resistance across the air gap between mould and strand where heat flow takes place both by conduction and radiation

ii. conductive resistance through the mould wall.

iii. convective resistance at the mould/cooling water interface.

Using mould wall temperature measurements Watanabe\textsuperscript{12} has found that the air gap accounts for 84% of the total resistance to heat flow. Thus the pattern of heat removal in the mould is largely a function of the dynamics of gap formation. Evolution of the gap depends on the shrinkage of the solidifying shell and
its ability to withstand ferrostatic pressure. As the billet makes its journey through the mould, the corners lose contact with the mould first owing to the effects of two-dimensional heat flow and the heat flux at the corners drops off. As the shell thickness increases down the mould, the influence of the increased gap is manifested as a reduction in heat flux. From the heat flux measurements reported in the literature, it is clear that the bulk of the heat is extracted in the upper half of the mould where the gap is smallest and strand surface is hottest. The lower part of the mould is thermally inefficient since the shell is strong enough to withstand the ferrostatic pressure resulting in an increased air gap. Fig 3 shows a typical axial heat flux profile from billet moulds.

2.2.1 Influence of Steel Composition on Heat Transfer

Many of the parameters that influence heat transfer in the mould, do so by changing gap formation on heat transfer. The width of the gap at a given location is dependent on the strength of the shell to withstand the ferrostatic pressure. The composition and temperature of the steel determine its strength and have a strong influence on heat transfer. Data from an experimental continuous caster by Singh and Blazek\(^1\) and from industrial machines by Grill and Brimacombe\(^13\) shows a distinct minimum in heat flux at 0.1%\(C\), Fig 4. Also the corresponding steel shells have rippled surfaces compared with the smoother surfaces obtained in higher carbon steels.
Figure 3 - Typical heat flux profile in billet moulds
Figure 4 - Plot of continuous casting data of overall heat flux in the mould against carbon content of the steel. After Singh and Balzek\textsuperscript{1} and Grill and Brimacombe\textsuperscript{13}. 

\begin{align*}
\text{Heat Flux (kW/m}^2\text{)} & \\
\text{Carbon (\%)} & \\
\end{align*}
The increased gap width resulting from such a surface seems to be the obvious cause for lowered heat transfer rates. As to the mechanism involved in formation of such a wavy shell, Wolf and Kurz attribute it to the microsegregation of phosphorous (sulphur is taken care of by Mn in steel) and its effect on the mechanical properties of steel. It was shown that phosphorous segregation is a minimum for 0.1% C steels, and this gives the solidified shell in the continuous casting mould a higher hot tensile strength. This strong shell, as it shrinks forms a rough or rippled surface. The spacious F.C.C crystal lattice of austenite in higher carbon steels, on the other hand allows for more segregation of Phosphorous and the resulting weaker shell remains in better contact with the mould wall under the ferrostatic pressure. This lead to uniform shell growth. They also have shown that higher phosphorous levels in a 0.12% C steel give rise to increased heat fluxes and thicker shells. It should, however, be of interest to see if such wavy shells do form in the absence of elements like phosphorous which have a low distribution coefficient.

Grill and Brimacombe explained the unusual surface roughness of low carbon steel in the light of the shrinkage inherent in the $\delta \rightarrow \gamma$ transformation of the peritectic reaction. These authors point out that compared to higher carbon steels, 0.1%C steel undergoes greater solid state transformation which is accompanied by a contraction of 0.38%. Thus 0.1%C steel experiences greater shrinkage than higher carbon steels and the large air gaps that appear repeatedly because of enhanced
shrinkage cause the observed low heat extraction rates. Recent investigations by Hurtuk and Tzavaras\textsuperscript{15} show that these wavy surfaces appear not only in Fe-C system, but also in Fe-Ni alloys where the peritectic reaction prevails. Hurtuk\textsuperscript{16} has also shown that plain carbon steels containing no phosphorous showed similar wavy surfaces when the carbon was 0.1%.

2.2.2 Influence of Operating Variables on Heat Transfer

It has been shown by many investigators that higher casting speeds increase heat flux in the mould. Nevertheless, the specific amount of heat extraction (J/Kg) decreases\textsuperscript{17} and so does the net shell thickness\textsuperscript{18} when the billet exits the mould. Though earlier publications\textsuperscript{1,17,19} report that pouring temperature has negligible effect on heat transfer in the mould, recent investigations\textsuperscript{20} by Samarasekera and Brimacombe reveal that higher superheats give rise to higher heat fluxes in the mould.

Cooling water velocity seems to affect the heat extraction from the the billet mould substantially\textsuperscript{20}. Use of oil lubricant leads to higher heat fluxes near the meniscus compared to mould powders, while the latter yield higher heat fluxes in the lower regions of the mould.\textsuperscript{21}
2.2.3 Influence of Mould Design on Heat Transfer

As the bulk of the heat is extracted in the upper portion of the mould and the lower part acts mainly as a supporting system for the strands, longer moulds do not seem to have any advantage. Brimacombe\textsuperscript{22} has suggested that mould length should be increased proportionately to increase in the casting speed to reduce the increased danger of breakouts.

Mould taper seems to improve heat transfer presumably because it reduces the gap width over the lower regions\textsuperscript{19,23}. Excessive mould taper however causes increased mould wear and resistance to withdrawal.\textsuperscript{23,24}

With directional corrugations and tapered ribs in moulds it is claimed that 8-9\% increase in heat transfer rates can be obtained, possibly because of reduced air gaps.\textsuperscript{25,26} Despite the frequent use of such designs in the Soviet Union the higher machining costs involved make their application in the west impractical.

2.2.4 Influence Of Mould Behaviour On Heat Transfer

When steel is cast through billet moulds the mould walls heat up nonuniformly because heat flow is mainly gap dependent as was shown in Fig 3. The resulting temperature distribution gives rise to differential thermal expansion as hotter regions expand more than colder regions so that the mould wall changes its shape. In areas of high thermal gradients, such as near the meniscus where the yield stress is locally reduced due to higher temperatures, plastic flow takes place to result in permanent
deformation. Fig 5 shows a typical mould distortion profile for billet moulds. Though the exact extent of the distortion varies from mould to mould and for different type of constraints, the predominant bulge at the top of the mould is characteristic of billet moulds. Samarasekera et al\textsuperscript{27} have calculated the extent of distortion from an elasto-plastic finite-element analysis. With the help of data collected from the North American Steel Industry Brimacombe et al\textsuperscript{28} have shown that the type and extent of distortion depends on the meniscus level, deposition of solids on the cold face and possibly the type of constraint. Also wall thickness can have significant effect on thermal distortion. Increasing wall thickness results in an increase in both peak wall temperatures and thermal gradients leading to more permanent deformation.\textsuperscript{27}

Samarasekera and Brimacombe\textsuperscript{29} showed that under conditions of intermittent boiling in the mould-water channels, it is possible to have dynamic distortion. Wall thickness, water velocity, water back pressure and steel carbon content are some of the factors that could trigger boiling and lead to mould wall movement. The possibility of asynchronous intermittent boiling on different faces of the mould resulting in a dynamic distortion has been considered to be an important factor in causing rhomboidity and longitudinal corner cracks.\textsuperscript{30}
Figure 5 - Typical mould distortion profile of billet moulds with constraints on two straight sides
2.3 Mould-related Defects

Quality in billet casting as related to the mould is determined by internal soundness, surface topography and the shape of the billets. Typical defects have been schematically shown in Fig 1. While rhomboidity and crack formation are related to the mould behaviour during casting, surface roughness is generated by improper selection of parameters of the mould oscillator. In this section the influence of mould design and operating variables on rhomboidity and crack formation is reviewed. Factors that control the depth, spacing and severity of the oscillation marks are considered followed by an overview of the mechanisms proposed to explain the formation of oscillation marks.

2.3.1 Rhomboidity

Rhomboidity is often characterised by the difference in diagonals of the cross-section being cast. Frequently rhomboidity is accompanied by longitudinal corner cracks. In extreme cases diagonal cracks may result. Excessive rhomboidity renders the billet unfit for rolling.

Rhomboidity is caused by non-symmetrical cooling of the billet either in the mould or in the sprays. Frequently rhomboidity has been observed to change orientation during the casting of a heat\(^\textsuperscript{26}\). Steel composition appears to influence rhomboidity. Steels containing 0.18 to 0.25% carbon\(^\textsuperscript{31,32}\) and higher carbon (>0.4%) grades\(^\textsuperscript{29,33,34}\) give rise to more rhomboidity. Smaller cross-sections, \(^\textsuperscript{31}\) higher pouring
temperatures and higher casting speeds\(^{17,23}\) aggravate rhomboidity. Poor alignment between the mould and submould assembly\(^{26,31,33,35}\) is a significant factor contributing to rhomboidity. It also has been postulated\(^{29,30}\) that when intermittent boiling occurs asynchronously on different faces of the mould, the mould itself can assume a rhomboid shape and could give rise to greater rhomboidity in the solidifying shell. Rhomboidity and cracking increase with increasing service life of the mould and increasing wear at the bottom of the mould.\(^{31}\)

In practice, different corrective measures have been sought to minimise rhomboidity and the associated cracks. Emphasis has been placed on modifications to cooling in the mould as a means to reduce these defects. Higher heat transfer rates obtained with corrugated moulds\(^{26}\) seem to reduce rhomboidity. At Funabashi steel works\(^{36}\) a "soft-cooling" practice has proved to be effective in reducing rhomboidity. This is accomplished by machining horizontal serrations on the outside surface of the mould in contact with the cooling water. As Samarasekera and Brimacombe\(^{21}\) have suggested the reduction in rhomboidity by this measure may be due to suppression of intermittent boiling. A technique currently used to correct corner cracking in high-carbon steels is to reduce water flow rates relative to those employed in low-carbon steels.\(^{29,34}\) It has been suggested\(^{29}\) that lower water flow rates cause less intermittent and more vigorous boiling whereby cooling of the mould is more uniform and rhomboid mould conditions are less likely. Boiling, however, causes excessive scale deposition on the mould walls which then
become hotter and distort. Thus, with this practice moulds have to be replaced frequently to maintain acceptable billet quality. Samarasekera and Brimacombe\(\textsuperscript{29}\) suggest that suppression rather than enhancing boiling should improve the billet quality to a considerable extent. This could be accomplished by increasing water velocity, raising water pressure, enhancing surface roughness or increasing wall thickness.

It is also important to consider sub-mould conditions to reduce rhomboidity. Proper maintenance of alignment between mould and submould assembly is essential to minimize rhomboidity.\(\textsuperscript{33}\) Tokuyama and Suzuki\(\textsuperscript{37}\) show that if the spray angle in the secondary cooling zone is decreased so that water does not reach the corners, rhomboidity may be mitigated. Corner rolls may be installed at the top end of the roller apron in order to correct rhomboidity\(\textsuperscript{31}\) mechanically.

2.3.2 Crack Formation

Cracks in continuous casting arise due to a combination of thermal stresses caused by adverse thermal gradients and mechanically induced stresses acting on regions of low ductility of steel at high temperatures. Taken together there are three distinct temperature ranges viz; above 1340°C, 800-1200°C, 700-900°C in which steel has low strength and/or ductility.

Mould related cracks are attributed to the low ductility of steel above 1340°C. These cracks are essentially interdendritic with smooth surfaces indicative of hot tearing near the solidification front.\(\textsuperscript{26,38-40}\) These cracks are filled with
liquid rich in solute elements as well as inclusions.\textsuperscript{26,40} The high temperature zone of low ductility is brought about by the presence of liquid films in the interdendritic regions whereby freezing is delayed until temperatures well below the solidus are reached. When the strain to failure exceeds, 0.2 to 0.3 percent according to Vom Ende and Vogt\textsuperscript{41}, cracks can appear.

Off-corner internal cracks are observed in transverse sections normal to a given face and within 1-2 cm of the corner. They may form at one or more off-corner locations in a given section. In some instances, the cracks are associated with longitudinal surface depression and in more severe cases the innermost part of the crack may curve inward to follow a diagonal line (or a diagonal crack) joining opposite corners of the billet.

Brimacombe et al\textsuperscript{38} proposed a mechanism to explain the formation of these cracks based on the tensile strains imposed on the solidification front at the off-corner regions. These strains arise because of bulging of the midface against the cold corner, Fig 6. Randomness in the location of these cracks was accounted for by their argument that bulging could also be randomly occurring on different sides of the billet owing to wobbling of the mould, poor setting of foot rolls or misalignment of the machine. They suggested that higher water fluxes in the upper sprays could reduce the intensity of the cracking problem by imposing compressive strains near the solidification front.

Recent investigations by Zetturland and Kristiansson\textsuperscript{42} have
Figure 6 - Mechanism of crack formation at off-corners
shown that mould wear, especially in the lower part to be an important factor in causing off-corner cracking. They have laid emphasis on the reduction of heat extraction in the lower part of the mould leading to substantial reheating of the surface. Compression at the surface and tensile stresses at the solidification front could lead to off-corner cracking.

Longitudinal corner cracks as seen in transverse section are generally 1 to 2 mm deep, although under unfavourable conditions, cracks with a depth of 6 to 7 mm have been observed. Often crack width is seen to be greater in the interior than near the surface. Corner radius has a significant influence on the location of these cracks. With a large corner radius longitudinal cracks appear on the corner while with smaller radii, the cracks form more frequently off the corner. Corner cracks mostly occur in association with rhomboidity, at the obtuse corners of a rhomboid billet. Earlier studies have revealed that when rhomboidity is reduced through corrective measures for adverse conditions in the mould there is a marked decrease in the severity of longitudinal corner cracks. As to the relation between rhomboidity and corner cracking, Samarasekera and Brimacombe point out that tensile strains acting parallel to the diagonal joining the acute angle corners could cause internal cracking along the diagonal joining the obtuse-angle corners. Tensile strains are generated at the solidification front due to surface reheating if the obtuse-angle corner of the billet pulls away from the billet. Depending on the crack depth, the extent of reheating
and the magnitude of tensile strains generated by the ensuing shrinkage of the shell as it cools deeper in the mould, the crack may penetrate to the surface and become a visible defect at the corner.\textsuperscript{29}

Diagonal cracks are also associated with rhomboidity. Diagonal cracks usually run between obtuse corners of the rhomboid section. These cracks form\textsuperscript{39} initially in the high temperature zone of low ductility, but may grow outward towards the corners depending on the magnitude of the strain. Control of rhomboidity should eliminate these cracks.

2.4 Oscillation Marks

Steel cast continuously at relatively high speeds in reciprocating moulds is usually characterised by the presence of fine lateral surface markings. Though individually of somewhat irregular shape there is a regular spacing between these marks. While these marks do not normally give rise to difficulties in rolling, lower heat extraction rates at the oscillation marks\textsuperscript{44} locally reduce the shell thickness increasing the risk of a breakout below the mould which could prevent the attainment of optimum casting speeds. These marks are also associated with bleeder-type slivers which, when severe, result in unacceptable surface quality. In slab casters lubricated by mould powders these marks are deeper and are potential sites for surface cracks to form. Wolf\textsuperscript{45} reports that local coarsening of the solidification structure caused by reduced heat flow near the oscillation mark is detrimental to steel ductility and creates
the hazard of transverse cracks during strand straightening, particularly in the case of steels with fine precipitates of nitrides of Al, V or Nb.

Subsurface structures at an oscillation mark in slabs usually exhibit a hook-like mark covered by extra metal which when viewed in cross section appears as a lap. Emi et al from their investigations on oscillation marks in slabs report that the pitch of the oscillation marks is identical to the distance between these hook markings. This hook forms in the valley of the oscillation mark and Tanaka et al have shown that positive and negative segregation is associated with the mark. Higher segregation is observed in deeper oscillation marks. Saucedo et al have shown that dendrites near the oscillation mark orient differently compared to their orientation perpendicular to the mould wall elsewhere.

It emerges clearly from the literature that the pitch of the oscillation marks is nearly the ratio of casting speed to the oscillation frequency. Stroke length seems to have a significant influence on the oscillation marks. Many investigators have shown that short strokes decrease the depth of oscillation marks. Higher frequency oscillation also has a similar effect. Short and frequent strokes cause shallow but a greater number of oscillation marks; but longer the negative strip lasts the oscillation marks tend to be deeper. However, Schoffmann and Takeuchi et al report that oscillation marks are flatter and less noticeable when the difference in speed between the mould and the strand during the
negative strip period is small.

Kawakami et al\textsuperscript{53} point out that the maximum depth to which the meniscus shell is bent also increases with increasing negative strip time. Jacobi et al\textsuperscript{57} suggest an optimum negative strip time between 0.15 to 0.25 seconds whereby sufficient compressive stresses are generated in the shell to 'heal' the damage done during the upstroke; this negative strip time also produces oscillation marks that are not too deep. Komatsu et al\textsuperscript{58} have observed that the compressive force applied to the shell in the negative stripping period decreased considerably with the negative strip ratio (NSR) which is the ratio of negative strip time to the total down stroke time expressed as a percentage. When the NSR was decreased from 62 to 35\%, compressive force was not applied to the shell at all. It should be noted that this corresponds roughly to a negative strip time of 0.14 seconds where according to Jacobi et al\textsuperscript{57} oscillation marks are shallow.

Rape seed oil lubrication gives shallower marks compared to the oscillation marks characteristic of mould powder lubrication.\textsuperscript{54, 55} Brown\textsuperscript{59} experimenting with amounts of lubrication reports that the oscillation marks showed a series of transverse cracks when no oil was used.

Higher carbon steels do not exhibit the deep oscillation marks that low carbon steels show. Wolf\textsuperscript{55} suggests that most pronounced oscillation mark formation in the steels with carbon around 0.1\% C can be attributed to the maximum shell strength (associated with a minimum in micro-segregation) and maximum
shrinkage of the meniscus shell. Also austenitic stainless steel with a Ni/Cr ratio of about 0.55 have deep oscillation marks.

There are many models in the literature attempting to explain the formation of oscillation marks in continuously cast billets and other shapes. One of the earliest and broadly accepted mechanism was proposed by Savage\textsuperscript{50} in 1961 for billet casting and was later applied to slab casting by Sato\textsuperscript{51}. It is assumed that the thin and fragile shell that forms during the downstroke is broken and carried upward in the upstroke. In the ensuing downstroke compressive stresses of negative strip weld the piece of steel shell to that below resulting in an oscillation mark. Laps usually associated with the marks may be such joints. This model suffers from many questionable assumptions and has never been experimentally verified.

With the help of a mould simulator Kawakami et al\textsuperscript{53} have examined an old theory suggested by Schoffmann\textsuperscript{10} and Emi et al\textsuperscript{46}. This theory was formulated mainly to explain oscillation marks in slabs where molten slag lubricates the mould. It is postulated that in the negative strip time mould slag flows into the gap between mould and slab and pushes the ingot surface away from the mould wall. At the end of the negative strip or the beginning of the positive strip period, the viscous layer of powder tends to detach from the tip of the shell and molten steel begins to flood over the bent tip so that oscillation mark forms. It is needless to say that the existence of slaggy material on the steel surface is a necessary
condition for the formation of oscillation marks by this mechanism.

Freezing of the meniscus and ensuing overflow is a classical theory suggested by Thorton\textsuperscript{60} to explain surface ripples in static ingot casting. Wray\textsuperscript{61} has shown that many types of ripples appear on static ingots but laps are attributable to meniscus freezing. Saucedo and Beech\textsuperscript{69} have applied meniscus solidification as in static ingot castings to explain oscillation mark formation in continuous castings. With the help of a mathematical model\textsuperscript{62} they have shown that part of the meniscus can freeze in a matter of 0.1 to 0.2 seconds. They suggest\textsuperscript{49} that strong rippling occurs when the velocity of the mould equals the velocity of the billet. However this is contrary to the observation that oscillation mark depths and the depth of the meniscus shells increase with increasing difference between the downward mould speed and eating speed. Also this model does not account for the various shapes of the meniscus shells.

2.5 Scope of the Present Study

It should be noted that the principal connection between the mould and the billet is through heat transfer. Therefore the influence of the mould on billet quality should be reflected in the heat extraction.

Though mould generated rhomboidity has been investigated in terms of several operating variables, steel composition and
mould geometry, the location in the mould where billets become rhomboid is unknown. It is not clear how rhomboidity could be generated high up in the mould where the ferrostatic pressure is quite low. The relation between rhomboidity and mould behaviour as reflected in heat transfer and mould distortion needs to be examined more carefully.

Off-corner cracking has been suggested to be mainly due to the bulging of the mid face against the cold corner. It is not clear where in the mould this occurs and how such bulging could take place and what factors influence it. Clearly temperature and the mechanical properties of the steel should play a decisive role in crack formation. The influence of factors like mould-metal gap and heat transfer are important in locating the position in the mould where off-corner cracking could take place. This would be quite useful in establishing procedures to avert cracking or to inhibit crack growth.

Oscillation marks in billets have never been systematically examined in the literature. It is unknown as to how the mould interacts with the billet to form these undulations on the surface which when severe cause the surface quality to deteriorate. The relation between heat flux at the meniscus level in billet moulds on the oscillation mark depth should be examined. Focus should be laid on the influence of oscillation marks on heat transfer and solidification.

The principal aim of the present study is to relate heat transfer conditions in the mould to surface, subsurface and internal characteristics of the billet being cast. More
specifically, the objectives of the study are as follows.

i. to study the influence of casting variables on the structure of the billets

ii. to examine rhomboidity from the standpoint of casting parameters, steel composition and the dimensional stability of the mould and to clarify the contribution of the mould to rhomboidity

iii. to establish the mechanism of formation of off-corner cracks

iv. to examine the topography and subsurface structure of the billets to shed light on the nature and cause of oscillation marks.

Heat flux data and billet samples from industrial experiments were obtained to achieve these objectives. Billet sections were cut and examined for the columnar zone length, rhomboidity and off-corner cracks. Billet surfaces and subsurface structures were carefully assessed and related to mould oscillation. The influence of superheat, carbon content and mould water flow rate was investigated.

Shell growth profiles and thermal fields in the shell were established with the aid of a one-dimensional unsteady-state heat-transfer model. The model was employed to calculate the distance below the meniscus at which the cracks formed and the thermal conditions at such locations were examined to determine a mechanism for their formation. A two-dimensional heat-transfer model was developed to study the extent of meniscus solidification. From the model predictions and on examination
of the surface and subsurface features of the billets, a mechanism has been formulated to explain the formation of oscillation marks.
III. EXPERIMENTAL PROCEDURES

The current study involving evaluation of billet quality, as affected by mould conditions, is an extension of a major project supported largely by AISI to study heat transfer conditions and distortion in billet moulds. All the experiments were conducted at Western Canada Steel located in Vancouver, B.C. The billet caster at Western Canada Steel is a recently commissioned Rokop-curved mould machine having four strands. Billet section sizes in a range of 140mm (5.5") to 203mm (8") square are produced although 140mm billets are most typical. The casting speed is normally 1.5 to 2.0 m/min (60 to 80 ipm). The specified mould characteristics are given in Table I.

Temperature measurements were made in the billet mould for selected time intervals during a heat and time-averaged heat-flux profiles were obtained for these time intervals using a mathematical model in a separate study. Billet sections that formed in the mould while temperature data was being gathered were collected at the gas cutting unit allowance being made for the time taken to travel between the two locations. To establish links between the measured heat fluxes and billet quality the structure, surface features, rhomboidity and crack formation in the billet section were examined.
3.1 Heat Flux Data Generation

The thermal response of the mould wall was monitored by thermocouples located at the midface and off-corner positions of the outside curved wall and on one of the straight walls. The arrangement of thermocouples is shown in Fig 7. The thermocouples were of intrinsic constantan wire type and were embedded in 3.1mm deep holes in the mould wall as shown in Fig 8. Signals from the thermocouples were fed to a Hewlett-Packard 3485A scanning Digital Voltmeter which has the capability of scanning up to 50 channels at various preset speeds. The data was recorded on a Hewlett-Packard 5055A Digital Recorder that was attached to the Voltmeter. The output was recorded on both papertape and punch tape. The latter permitted the data to be fed directly to the UBC mainframe computer for analysis. The thermal data was converted to axial heat flux profiles in a separate study.

A two-dimensional heat flow model of the mould wall developed earlier by Samarasekera and Brimacombe was used separately to determine heat flux profiles for different heats. The model was employed to predict the temperature field for different heat flux profiles at the hot face of the mould. By comparing the calculated axial temperature profile at the depth of thermocouples to the measured temperature profile, the heat flux which gave the best fit was obtained.

Heat flux data, thus generated by Samarasekera and Brimacombe was used in the present investigation as an input to a one-dimensional heat transfer model to calculate the shell
Figure 7 - Arrangement of thermocouples in mould wall
Figure 8 - Thermocouple design
thickness profiles and temperature fields in the shell.

3.2 Collection of Billet Samples

As the temperature measurements are made in the mould three billet samples were obtained from each heat one in the beginning, one in the middle and one toward the end of the heat. The temperature of the steel in the tundish was measured in each heat. In some heats two measurements of superheat were made one in the beginning and one toward the end of heat. Efforts were made to obtain a range of water flow rates in the mould from 16 to 34 l/s. Billet samples obtained were approximately 20cm in length and were later transported to the laboratory to be cut into transverse sections of 10mm thickness as shown in Fig 9. A total of 12 campaigns consisting of a total of 70 heats were monitored at Western Canada Steel. Table II gives the composition of the steels in all the campaigns.

It should be noted that during Heat 24109 the spray cooling system failed to be applied to the billet. A billet sample from this heat was obtained for analysis; composition of the heat is given in Table II.

3.3 Sulphur Printing and Crack Rating

Sulphur prints were taken of the transverse sections of about 150 billets after they were surface ground and examined for cracks. Among the mould-related cracks, off-corner cracks were observed in many cases. Location of the crack in the
Figure 9 - Transverse and longitudinal sections of the billet sample
off-corner region (distances between the crack and the two surfaces of the billet that form the corner) is noted from sulphur print. The total number of cracks present in each sulphur print was recorded. Severity of cracking was estimated on an arbitrary scale of 0 to 6 based on the number as well as the extent of cracking.

3.4 Macroetching

Billet sections from campaigns 3, 5, 6 and 7 were initially macroetched in a 50% hydrochloric acid solution at 70°C. These macrostructures were examined and the location of white bands was recorded. About 100 billet sections from remaining campaigns were later macroetched to reveal the presence of solidification bands and to estimate the columnar zone length as a function of composition, superheat and mould water flow rate. Selected macrostructures were photographed using a 10 mmX 13 mm negative after immersing the billet section in water to obtain better detail.

3.5 Surface and Sub-surface Features

In most of the heats there was evidence that the strand was being excessively squeezed by the pinch rolls because the 140 X 140 sq.mm section was deformed into a slightly rectangular billet. Flatter oscillation marks were observed on the outer and inner radius faces which were in contact with the rolls and cracks appeared toward the center perpendicular to the curved
faces of the billet. Thus only surface features on the straight faces were analysed in the present study.

The spacing between the oscillation marks was measured at several locations in a series of heats. The depth of the oscillation marks was initially characterised visually by an index of 1 to 5 of increasing severity in 10 heats covering a carbon range of 0.13 to 0.41 and a superheat range of 6°C to 51°C in the tundish. The depth and extent of oscillation marks on high carbon steel billets was later characterised more precisely using a profilometer. This profilometer, assembled in our laboratory, consisted of a linear displacement transducer clamped to a travelling microscope to facilitate smooth movement of the former on the specimen surface. The signal corresponding to the vertical displacement of the transducer stem was processed by a signal conditioner (digital indicator of the 3000 instrument series made by the Daytronic Corporation) and fed to a chart recorder. The accuracy of the measurement was to within 0.02032 mm. The surface of about 30 billets (0.20 to 0.40% carbon) was measured in this way regarding the depth of the marks. Profiles of the two opposite sides of the billet on the off-corner as well as midface regions were obtained. An average of the first 5 major depressions was taken to represent the depth of oscillation mark on each surface.

Longitudinal sections of 10 mm X 10 mm X 200 mm (as shown in Fig 9) were cut from 12 billet sections across the oscillation marks. These sections were surface ground and later polished to 0.3 micron levels. Each two of these sections were
bolted together so as not to round off the edges of the surface perpendicular to the oscillation mark. Polished samples were etched for cast structure mostly using the Oberhoffer's etch. Hot picric acid was also tried on some samples.

3.6 **Measurement of Rhomboidity**

The rhomboidity of 150 billets was characterised by the difference between the diagonals. The shapes of the billets were drawn on transparencies and the distance between opposite faces was measured.
IV. MATHEMATICAL MODELS

4.1 One-Dimensional Heat Transfer Model

In order to predict the shell thickness profile and temperature fields in the growing shell, a one-dimensional heat-transfer model developed by Hibbins\textsuperscript{63} was employed after a few minor modifications. Heat-flux profiles developed by Samarakera and Brimacombe\textsuperscript{20} were employed as an input to the model after fitting the data with polynomials. Since these heat-flux profiles were mainly obtained from the midface area where corner effects would be negligible, it was considered that this model would suffice.

4.1.1 Formulation

A one-dimensional unsteady state heat conduction equation given below describes heat transfer in a continuously cast billet

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) = \frac{\rho c}{\partial t} \left( \frac{\partial T}{\partial t} \right)
\]

where

\( \rho \) = density
\( C \) = Specific heat
\( T \) = Temperature
\( t \) = Time
\( k \) = Thermal Conductivity

If \( k \) is assumed constant over small time intervals this equation

becomes

\[ k \left( \frac{\partial^2 T}{\partial x^2} \right) = \rho c_p \left( \frac{\partial T}{\partial t} \right) \quad - - - 4.2 \]

Solution of this second-order partial differential equation requires knowledge of one initial condition and two boundary conditions. For the case of continuous casting, the initial condition is

At \( t=0 \) and \( 0 \leq x \leq x_m \),

\[ T = T_{\text{pour}} \quad - - - 4.3 \]

where

\[ x_m = \text{Mid point of transverse section} \]

\[ T_{\text{pour}} = \text{Pouring temperature} \]

The two boundary conditions may be determined by considering continuity of heat transfer at the surface and centre plane of the billet. Thus at the surface of the slab.

At \( t>0 \) and \( x=x_m \)

\[ -k \left( \frac{\partial T}{\partial x} \right) = Q_{\text{mold}} \quad - - - 4.4 \]

where

\[ Q_{\text{mold}} = \text{Heat flux out of mould} \]

At the centre plane, if symmetry of heat transfer on each face is assumed, the net rate \( \Theta \) of heat transfer is 0, so that

At \( x=0, t \geq 0 \)

\[ \frac{\partial T}{\partial x} = 0 \quad - - - 4.5 \]

Solution of the differential equations for heat transfer has in
the past been accomplished by analytical and numerical methods. The numerical methods have proved themselves to be most versatile in the solution of solidification problems because they permit the use of varying boundary conditions, release of latent heat over a broad freezing range and temperature dependent thermo-physical properties. Of the various numerical methods the explicit and implicit finite-difference techniques have been employed widely in casting applications. The implicit method has an advantage in that it is free of a stability criterion that restricts the independent choice of time and distance intervals as required by the explicit technique. For the purposes of this model this was the justification for use of the implicit-finite difference method.

4.1.2 Derivation of the Finite Difference Equations

The most elegant solution of the unsteady-state, heat-conduction equation involves the approximation of the partial differentials of Equation(4.2) by the use of the Taylor series. Though the derivation of the finite difference equations in this way is more rigorous in that the order of the errors in the approximation is known, identical equations can be derived by performing a simple heat balance for each node. Derivation of the finite-difference equations is presented in Appendix B.
4.1.3 Characterisation of Input Conditions

An important aspect of mathematical model formulation is the manner in which thermo-physical properties and boundary conditions are handled. In particular characterisation of the thermal conductivity of the liquid and the release of latent heat must be considered. Turbulent mixing in the liquid pool makes it difficult to assign proper values to the thermal conductivity. Brimacombe\textsuperscript{22} has shown that the exact value of thermal conductivity employed in the liquid pool does not affect the calculated temperature field significantly. The effective thermal conductivity in the liquid pool has been estimated from the literature to be seven times the thermal conductivity of the liquid metal at the particular temperature.

Latent-heat release is accomplished by a technique commonly employed by other workers\textsuperscript{65-67} i.e., adjusting the specific heat between the liquidus and solidus temperatures as shown below.

\[
C_m = C + \frac{L}{T_l - T_s}
\]

where

- \(C_m\) = Specific heat in the mushy zone
- \(C\) = Specific heat evaluated at the known temperature of the node
- \(T_l\) = Liquidus temperature
- \(T_s\) = Solidus temperature
4.2 Meniscus Solidification Model

Of the proposed mechanisms for oscillation-mark formation in billet casting, solidification of the meniscus has been given considerable importance in recent years. During the mould downstroke, it has been speculated that the meniscus is allowed to remain in contact with the mould wall for a fraction of a second under conditions similar to those in static casting. From mathematical model predictions Saucedo et al. proposed that the strong chilling power of the mould creates steep temperature gradients allowing partial solidification of the meniscus. They assumed that the partially solidified steel behaved as a solid when only 20 percent solidified, and used this as a criterion for the formation of oscillation marks. They employed an arbitrary heat transfer coefficient for characterising the heat flux from the steel to the mould.

Because measured values of meniscus heat flux were available for the present study, it was considered worthwhile to examine the possibility of meniscus solidification in billet casting. A two-dimensional heat-transfer model was chosen to calculate heat transfer from a curved-boundary losing heat from the top by radiation and convection and from the straight side to the mould. Fig 10 shows a schematic of the arrangement of nodes. Considering no relative velocity between the mould and the billet in the downstroke, the heat flow due to bulk motion is neglected. Also, like in the previous model, heat flow toward the corners is considered negligible. Expecting rapid solidification in a short time interval, the model was
Figure 10 - Arrangement of nodes in the meniscus solidification model
formulated to simulate heat flow in unsteady-state.

4.2.1 Formulation

The equation governing such unsteady state heat transfer in two directions can be written as

$$\frac{\partial}{\partial x} \left[ kA\left( \frac{\partial T}{\partial x} \right) \right] + \frac{\partial}{\partial z} \left[ kA\left( \frac{\partial T}{\partial z} \right) \right] = VC_p\left( \frac{\partial T}{\partial t} \right) \quad -- \quad 4.7$$

where

A = Area of the node

V = Volume of the node

To solve this equation one initial condition and four boundary conditions are required. As shown before in Eq.(4.2) the initial condition is

$$t=0, \quad 0 \leq x \leq x_{\text{max}}, \quad 0 \leq z \leq z_{\text{max}},$$

$$T = T_{\text{pour}}, \quad -- \quad 4.8$$

The boundary condition for $$t>0, \; x=0$$ plane is

$$-k\left( \frac{\partial T}{\partial x} \right) = Q_{\text{mold}}$$

At $$z=0$$ the radiative and convective heat flux is given by

$$Q = h_{\text{conv}} \left( T - T_{\text{amb}} \right) + \sigma \epsilon \left( T^4 - T_{\text{amb}}^4 \right) \quad -- \quad 4.9$$
where

\[ h_{\text{conv}} = \text{Convective heat transfer coefficient} \]
\[ \sigma = \text{Stefan Boltzmann constant} \]
\[ \varepsilon = \text{Emissivity} \]
\[ T_{\text{amb}} = \text{Ambient Temperature} \]

At an arbitrary distance in the \( x=0 \) plane and \( z=0 \) plane, two adiabatic boundaries were assumed to exist.

At \( z = z_{\text{max}}, \) \( 0 \leq x \leq x_{\text{max}} \)

\[-k \frac{\partial T}{\partial z} = 0 \]

--- 4.10

At \( x = x_{\text{max}}, \) \( 0 \leq z \leq z_{\text{max}} \)

\[-k \frac{\partial T}{\partial x} = 0 \]

--- 4.11

where

\[ x_{\text{max}} = \text{Maximum distance in } X\text{-direction} \]
\[ z_{\text{max}} = \text{Maximum distance in } Z\text{-direction} \]

Solution to the differential equation was done by the implicit technique as in the case of the previous model. However, to avoid the problems associated with solving a large number of simultaneous equations in the implicit method a special procedure, often employed by other workers, called the alternating-direction implicit method was used. It has an unconditional stability and converges with discretization error of the order of \(((\Delta x)^2 + (\Delta t)^2)\) (where \(\Delta x\) is the node size in \(X\)-direction and \(\Delta t\) is the time step).

In this method, each time interval \(\Delta t\) is subdivided into \(\Delta t/2\) and calculations are performed successively over the half
time steps. In the first step calculations are made implicit in the X-direction and explicit in the Z-direction to obtain an intermediate temperature $T^*$. The final temperatures are determined in the second half time step by doing a similar calculation, but, implicit in Z-direction and explicit in X-direction using the intermediate temperatures obtained in the first step. Thus, in each half time a system of linear differential equations similar to those in the previous model are obtained and solved using the Gaussian elimination technique.

4.2.2 Characterisation Of Input Conditions

The observed meniscus profiles reported by Tomono et al. is shown in Fig 11. For the purpose of the present model the height $Z$ and width $X$ are taken from the observed meniscus profile. Node size in the X-direction i.e., $\Delta x$ is kept constant while in the Z-direction it i.e., $\Delta z$ is varied using a root curve of the form shown below and the meniscus shape is arbitrarily defined.

\[
\Delta Z(N) = \sqrt{\left(\frac{Z_{\min}}{\min} \right)^{2/\min} \{ X_{\min} - \left[ \Delta X \ (N-1) \right] \}} \nonumber \\
- \sqrt{\left(\frac{Z_{\min}}{\min} \right)^{2/\min} \{ X_{\min} - \left[ \Delta X \ (N) \right] \}} \quad -- \quad 4.12
\]
Figure 11 - Observed and calculated meniscus profile after Tomono et al. 69
where

\[ X_{\text{min}} = \text{Width of the meniscus} \]
\[ Z_{\text{min}} = \text{Depth of the meniscus} \]
\[ \Delta Z = \text{Node size in Z-direction} \]
\[ N = \text{Node number} \]

No attempt was made to obtain a fit with the observed profile. While rectangular nodes are selected elsewhere, triangular nodes are assigned to the curved boundary as shown in Fig 10.

Liberation of latent heat is accomplished in this model using a different technique. Instead of artificially increasing the specific heat to incorporate the latent heat released, it is added as a heat generation term as shown in the equation. The heat accumulation \( Q_{\text{acc}} \) in any node in half time step is given by

\[
Q_{\text{acc}} = -\rho VC_p \left[ \frac{T^N - T^*}{(\Delta t/2)} \right] - \left[ \frac{\rho V L \Delta f^*}{(\Delta t/2)} \right]
\]

where

\[ T^N = \text{Temperature of node at the present time step} \]
\[ T^* = \text{Temperature of node after half time step} \]
\[ L = \text{Latent heat of solidification} \]
\[ \Delta t = \text{Time step} \]
\[ \Delta f^* = \text{Fraction of solid that will appear in the half time step under consideration}. \]
Because $\Delta f_s^*$ is unknown, it has been approximated by $\Delta f_s^N$ which is the fraction of solid formed during the previous time step to result in the present temperature. Thus eq.(4.13) becomes

$$Q_{\text{acc}} = -\rho VC_p \left[ \frac{T^N - T^*}{(\Delta t/2)} \right] - \left[ \frac{\rho VLAf_s^N}{(\Delta t/2)} \right]$$

where

$$\Delta f_s^N = \text{fraction solid that formed in the previous time step to result in the presently known temperature } T^N.$$

But such a formulation led to an oscillating solution leading to meaningless temperatures. Eq.(4.14) was later modified as

$$Q_{\text{acc}} = -\rho VC_p \left[ \frac{T^N - T^*}{(\Delta t/2)} \right] - \left[ \frac{\rho VLAf_s^N}{(\Delta t/2)} \right] \left[ \frac{T^N - T^*}{T^P - T^N} \right]$$

Approximating $T^N - T^*$ as $T^P - T^*$ where $T^P$ is the temperature at the previous half time step, eq.(4.15) becomes

$$Q_{\text{acc}} = -\rho VC_p \left[ \frac{T^N - T^*}{(\Delta t/2)} \right] - \left[ \frac{\rho VLAf_s^N}{T^P - T^N} \right] \left[ \frac{T^N - T^*}{(\Delta t/2)} \right]$$

With this technique there will be no latent heat missed even when the nodal temperature jumps the liquidus or solidus temperatures. Latent heat was released both using the Fe-C diagram and considering linear solidification over the mushy zone. After each time step the fraction of solid in every node is calculated using one of the above techniques and no
difference was observed.

One of the problems with the alternating-direction implicit finite difference technique is the treatment of the radiation boundary condition. Introduction of the radiation condition into the heat balance equations renders the equations non-linear. In order to overcome the problem, the boundary condition Eq.(4.14) can be linearised as

\[ Q_{meni} = H_{total} (T_{ij} - T_a) \quad -- -- 4.17 \]

where the over heat transfer coefficient \( H_{total} \) is given by

\[ H_{total} = h_{conv} + \frac{\sigma \varepsilon (T^4 - T_{amb}^4)}{T^N - T_{amb}} \quad -- -- 4.18 \]
V. RESULTS

5.1 Metallographic Examination

After macroetching of billet sections, transverse as well as longitudinal, various features like the columnar zone length, and solidification bands were examined and the results are described below.

5.1.1 Columnar Zone Length

Typical of the radial casting machine from which the billets were obtained, the columnar dendrites growing from the outside radius face were seen to be shorter than those growing from the inner radius face (from this face the dendrites frequently penetrated to the centre of the billet). The columnar zone length was measured from the midface on all sides except for the inside radius face and the results are tabulated in Table III. The influence of carbon, phosphorous, superheat, average mould heat flux, meniscus heat flux and Mn/S ratio on the columnar zone length measured from the outside radius were examined carefully.

Fig 12 shows a plot of columnar zone lengths of all the billet samples as a function of the carbon in steel. It can be seen from the plot that as carbon is increased from 0.13 to 0.38, the length of the columnar zone decreases. Between 0.28% and 0.38% carbon, the average columnar zone length (average of the length of columnar zone in the three billets obtained during the heat) remains unchanged. However, steel billets with
Figure 12 - Plot of carbon versus the length of columnar zone (measured from the outside radius)
carbon content of 0.38-0.45% exhibit much longer columnar zone lengths compared to 0.28-0.36 carbon steels. There appears to be a sudden change in the columnar zone length in the vicinity of 0.37% C.

As shown in Figs 13 and 14 Phosphorous seems to influence the columnar zone length. In low-carbon steels (0.13-0.20) higher phosphorous tends to promote the growth of the equiaxed zone (Fig 13). In 0.28-0.36% carbon steels, Fig 14, Phosphorous appears to reduce the length of columnar zone only beyond a level of 0.025% P. In steels containing greater than 0.36% carbon the columnar zone remained large irrespective of the phosphorous content of steel.

Contrary to the general belief that higher superheats influence the columnar zone lengths singularly, the macrostructure of the billet sections showed minimal dependance on superheat. Considering that the superheat should drop from the beginning to the end of heat, the columnar zone length of the third billet should be shorter than that of the first billet obtained in the beginning of the heat. It has been observed that in about 40% of the heats, the third billet shows a larger or an equal columnar zone length compared to the first billet. In low-carbon steels, no correlation could be obtained between the superheat and columnar zone length. In steels with 0.28-0.36% carbon, as shown in Fig 15, there appears to be a trend wherein higher superheats gave rise to slightly higher columnar zone lengths. But part of this effect may again be due to the presence of phosphorous. Thus while higher phosphorous in
Figure 13 - Plot of phosphorous versus the length of columnar zone (measured from the outside radius) in steels with carbon ranging from 0.13-0.20
Figure 14 - Plot of phosphorous versus the length of columnar zone (measured from the outside radius) in steels with carbon ranging from 0.28-0.36
Figure 15 - Plot of superheat in the tundish versus the length of columnar zone (measured from the outside radius) in steels with carbon ranging from 0.28-0.36%.
steel favours a large equiaxed zone, higher superheat appears to oppose it. In the range of superheats under consideration, phosphorous seem to have a more dominant influence in determining the extent of columnar zone. Beyond 0.38%C, there appears to be no influence of either the phosphorous content or the superheat since the columnar zone length is very large, extending almost to the centre of the billet.

Fig 16 shows the plot of columnar zone length from the three billets of each heat plotted against the measured average mould heat flux. In spite of the scatter there is a good correlation showing higher mould heat fluxes giving rise to shorter columnar zone lengths. It should be noted, however, that steels with carbon greater than 0.36% showed higher heat fluxes as well as large columnar zones. The meniscus heat flux obtained from the experiments did not correlate with the structure in the individual carbon ranges examined. mm. Viz: 0.13-0.20, 0.28-0.36, 0.38-0.41.

5.1.2 Subsurface Structure

When subsurface etches were examined, meniscus-shaped 'hooks' are evident at the location of each oscillation mark in the case of high-carbon steel billets. Figs. 17 to 20 show typical 'hooks' present in samples 24276-2, 24276-3, 24277-1 and 24277-3. Fig 21 shows no difference in the length or the shape of 'hooks' present at the midface and off-corner regions of the billet 24277-2. Of the 10 samples examined, only two samples 24276-1 and 24266-1 did not exhibit the formation
Figure 16 - Plot of average mould heat flux versus length of columnar zone (measured from the outside radius)
Figure 17 - Structure around oscillation mark of the second billet from heat 24276. (11X)
Figure 18 - Structure around oscillation mark of the last billet from heat 24276. (11X)
Figure 19 - Structure around oscillation mark of the first billet from heat 24277. (11X)
Figure 20 - Structure around oscillation mark of the last billet from heat 24277. (11X)
Figure 21 - Structure around oscillation mark of the second billet from heat 24272; off-corner region on the left and midface region on the right. (11X)
of meniscus shaped 'hooks'. On the other hand low-carbon steel billets (24261-2, 24270-3, 24269-3) did not show the presence of hooks. Fig 22 shows the substructure obtained for 24269-3 and Fig 23 shows a close-up of one of the areas corresponding to an oscillation mark. Table IV summarises the information obtained from the subsurface etches regarding the presence of hooks.

In high-carbon steels, the appearance of hooks seems to be related to superheat, water velocity and the depth of oscillation marks. In each of the heats investigated, deeper oscillation marks seem to be associated with 'hooks'. Fig 24 shows the subsurface etches of Heats 24276-1, 24276-2, 24276-3. The first billet sample has no hooks; but the ensuing billets do. The length of the hooks in the third sample is about double of those seen in the second sample. This would, at a first glance, suggests that as the superheat of the steel drops from 1st to 3rd sample hooks appear to grow longer. Heat number 24266 shows a similar trend. However, heats 24277 and 24272 show the opposite behaviour. This suggests that there is yet another factor influencing the formation of hooks. In heats where mould water velocity was 6.7 to 7.2 m/s hooks seem to appear irrespective of the superheat. Similarly at higher water velocities of 9.7 m/s either no hooks or only minor hooks appear depending on the superheat. It should also be noted that in heat 24272, with water velocity of 9.7 m/s the formation of 'hooks' was greater than when a velocity of 3.1 m/s was employed.

Fig 25 presents a close up of the 'meniscus shaped hook'
Figure 22 - Structure around oscillation marks in the longitudinal section of the last billet from heat 24269. (2.9X)
Figure 23 - Close up of the structure around oscillation mark of the last billet from heat 24269. (11X)
Figure 24 - Structure around oscillation marks in the longitudinal sections from the heat 24276; from left to right. First billet, second billet and last billet. (2.9X)
Figure 25 - Close-up of the structure around oscillation mark of the second billet from heat 24276. (17X)
from the second billet of the heat 24276. The orientation of the dendrites adjacent to the hook, i.e., perpendicular to the curvature, clearly reveals that the direction of solidification is different from that elsewhere (close to the edge of the billet). The fine 'chill' type of structure around the oscillation marks indicates that during the formation of these marks heat extraction rates were very high. This could clearly be seen by comparing this chill structure to the pronounced dendritic growth near the surface in between the oscillation marks.

Usually these hooks are associated with some amount of overflow of metal on top. The structure in this portion of steel is fine with small crystallites. These overflows look like 'bleeds' when viewed normally from the billet surface; there is no evidence of 'tears' causing metal to bleed as suggested originally by Savage.

5.2 Band Formation

When macroetches of transverse sections are carefully examined, a white band can be seen running all around each section about 4-7 mm from the edge of the billet. It is often not clearly visible making photography difficult. However, Fig 26 shows the white bands in a corner area of the billet from Heat 24249. Fig 27 shows the white band in the midface area of the billet 24242-3. It was observed that when the corresponding surface has a deep oscillation mark, the white band is very wavy and is positioned closer to the edge of the billet. Fig 28
Figure 26 - White band in the obtuse angle corner of the second billet from heat 24259. (2.5X)
Figure 27 - White and dark bands at the edge of the last billet from heat 24242.
Figure 28 - Thin and wavy white band at the midface of the second billet from heat 24251.
depicts such an occurrence. This could be more clearly seen in the longitudinal etches for example in Fig 24. The band draws especially close to deeper oscillation marks. Conversely, the white band is straight in sample 24276-1 which had no hooks and very shallow oscillation marks. At this white band, there seems to be a fluctuation in the composition of steel causing it to etch differently. Attempts have been made to analyse the compositional variation across the band using the microprobe. Because the difference in composition is below the resolution of the probe no positive identification of either the extent or the type of segregation could be made.

In most of the transverse section there is yet another visible 'dark' band about 9-12mm from the edge of the billet (this distance is at the midface). Deeper etches show this band more distinctly. Fig 29 is a unique example of such a dark band formation all around the transverse section. Fig 30 also shows a dark band in Billet 23490-3. In the majority of billet sections, the dark band appears as seen in Fig 31 showing the transverse section of Billet 24251-3. It has been observed that in many billet sections the 'white' and 'dark' bands overlap near the corner/off-corner area. The dark band either appears distinctly close to the white band or disappears gradually as one proceeds to look from midface to the corner. Figs 27 and 32 are typical examples of this observation.

It should be pointed out that the maximum distance between the dark band and the surface of the billet is not always at the midpoint of the face (see Fig 31). On different faces this
Figure 29 - Prominent dark band in the second billet from heat 24221.
Figure 30 - Dark band in the last billet from heat 24490.
Figure 31 - Dark band merging into white band at the off-corner region; last billet from heat 24251.
Figure 32 - Dark band merging into white band at the off-corner region; second billet from heat 23471.
maximum distance is off-center by varying lengths. This clearly points out that in any given cross-section under consideration heat extraction is not the same on all four faces and the highest heat flux need not necessarily be at the mid-point of the face.

The distance from the edge of the billet where these bands appear at the midface and off-corner areas of the transverse sections was measured in a series of billet samples. The results are presented in Table V. It has been observed that in low-carbon steel billets these bands are not visible except in a few instances (mainly because low-carbon billets etch poorly without much detail) whereas in high-carbon billets they are readily visible. However, where the structure is completely equiaxed, band formation is not always clearly visible to make any measurements; but again, completely equiaxed structures show very little detail when macroetched.

One of the interesting observations is that in rhomboid billet sections, the white band is closer to the edge of the billet at the obtuse-angle corners than at the acute-angle corners. In other words, the short diagonal of the rhomboid billet invariably has the white band closest to the edge of at least one off-corner area. This characteristic of the white band reveals a typical re/entrant corner, e.g., Fig 26 shows magnified view of white band formation closer to the edge of the billet at the obtuse angle corner. Fig 33 shows the whole transverse section of the billet presented in Fig 26.
Figure 33 - Macro-etch of the transverse section of the second billet from heat 24249.
5.3 Crack Formation

Off-corner cracks were examined in billets from Heats 24090 to 24278. These cracks often are associated with a surface depression (Fig 34) and are positioned about 4 to 6 mm from the billet surface. They appear randomly on any one, or many, of the eight off-corner sites. Table VI shows the placement of nearest (to corner) off-corner cracks and the total number of cracks in each billet sample. Off-corner cracks appear to form in the vicinity of the white band. Fig 35 shows the proximity of the white band and the crack(s) at the off-corner region.

Table VII presents the severity of cracking in the various billets examined together with selected operating data. When the number of cracks per sample are plotted against the water flow rate employed, Figs 36 to 38, it can be seen that the severity of cracking is highest at 26.50 - 27.76 l/s (equivalent to a water velocity of 7.25 - 7.65 m/s). Also around 17.66 - 18.93 l/s (equivalent to a water velocity of 3.35 - 3.85 m/s) of water flow rate also there appears to be extensive cracking in the billets. This seems to be true both in the case of low- (<0.20%C) and high-carbon steels.

In the range studied neither steel chemistry nor superheat influenced the crack severity with the exception of the sulphur in the steel. Though the amount of sulphur did not correlate well with the crack severity, Mn/S ratio had a definite influence. Fig 39, 40, 41 show the relation
Figure 34 - Off-corner cracks from the heat 24276.
Figure 35 - Location of off-corner cracks and white band at the obtuse angle corner of second billet 24277.
Figure 36 - Plot of water velocity versus the number of off-corner cracks per billet. Carbon range 0.13-0.41.
Figure 37 - Plot of water velocity versus the number of off-corner cracks per billet. Carbon range 0.13-0.20.
Figure 38 - Plot of water velocity versus the number of off-corner cracks per billet. Carbon range 0.28-0.41.
Figure 39 - Plot of Mn/S versus the severity of off-corner cracks water velocity range 6.15-7.2 m/s.
Figure 40 - Plot of Mn/S versus the severity of off-corner cracks water velocity <6 m/s.
Figure 41 - Plot of Mn/S versus the severity of off-corner cracks water velocity >8.65 m/s.
between crack severity and Mn/S ratio in three ranges of water flow rates employed. Ratios above 25-30 seem to prevent crack formation irrespective of the water flow rate. In the water velocity range 6.7 to 8 m/s (water flow rate of 25-28 l/s), as the Mn/S increased from 14 to 36, crack severity showed a steady drop, Fig 39. However, in other water velocity ranges investigated, i.e., above 9.7 m/s (water flow rate of 32 l/s) and below 6.7 m/s (water flow rate of 25 l/s) crack severity seems to vary randomly when the Mn/S ratio is lower than 25-30, Fig 40 and 41 respectively.

In Heat 24109 which was cast without secondary cooling water it was found that the off-corner cracks developed on all four sides of the billet and penetrated quite deeply toward the centre of the section along the diagonal (Fig 42). It can be seen that there is bulging at the midface on the straight sides and a surface depression near the crack. As explained earlier the outer and inner radius faces of the billet were rolled so that bulging could not be seen.

The influence of mould wear (towards the bottom) on cracking is considered here. Fig 5 shows the mould distortion of the mould in which billets from Campaigns 5 and 6 were cast. In spite of the bulge on the curved sides toward the bottom of the mould, billets cast in this mould did not show any off-corner cracking. Fig 43 shows the distortion profile of the mould in which all the billets of Campaign 12 were cast. It is quite evident that despite negligible mould wear at the exit, cracking was observed in the samples cast through this mould.
Figure 42 - Off-corner cracks in the heat 24109.
Figure 43 - Mold distortion after Campaign 12.
This suggests that mould wear seems to be not a pre-requisite for off-corner cracking.

5.4 Rhomboidity

Rhomboidity, as characterised by the difference in diagonals, was measured in a number of billets. Table VIII shows the results. Variation in rhomboidity ranges from 0.0 to as high as 9.5mm in the difference in diagonals. Carbon, water flow rate and superheat of the steel showed no discernable influence on rhomboidity. Over a Campaign of 40 heats, rhomboidity fluctuated randomly.

In Campaign 8 when the mould was constrained at two thermocouple locations on the straight wall in Heat 24090, rhomboidity was negligible. It should be noted that even after releasing the constraints in the heat 24100 (Campaign 9), which ran only for 20 minutes negligible rhomboidity was observed in the three billets that were collected. Slight concavity was observed in the billet face in contact with the constrained side of the mould as shown in the Fig 44.

5.5 Oscillation Marks

The continuous-casting mould at Western Canada Steel is oscillated vertically at a speed depending on the casting velocity to result in a predetermined negative strip time during
Figure 44 - Concavity in the straight face in the second billet from 24090.
the downstroke. The various casting speeds and the corresponding oscillation frequencies employed at the Western Canada Steel are presented in Table 3.1 of Chapter 3. At an average casting speed of 36mm/sec (85ipm) the oscillation speed employed is 75 min
-1 to result in a negative strip time of 0.27 s. This is calculated using the Equation 2.1 (in chapter.2) for sinusoidal oscillation of mould. The stroke length presently is 18.44mm.

Billet surfaces are characterised by periodic undulation with a spacing of 29-30mm. This coincides with the pitch of oscillation marks calculated as the ratio of casting speed to oscillation. It should be emphasised that the shape of these marks is quite irregular and the spacing varies by ±2mm. But considering the variation in the casting speed and oscillation frequency such variation is relatively small.

Figs 45 to 49 show some of the typical surfaces of the billets of low- and high-carbon steels. Based on visual observation the severity of oscillation marks was indexed and the results are presented in Table IX. From Fig 50 it is clear that low-carbon steels show distinctly deeper marks compared to higher carbon steels.

Profilometer measurements of the oscillation marks in high-carbon steel billets are presented in Table X. These reveal that in most of the heats the depth of oscillation marks increases from the beginning of casting to the end probably as a result of decreasing superheat. However, in heats where water velocity has been changed the influence of superheat is not
Figure 45 - Billet surface from the heat 24270 (0.13% C, last billet) casting direction down.
Figure 46 - Billet surface from the heat 24271 (0.20% C, second billet) casting direction down.
Figure 47 - Billet surface from the heat 24276 (0.30% C, first billet) casting direction down.
Figure 48 - Billet surface from the heat 24265 (0.35%C, second billet) casting direction down.
Figure 49 - Billet surface from the heat 24273 (0.41% C, third billet) casting direction down.
Visual Estimation of Depth

1. None
2. Mild
3. Deep
4. Very Deep
5. Severely Deep

Figure 50 - Plot of carbon versus visual estimation of the depth of oscillation marks.
evident.

In heats 24266, 24263, 24277 as the water velocity is increased from a low value of 4 - 7.5 m/s (water flow rate of 20 - 27.5 l/s) to above 9.2 m/s (water flow rate of 31.5 l/s), oscillation marks tend to become shallower in spite of a possible drop in superheat. However, in case of the Heat 24265, there appears to be no change in the depth of oscillation marks after increasing the water velocity from 7.1 - 8.1 m/s (water flow rate of 21.45 to 32.80 l/s). Billet samples from Heat 24272 present a different situation to the above. As the water velocity is decreased from 9.7 m/s (water flow rate of 32.80 l/s) to 3.1 m/s (water flow rate of 16.72 l/s), the oscillation marks seem to become shallower. Excluding this sample at 3.1 m/s (water flow rate of 16.72 l/s), one can generalise, that irrespective of superheat, lower water velocities 4 - 7.2 m/s (water flow rates of 20 - 26.5 l/s) give rise to deeper oscillation marks than those above 9.15 m/s (water flow rates of 31.54 l/s).

Above 9.15 m/s (water flow rate of 31.54 l/s), phosphorus seems to have a strong influence on the depth of oscillation marks (obtained as an average of the three samples available for the heat). This can be seen in Fig 51. Any such dependency of composition could not be observed at water velocities lower than 9.15 m/s (water flow rate of 31.54 l/s) in the high-carbon steel billets.

Table X presents the depth of oscillation marks both at the midface and off-corner regions from each billet. It is
Figure 51 - Plot of phosphorous versus depth of oscillation marks, water velocity >8.65 m/s.
interesting to note that the oscillation mark appears to be
deep in the off-corner region than in the midface. This can
be observed in Fig 45 to 49. For the unaided eye low-carbon
steel billets present deep off-corner valleys (Fig 45)

5.6 Model Predictions

Characteristics of shell formation based on heat-flux data
derived from temperature measurements in the mould are presented
here. After establishing thickness profile and thermal fields
in the shell with the help of a one-dimensional heat-transfer
model, the possibility of meniscus solidification is examined
using the two-dimensional heat-flow model described earlier.

5.6.1 Solidification of Billet Section

The shell profile and shell thickness at the mould exit was
calculated for Heats 24258 to 24278 using the 1-D unsteady state
heat transfer model. Heat flux data established by Samarasekera
and Brimacombe were fitted with polynomials and used as an input
the model. Figs 52 to 54 show such heat-flux profiles for high-
carbon steels at 9.1 m/s, 8.1 m/s and 7.1 m/s respectively.
Also Figs 55 to 57 show heat-flux profiles for low-carbon steels
at 9.1, 8.1 and 7.1 m/s.

The exit shell thickness calculated for various high-carbon
heats is tabulated in Table XI and is seen to be ranging from
Figure 52 - Heat flux profile for low carbon steel, water velocity 9.7 m/s.
Figure 53 - Heat flux profile for low carbon steel, water velocity 6.85 m/s.
Figure 54 - Heat flux profile for low carbon steel, water velocity 5.55 m/s.
Figure 55 - Heat flux profile for high carbon steel, water velocity 9.7 m/s.
Figure 56 - Heat flux profile for high carbon steel, water velocity 7.2 m/s.
Figure 57 - Heat flux profile for high carbon steel, water velocity 5.55 m/s.
8.31 to 11.2mm. The location of the dark band is also presented in the Table XI. Exit shell thickness and the position of dark band are compared for the heats under consideration in Fig 58.

Table XII presents the exit shell thickness for the low-carbon heats. The shell thickness of the billets at the mould exit thus varies from 7.59-11.2mm. The chill band could be seen only in Heats 24259 and 24269 and its location is given in Table XII. From Table XI, Table XII and Fig 54 it can be said that the chill band appears in the billet after the latter exits the mould.

The measured distance from the surface of the billet to the white band in the midface also are presented in Tables 5.9 and 5.10. The distance below the meniscus where the shell thickness corresponding to the white band develops is also presented in these tables. Thus on an average it can be concluded that in high-carbon steel, the white band forms around 450 - 550 mm below the meniscus. In low-carbon steels, this position shifts upwards to 300 - 450 mm.

While formulating the shell thickness profiles the temperature grid after each time step has been employed to find the cooling rates of individual locations. Figs 55 to 59 show some typical cooling-rate plots for high-carbon steels. Cooling rates of the surface, the location corresponding approximately to the white band and the location ahead of the white band are plotted against the distance and time below the meniscus. It can be seen that at about 400 mm below the
Figure 58 - Location of dark band and exit shell thickness in high carbon steel heats.
Figure 59 - Cooling rates of three different nodes down the mould, high carbon steel. Water velocity 9.7 m/s.
Figure 60 - Cooling rates of three different nodes down the mould, high carbon steel. Water velocity 7.2 m/s.
Figure 61 - Cooling rates of three different nodes down the mould, high carbon steel. Water velocity 5.55 m/s.
meniscus, the surface node gets reheated. Furthermore at about 480 - 640 mm from the meniscus, while the surface node reheat, the position corresponding to the shell thickness of 7 mm a constant cooling rate in the presence of a decreasing heat extraction rate. Similar phenomena were observed in the case of low-carbon steels but lower in the mould (560 - 720 mm) as illustrated in Figs 62 and 64. It should also be noted that below 640 mm from the meniscus, the surface undergoes extensive reheating some times at a rate of -25 °C/s

5.6.2 Meniscus Solidification In Billet Casting

Solidification at the meniscus has been examined with the help of these 2-D unsteady state meniscus model. Considering the relation between the oscillation marks and negative strip time, it was thought an average estimate of 0.3 seconds of negative strip time could serve very well as the maximum time available for solidification. It is implied that metal at the meniscus does not move down the mould during this time or moves with no metal being added at the meniscus and the heat flux is constant over the interval of calculation. For all practical purposes, solidification of a static metal meniscus has been undertaken to simulate casting conditions in the negative strip time of a continuous casting mould. In considering such solidification, it is necessary to have a criterion as to what fraction of solid in the steel would make it behave as a rigid body. Saucedo and Beech\(^6\) have considered
Figure 62 - Cooling rates of three different nodes down the mould, low carbon steel. Water velocity 9.7 m/s.
Figure 63 - Cooling rates of three different nodes down the mould, low carbon steel. Water velocity 6.85 m/s.
Figure 64 - Cooling rates of three different nodes down the mould, low carbon steel. Water velocity 5.55 m/s.
that a fraction of solid greater than 0.2 is sufficient to produce a dendritic arrangement that will behave rigidly. Considering the uncertainty involved in deciding the extent of mushy zone because of the lack of information about the liquid thermal conductivity as affected by fluid motion etc., it was thought best to employ 100% solid in steel as the rigidity criterion. The model was run essentially for 0.1%C steel and 0.3%C steel employing various heat fluxes and at different superheats.

There is no data available in the literature for heat-extraction rates in the negative strip time. Meniscus heat fluxes reported by Samarasekera and Brimacombe are only average values over the entire oscillation cycle. These range from 3200-5000 KW/M² for high-carbon steels and 3200-4000 KW/M² for low-carbon steels for superheats well above 1°C. At the superheats encountered in the experiments at Western Canada Steel and using meniscus heat fluxes established by Samarasekera (which are presented in Table III) solidification was not found to occur at the meniscus even after 0.3 seconds of simulation.

It was considered worthwhile to examine as to what value of peak heat flux would be needed for solidification at the meniscus. With 1°C superheat in the melt, a minimum of 4186 KW/M² (100 Cal/cm²sec) was found to be necessary to freeze the portion of meniscus closer to the mould for the 0.1% carbon steel whereas 5233 KW/M² (125 Cal/cm²sec) is the minimum heat flux for 0.3%C steel. Figs 65 and 66 show the growth of solid in the 0.1%C and 0.3%C steel respectively at these minimum
Figure 65 - Model predicted solidification at the meniscus-low carbon steel.
Figure 66 - Model predicted solidification at the meniscus - high carbon steel.
heat flux values. While with $4186 \text{ KW/M}^2$ solidification of the meniscus just begins, Fig 65 shows extensive solid growth at $6279 \text{ KW/M}^2$ for the low-carbon steel. Fig 66 shows similar calculation for the 0.3%C steel at $1325 \text{ KW/M}^2$ ($175 \text{ Cal/cm}^2\text{sec}$) and $8372 \text{ KW/M}^2$ ($200 \text{ Cal/cm}^2\text{sec}$). Not surprisingly as the heat flux is increased the extent to which the meniscus solidifies increases in addition to the shell becoming thicker adjacent to the mould.

Higher superheats definitely need higher heat fluxes for the same extent of freezing. It was found that while $4186 \text{ KW/M}^2$ ($100 \text{ Cal/cm}^2\text{sec}$) at $1^\circ\text{C}$ of superheat gives rise to solidification at the meniscus, at $20^\circ\text{C}$ no solid was present. Also, as the time for solidification is decreased, higher heat fluxes would be needed for the same extent of solidification.

However, provided either with higher heat fluxes in the negative strip time or colder steel adjacent to the mould walls, it is physically possible to have part of the meniscus frozen.
VI. DISCUSSION

6.1 Macrostructure Of Billet Sections

As was shown in section 5.1.1 of the last chapter, factors which influence the extent of the columnar zone are primarily the carbon and phosphorous contents. As carbon is increased from 0.13 to 0.36%, columnar zone length decreases from a high value of 65mm to below 44mm at 0.29%C and remains almost constant. However, at 0.38%C and beyond there appears to be a steep rise in the columnar zone length. Similar observations have been made in bloom casting by Miyahara et al \(^6^9\). However, the rise in columnar zone length was after 0.42%C. Tiwari and Beech\(^7^0\) observed that at high superheats, the equiaxed area increases to a high value at 0.35%C and steadily decreases thereon as the carbon content increases.

The influence of increasing carbon content on the earlier columnar-equiaxed transition may be due, at least in part to increased constitutional supercooling. There may be a similar explanation for the influence of phosphorous on the columnar zone length. It should also be pointed out that dendrite arm remelting becomes easier as the alloy content of the steel increases and the resulting nuclei from the early stages of solidification drift away and then descend through the bulk liquid to later contribute to the formation of the equiaxed
zone. The settling of dendrite debris into the lower part of the liquid pool where they interfere with columnar growth certainly is responsible for the non-symmetrical structure observed in the billet sections, i.e shorter columnar zone adjacent to the outside radius face. Flow of colder steel to the lower part of the liquid crater owing to density differences would enhance such a non-symmetry of the structure.

Another important effect of carbon is the shrinkage associated with the $\delta \rightarrow \gamma$ transformation which contributes to the waviness of the billet surface. The waviness would reduce with the amount of primary-$\delta$ beyond carbon levels 0.16%. Increased smoothness of the billet surface at higher carbon in steel increases the heat transfer rates because the air gap is reduced. This should lead to more effective removal of superheat in the mould and thereby contribute to the growth of the nuclei in competition with the columnar dendrites by reducing the gradients at the columnar dendrite tips. The survival of the nuclei is as well enhanced by removal of more superheat. Aided by increased constitutional supercooling, columnar zones are shorter as carbon or phosphorous are increased.

The sudden increase in the columnar zone length around 0.38%C in steels is a new finding in billet casting. Considering the Fe-C equilibrium phase diagram, such a transition appears to be more likely at a carbon level of 0.51%. Upto 0.51% C in steel, solidification proceeds through the peritectic reaction involving the $\delta$-phase with a solubility of
0.1% for carbon. Beyond 0.51% C the liquid freezes directly to γ-Fe which can dissolve up to 2.0wt% of carbon. Thus, the extent of constitutional supercooling would be limited in the case of steels with greater than 0.51wt% C. In the case of the peritectic reaction, there would be more contribution to the equiaxed zone from dendrite arm remelting because these crystallites will be in the form δ-Fe and would therefore provide greater resistance to re-solution (due to their higher melting points) compared to γ-Fe crystallites in steels in the 0.51%C. Tiwari and Beech⁷⁰ suggest that there is yet another way the peritectic reaction promotes equiaxed zones i.e., by increasing the survival rate of the 'falling crystallites'. These crystallites would transform from δ to γ on the mould wall before moving into the liquid. On remelting of such nuclei, the change from γ to δ must occur and therefore an envelope of δ will form initially around the γ-phase. This envelope may provide a greater barrier to re-solution than if the γ and the liquid were in direct contact. The delay so caused in remelting would result in an increase in the number of surviving crystallites and therefore a larger equiaxed zone.

It is not clear, however, why this transition to pronounced columnar dendrite growth takes place at a carbon level of 0.38% rather than 0.51%. Under the influence of the alloying elements present in the steel (viz., Mn, Si, Cr, Al, P, S) it is not known as to how the peritectic reaction would take place. Needless to say the solidification conditions are far from equilibrium.
It is interesting to note that although the columnar zone length goes up after carbon levels of 0.38% the average heat extraction rates remain high and comparable to the heats with carbons levels of 0.29-0.36. This shows that the influence of heat transfer is only secondary, the primary contribution arising from compositional factors. Similarly the superheats under consideration seem to be generally quite high but again the composition of the steel seem to dictate the columnar-equiaxed transition.

6.2 Band Formation

Details about the white and dark bands in transverse sections are presented in Section 5.1.3 of the last chapter. Considering the continuity of these bands as shown in Figs 26 to 33, it is reasonable to consider formation of each band as a one-time event i.e., happening simultaneously across the crosssection at the same distance below the meniscus. It was shown in section 5.5 that the dark band appears to occur approximately soon after the billet exits the mould and the white band appears at about 450-550 mm below the meniscus in the case of high-carbon steels and 300-450 mm below the meniscus in the case of low-carbon steels. It was also shown that around these areas of the mould the billet seems to exhibit peculiar thermal behaviour.

Weinberg suggests that the presence of such white (or
lightly etched) bands in ingot solidification is due to the washing action of liquid on the solidification front. In the present study of continuous casting it is well known that because of the input stream there is significant circulation of liquid steel in the mould area. While experimenting with addition of radioactive isotopes to delineate the shell profile, several investigators including Morton and Weinberg\textsuperscript{72} and Lait et al\textsuperscript{73} have shown that the fluid flow is sufficiently turbulent to mix the isotope fairly quickly into the liquid pool as it is being added. It has been shown that around 450-550 mm below the meniscus, the shell corresponding approximately to the location of the white band undergoes a constant cooling rate (Figs 59 to 64). This could mean that the speed of the solidification front is retarded. Considering the fluid motion in the liquid crater of the continuously cast strand, the fluid stream then has more time to wash the interdendritic-rich liquid from the solidification front.

Considering the 'deeply etched' or dark nature of the other band it can be speculated that the dark band represents an area of enhanced solidification. The dark band seems to correspond to a sub-mould shell thickness. It has been shown (in Figs 59 to 64) that the billet shell undergoes substantial reheating as the billet is exiting the mould. This reheating could be attributed to increased gaps resulting from the strong shell and the correspondingly lowered heat fluxes toward the exit of the mould. It is quite possible that the impingement of the first sub mould-sprays would accelerate the solidification
front which was growing slowly up to this point. It is known that location of the first spray nozzle below the mould is within 1.25 cms below the mould. This would lead to enhanced freezing of the interdendritic liquid rich in solute elements without giving time for the circulating fluid stream to wash it away.

The importance of the study of these bands lies in the fact that the white and dark bands which are wide apart at the midface seem to overlap at the off-corner. In the absence of heat flux data at the corner/off corner area, this would serve as a guide-line to estimate the shell thickness at the off-corner area. More importantly the above observation suggests that after the white band has formed, solidification in the off-corner/corner areas virtually stops even though it continues in the midface region. As will be shown later this appears to be an important clue to explain one of the reasons for mould-generated rhomboidity.

6.3 Crack Formation

The proximity of the offcorner cracks to the white band suggests that these cracks could have formed only after the billet has travelled at least 450-550 mm below the meniscus. However, as has been suggested earlier, there appears to be practically very little shell growth after this stage at the off-corner areas. Also there is reheating associated with the
billet shell after its exit from the mould. Because of lack of supporting rolls for the exiting billet, it is possible for the midface of the billet to bulge against the cold corner. As was mentioned earlier when reheating was enhanced in the absence of secondary cooling water, off-corner cracks resulted at all four corners. This fact further confirms the influence of reheating on the occurrence of these cracks. The location of the off-corner crack and the bulge in the adjacent face shown in Fig 42 clearly points out that these cracks would originate because of, as suggested by Brimacombe et al. the tensile strains generated at the solidification front due to the midface moving out against a cold corner. The present study indicates that these cracks form outside the mould or in the bottom-most part of the mould where the midface could freely bulge.

However, it is not clear as to how the mould cooling water affects the off-corner cracking. Samarasekera and Brimacombe suggest that intermittent boiling takes place near the meniscus area of the mould and could lead to dynamic distortion of the mould. As to how distortion caused higher up in the mould could enhance off-corner cracking is unknown; but it may lead to an unusually thin shell thickness in the corner region which may exacerbate bulging below the mould.

In the light of the above observation the data was analysed simply in terms of the Mn/S ratio. This ratio determines the available sulphur to form low melting FeS which allows dendrites to separate under tensile strain to form the off-corner cracks. It was observed that when this ratio is lower than 25-30, crack
severity was high. This appears to be much more clear when water velocities were lower than 9.7 m/s (water flow rates of 32 l/s). It is interesting to note that the billet from the Heat 24109 (which had no sub-mould water) has a Mn/S ratio of only 21 and thus it was prone to cracking.

The absence of the effects of mould wear (at the bottom) on the off-corner cracking points out that it is not a necessary condition. There is substantial reheating as the billet exits the mould and mould wear could only make it worse. Composition seems to a major factor in deciding whether cracking would occur. However, severe reheating could promote the cracking tendency. Also, from these results it would appear best to avoid water velocities lower than 9.7 m/s (water flow rate of 32 l/s).

As the above analysis would suggest, off-corner cracks could be prevented by a combination of the following measures:

- employing Mn/S ratios higher than 24
- ensuring spraycooling on the billet as it exits the billet. This would give rise to compressive stresses at the solidification front whereby cracking would be prevented
- placing foot rolls to guide and support the billet so that midface bulging would not occur.
- employing water velocities above 9.7 m/s.
- increasing mould taper to reduce reheating.
6.4 Rhomboidity

Considering the fact that the curved faces of most of the billets were rolled slightly as they were extracted from the caster by the pinch roll assembly, the measured rhomboidity is not a true representation of the off-squareness of the billet. Thus the influence of carbon, superheat, life of the mould and water velocity on rhomboidity, if any, could not be seen. In the following discussion on rhomboidity an extreme case has been selected where rhomboidity was minimum and approximately remained so during the course of the casting.

The constrained mould experiment described in the section 5.4 of last Chapter clearly points out the importance of mould wall movement and its influence on rhomboidity. It is known that the present mould at Western Canada Steel is held at the top on only two straight faces. Mould distortion owing to differential thermal expansion in the transverse direction would be significantly less on the curved sides of the mould as compared to the straight faces, owing to the absence of constraints. This could lead to non-symmetrical cooling of the billet causing non-uniform shrinkage which could generate rhomboidity. As can be seen, in the case of Heat 24090, where the side wall was constrained from moving away from the billet, rhomboidity was reduced to a minimum. Permanent deformation of mould wall was minimum during the Heat 24100 resulting in minimal rhomboidity.

The presence of rhomboidity in all other heats cast in the
un-constrained mould irrespective of carbon, superheat, water flow rate of mould points out the over riding influence of different cooling capacities of the straight and curved walls.

The observation that at obtuse angles of the billet the white band gets is quite thin (Figs 26 and 33) indicates that as to how rhomboidity could result from mould - billet interaction. In a square section if one of the four corners is thinner than others, then during spray cooling the difference in the contraction of adjacent faces would make the billet rhomboid. This clearly points out that even if the measured rhomboidity is not totally due to mould events, the genesis of it is certainly in the mould.

It is not clear, however, as to why such thinner corners form in solidifying section. As pointed out earlier, the fact that the mid-point of a face is not where the maximum shell thickness forms (based on observations of the dark band) in many billet sections) indicate that the heat transfer is not uniform on adjacent faces. It is possible that such variations precede a change in the gap, controlled to a great extent by the mould distortion for a given set of conditions (eg., water flow rate, carbon in steel etc.). It is known that the distortion is different on the straight and curved sides. Considering that the distortion in the mould is non-symmetric in a transverse-section it is possible that one of the four corners loses thermal contact earlier in the billet's journey through the mould. This would place the white band closer to the surface at that corner.
6.5 Oscillation Marks

It emerges quite clearly from the literature (presented in Chapter II) that oscillation marks form during the down stroke of the oscillation cycle. Dependence of their severity on the negative strip time indicates that any mechanism which attempts to explain the formation of these marks should manifest itself in this fraction of a second during which the mould overtakes the billet.

Compressive forces are suggested\textsuperscript{5, 6, 56, 47} to act on the solidifying thin shell during the negative strip period. For such force, which presumably is due to mould-billet friction, to act on a shell, the normal force should arise from a ferrostatic head present near the meniscus; but this is unlikely because the head at this point is exceedingly small\textsuperscript{42}.

Many of the theories reviewed in Chapter II apply to slab casting where in the liquid slag in the Mould-metal gap could act as a pump pushing against the solidifying thin skin in each negative strip time. Kawakami's\textsuperscript{51} argument that same applies to billet casting wherein scum resulting from oxides and other inclusions that float up seems rather far fetched. An even scum-layer over the entire surface of the metal pool is non-existant. It is not known whether they have tested the effects of superheats and carbon levels at all.

One of the theories that is more relevant to billet casting, suggested by Savage\textsuperscript{48} proposes that the shell is broken in each negative strip period and is carried above the metal.
level of the mould and is subsequently lapped on to surface of the billet. This could happen occasionally at some locations across the section. The probability for it to occur always and all around the surface of the billet at a given instant is very small. It is needless to say that according to this theory upcoming pieces of steel should be visible above the metal level during each oscillation stroke. However there are no such reports in the literature.

It is known that the billet mould with constraints at the top distorts leading to a 2% negative taper in the first few inches of the mould. Fig 44 shows the mould distortion observed in the mould employed in campaign 12 of the present experiments. Taper is more on the straight wall which is constrained than on the curved wall. It is also during 'negative strip' the mould moves faster speed than the billet. As the mould overtakes the billet in its downward travel, it is likely that owing to the negative taper the mould-metal gap closes down leading to higher heat transfer rates. At the metal meniscus (where the gap are negligible to start with), the heat extraction would be much more than in the positive strip period of the cycle. During the entire negative strip period, as the metal at the meniscus solidifies and tries to shrink and create a gap, the mould continually closes the gap. In other words a very high heat flux of the order of 7000- 8000 KW/M² could easily be realised in this short duration of time which as per the meniscus-solidification model would lead to solidification as shown in Fig 65 to 66. Fig 67 shows schematically the formation of the
oscillation marks (hooks, depression and overflow). While the meniscus is being frozen, it is possible for the mould to exert a strong normal force and cause the shell to buckle at its weakest point. The low-carbon steel billets due to their wavy-surfaces (Figs 45 and 46) offer convenient 'hinges' resulting in greater depressions while in high-carbon steels, the depression is small and is located in the thinnest area close to the meniscus.

The absence of meniscus-shaped hooks in low-carbon steels (Fig 23) could be explained by considering the peritectic reaction and extensive $\delta \rightarrow \gamma$ solid state transformation. This transformation, as has been mentioned earlier, is associated with about 0.38% shrinkage. It is also known that at the severe cooling rates under consideration, the solid state transformation takes place quite readily. No sooner a thin film of low-carbon steel solidifies it pulls off from the mould due to the shrinkage. This would result in the observed lower meniscus heat fluxes reported in Table III and meniscus solidification would not take place. Thus, though model predictions described in section 5.6 emphasise that it is easier to solidify low C steel menisci, this does not seem to be a physical reality.

Towards the end of the negative strip period, as the mould slows down and releases the billet, new metal overflows from the top of the solid meniscus. In the ensuing positive strip period, the mould flux drops off because of the increased gap resulting from the mould moving away from the billet. Till the
beginning of the next negative strip period, the billet would have travelled a distance equal to the ratio of casting speed to oscillation speed and would receive another oscillation mark.

It should be emphasised that it is not necessary for the mould to grab and hold the meniscus for all the available time of negative strip. The time of contact would be dependant on how soon the mould would close the gap created by shrinking shell at the meniscus. However, the chilled structure of the overflown metal suggests that the overflow must have taken place during the negative strip i.e., during a time of extensive heat transfer by the mould. The extent of solidification for a given negative strip period depends on the heat flux realised and the superheat. Calculations from the 2-D heat transfer model support this view. It was shown that while 4186 kW/M$^2$ at 1°C of superheat gives rise to solidification at the meniscus at 20°C no solidification was observed. Thus for a given negative strip and for a given time of extensive heat extraction from the meniscus, depending on the heat flux meniscus solidification could occur only below a certain superheat. At present the magnitude and the required dwell time of such a heat flux is not known.

Considering the short duration of such high heat fluxes at the meniscus, it is no surprise that the average heat flux obtained from these trails was much lower. The technique employed could not pick up the instantaneous surges of heat on the hot face of the mould one has to resort to much more sophisticated measuring system which would monitor the
temperature of mould continuously at the 'moving meniscus'.
Also care has to be taken about a constant metal level as it
would have an influence on the type and extent of taper at the
meniscus area.

It is not clear, however, as to why the off-corner regions
had deeper marks compared to the midface. As Fig 21 indicates,
there is no difference in the extent of meniscus solidification
between the midface and off-corner. The difference is only in
the depression. One possibility could be that the corner of the
billet is mechanically more rigid than any other area of the
section and as the mould tries to squeeze on the billet's thin
shell the area adjacent to the rigid mould corner would undergo
more deformation.

It was shown that phosphorous has a strong influence on the
depth of oscillation marks when the water flow rates are higher
than 31 l/s. This could be explained by considering the effect
of phosphorous on mechanical properties of steel. Phosphorous
has been shown to the decrease the high temperature fracture
strength of steels\. When the mould exerts a normal force in
the negative strip time a weaker shell would undergo more
deformation or buckling.

Water velocities lower than 9.7 m/s were shown to cause
deeper oscillation marks. Samarasekera and Brimacombe point
out at these lower flow rates intermittent or complete boiling
takes place leading to more dynamic distortion. Thus larger
tapers at the mould top would lead to severe deformation of the
billet surface in question. However, considering exceptions
like sample 24272 (at 3.1 m/s) and 24278 (at 7.2 m/s) more samples are needed to be examined to obtain any definite correlation.

Thus, this mechanism explains most of the observations made during this study. However, it remains to be seen that in case of constrained mould where such mould distortion is limited, whether characteristics of oscillation marks would remain the same. It is expected that in such a mould presence of hooks would be a minimum and so would be the depth of oscillation marks.

It should be clearly pointed out that the proposed mechanism does not explain the characteristics of oscillation marks in all casters. In slab casting, use of powder flux and absence of the negative taper in the plate moulds that are used to cast slabs presents an entirely different situation and different mechanisms should be looked into.
Figure 67 - Schematic diagram of the mechanism of formation of oscillation marks in billet casting.
VII. SUMMARY AND CONCLUSIONS

Billet samples obtained from a large number of heats were examined to study different aspects of solidification; columnar-equiaxed transition, segregation bands, off-corner cracks, rhomboidity, sub-surface structure and oscillation marks. Corresponding heat fluxes obtained from measured temperatures were employed in aid of two mathematical models to calculate the shell thickness in the mould at the meniscus as well as down the mould length. The findings of the study are as follows.

1. Columnar-equiaxed transition:

   Compositional factors were found to profoundly influence the extent of columnar zone in the billets examined.

   i. Effect of carbon:

      In the carbon range 0.13-0.36%, increasing carbon was seen to cause an early columnar-equiaxed transition partly by enhancing constitutional supercooling and facilitating easier melting of secondary dendrite arms. A sudden rise in the length of columnar zone in steels with carbon content more than 0.38% was observed for the first time in billet casting. It was thought that the solidification proceeds in these steels by directly forming γ from the liquid rather than through the peritetic
reaction which enables enhanced survival of nuclei generated at the mould wall and constitutional supercooling. However, as per the Fe-C equilibrium diagram such a shift in the solidification pattern should only take place beyond 0.52% carbon in steel. The reason for the transition at carbon levels of 0.38% and beyond is unknown.

ii. Effect of phosphorous:
Phosphorous was found to have strong influence on the columnar-equiaxed transition. In low-carbon steels increasing phosphorous levels from 0.012 to 0.036 was seen to decrease the columnar zone length. In high-carbon steels (0.28-0.36% C) phosphorous levels of greater than 0.025 were found to give rise to pronounced growth of the equiaxed zone. This effect of phosphorous has been attributed to the very low distribution coefficient of phosphorous. While melting of the secondary dendrite arms is enhanced, increased constitutional supercooling would facilitate survival and growth of the nuclei present in the melt. However in steels with more than 0.38% carbon no influence of phosphorous was observed.

iii. The influence of heat extraction:
Heat transfer effects were found to be of secondary importance in columnar-equiaxed transition. Higher heat transfer rates, as carbon is increased from 0.13 to 0.36%, were shown to be associated with a larger equiaxed zone. Increased smoothness of billet surface associated with higher carbon in steel is due to a decrease in the amount of primary δ-phase, the extent of δ to γ solid state transformation and the associated shrinkage. This leads to smaller mould-billet gap and the resulting higher heat flux extracts more superheat in the mould facilitating survival and growth of nuclei which gives rise to large equiaxed zone. The fact that the large columnar zones exist inspite of high heat transfer rates in steels with more than 0.38% C indicates that the influence of heat transfer is only of secondary importance and it is the composition of the steel that plays a significant role in promoting the growth of equiaxed zone.

**iv. Effect of superheat:**

It is rather surprising to find that the superheat in the steel showed negligible influence. Considering that the superheats employed are generally high, it appears logical that other factors dominated in controlling the
extent of columnar zone.

- Additional work has to be done to understand the nature of the columnar-equiaxed transition and the factors that control it. From the present study it can, however, be suggested that besides use of very low superheats and employing expensive electromagnetic stirrers, structure control could be accomplished by control of composition, i.e., addition of alloying elements with low distribution coefficient. Re-phosphorising and addition of boron not only would give rise to better structures but also strengthen low-carbon steels. However, care has to be exercised in selecting the element as some of these, especially phosphorous is known to cause temper embrittlement.

- Better molds should be designed to extract more heat from the billet and improve the structure.

2. **White and dark solidification bands:**
Examination of macroetches revealed that there exist two distinct bands within 10-11 mm of the edge of the billets. These were found to delineate the shell profile at an instant of time.

i. **White band:**

With the help of the one-dimensional model it was shown that the white band which is closer to the surface forms 450-550 mm below the meniscus where the solidifying shell undergoes
a constant cooling rate and the solidification front proceeds at a minimal speed.

ii. Dark band:
The shell thickness corresponding to the second band which was dark or deeply etched was found to have developed at the midface very close to the bottom of the mould.

iii. Mechanism of formation of the bands:
The white band has been attributed to the depletion of interdendritic solute owing to the washing action of fluid flow in the liquid pool against the slowly moving solidification front. However, the dark band by a similar analogy was suggested as resulting from the enhancement of solidification, probably, when the first sprays hit the billet and the inability of the turbulent liquid pool to wash the quickly growing solid.

iv. Based on the pool profile exhibited by these bands in the transverse sections it can be concluded that while solidification proceeds slowly at the midface after the formation of the white band 450-550 mm below the meniscus it appears to have virtually stopped at the off-corner/corner area.

v. Study of these bands has shown that in the majority of the billets heat transfer on the
four faces is far from being identical indicating that the mould billet gap is different on the four sides.

vi. Thin white bands at the obtuse angle corners of the billets, which is a result of improper heat extraction in the mould, could explain the origin of rhomboidal billets, an event occurring in the sprays because of differential contraction of adjacent faces.

- From the above observations it can be suggested that it would be advantageous to use shorter moulds in conjunction with placement of supporting rolls and spray-cooling in the sub-mould region.

3. Rhomboidity:

i. Rhomboidity, as characterised by the difference in diagonals was found to vary between 0 to 9 mm.

ii. No effect of carbon, life of the mould, or the water flow rate was found to influence rhomboidity, possibly because the billets are slightly rolled as they were withdrawn by the pinch rolls.

iii. Minimal rhomboidity was found when one of the straight walls of the mould was constrained in the meniscus area. It was concluded that difference in the distortion of the curved and
straight walls is an important factor in causing rhomboidity.

- It is suggested that new mould designs should be sought wherein the mould walls are constrained from displacing from the billet surface.

4. Off-corner cracking:
   i. Off-corner cracking was observed in a number of billet samples in one or many of the eight off-corner locations. The surfaces perpendicular to the crack are often associated with a depression at the off-corner and a bulge at the midface.
   ii. The present study is in agreement with the literature in that the cracks have formed because of tensile strains generated at the solidification front when the midface bulges. Rigidity of the cold corner would locate the strain in the off-corner region to result in a crack.
   iii. These cracks were found in close proximity to the white band indicating that they could have formed towards the mould-exit.
   iv. Reheating of the billet surface was found to be a key factor in causing these cracks. It was found from the one-dimensional heat transfer
model that as the billet exits the mould wherein off-corner cracking occurs, the billet surface undergoes extensive reheating. Also, absence of secondary cooling water was found to accentuate cracking at the off-corners.

v. Off-corner cracking was aggravated by mould water velocities of 6.5-7.2 m/s. Such low water velocities are known to cause intermittent boiling in the upper regions of the mould. It is unknown as to how events at the menicus could affect cracking which occurs in the lower parts of the mould.

vi. Mn/S ratios lower than 22-25 were found to increase the severity of cracking, possibly by increasing the available sulphur to form the low-melting FeS.

- Remedial measures must include, employing Mn/S ratios higher than 24, ensuring spraycooling on the billet as it exits the billet, placing foot rolls to guide and support the billet so that midface bulging would not occur, employing water velocities above 9.7 m/s and increasing mould taper to reduce reheating.

5. Oscillation marks:

i. Carbon content of steel was found to affect the depth of and structure below the oscillation marks. Steels with carbon lower than 0.20%
were found to have much deeper oscillation marks than the higher carbon steels.

ii. Meniscus-shaped hooks were found to lie below the oscillation marks in high-carbon steels. Low-carbon steels did not exhibit any hook formation.

iii. Hooks were found to be longer at lower superheats.

iv. A two-dimensional unsteady-state mathematical model was developed to study the possibility of meniscus solidification. It was found the necessary heat flux necessary to allow growth of solid over the meniscus has to be much larger than those obtained from experiments conducted in a separate study.

v. A new mechanism has been formulated to explain meniscus solidification, the formation of oscillation marks in billet casting. The negative taper in billet moulds constrained only at the top was thought to be the potential cause of these periodic depressions.

- Severity of oscillation marks could be reduced by constraining the mould from bulging below the constraint and employing low negative strip time.
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71. Weinberg F; Professor, Dept.of Metallurgy, University of British Columbia, Vancouver, B.C., Canada, Private Communication.


APPENDIX - I TABLES

Table - I

CHARACTERISTICS OF THE MOLD AT WESTERN CANADA STEEL

Curved Mold
Copper Grade: DHP 122
taper: 0.1064%
Length: 812.8 mm
Stroke: 18.44 mm
Water Gap: 4.76 mm
Negative Strip: 0.254 s
Wall Thickness: 7.9375 mm
Inside Corner Radius: 6.35 mm
Chrome Plate Thickness: 0.127 mm
Inside Bottom Dimensions: 143.129 mm²
Location of the first spray nozzle below the mold: 1.27 cm
Constraint Type 2: (Constraint on the two straight sides near the top).

OSCILLATION PARAMETERS

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Table V
Location of Solidification bands

Remarks:
- *wavy
- *white, thin and wavy
- *white band is twisted
- lot of off corner cracking
- *wavy, corner crack obtuse angle
- *wavy, no thinness less rhombidity
- *thin corner
- dark etch
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Table - V (Cont)
## Table VI

Location of off-corner cracks and their number in each billet sample

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## Table - VII

Severity of Off-corner cracks

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VISUAL ESTIMATION OF OSCILLATION MARKS

1-No marks  2-Very Mild  3-Mild  4-Deep  5-Very Deep

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APPENDIX B - DERIVATION OF FINITE-DIFFERENCE EQUATIONS FOR ONE-DIMENSIONAL UNSTEADY STATE HEAT TRANSFER MODEL FOR BILLETs

If a one dimensional section through the billet thickness is divided into elements or nodes containing a nodal point at the centre of each heat balances on the interior nodes may be derived. Similarly heat balances for half nodes at the surface and midplane as shown. In the absence of heat generation or consumption, the law of conservation states:

Rate of heat input - Rate of heat output = Rate of heat accumulation

\[ \dot{q}_{in} - \dot{q}_{out} = \frac{\Delta q}{\Delta t} \]  

For the general case of an interior node, i, the finite difference approximation incorporating Fourier's Law of heat conduction leads to

\[ k_1 A \left[ \frac{T'_{i-1} - T'_{i}}{\Delta x} \right] - k_2 A \left[ \frac{T'_{i} - T'_{i+1}}{\Delta x} \right] = A \Delta x \rho C_p \left[ \frac{T_{i} - T_{i-1}}{\Delta t} \right] \]  

where

- \( T' \) = Unknown nodal temperatures at the end of a particular time step \( \Delta t \)
- \( T_i \) = Known temperature of node i at the beginning of each time step.

The thermal conductivities have been calculated as the average values between adja scent nodes, where

\[ k_1 = \frac{k_{i-1} + k_i}{2} \quad \text{and} \quad k_2 = \frac{k_i + k_{i+1}}{2} \]  

\[ 3 \]
Equation 2 can be rearranged to give

\[- \left( \frac{k_1}{\rho C_p} \right) \left( \frac{\Delta t}{(\Delta x)^2} \right) T_{i-1} + \left( \frac{k_1+k_2}{\rho C_p} \right) \left( \frac{\Delta t}{(\Delta x)^2} \right) T_i - \left( \frac{k_2}{\rho C_p} \right) \frac{\Delta t}{(\Delta x)^2} T_{i+1} = T_i - 4\]

Heat balance for surface half node is

\[k_1 A \left[ \frac{T_{s-1} - T_s}{\Delta x} \right] - \dot{q}_{\text{mold}} = \rho C_p A \left( \frac{\Delta x}{2} \right) \left[ \frac{T_s - T_{s-1}}{\Delta t} \right] \]

Rearranging,

\[- \left( \frac{k_1}{\rho C_p} \right) \left( \frac{2\Delta t}{(\Delta x)^2} \right) T_{s-1} + \left( \frac{k_1}{\rho C_p} \right) \left( \frac{2\Delta t+1}{(\Delta x)^2} \right) T_s = T_s - \frac{2\Delta t}{\rho C_p} \]

In this derivation, the surface heat flux is approximated by its value at the beginning of the time step. For the case of the mid plane half, node the heat balance is

\[-k_2 A \left[ \frac{T_o - T_1}{\Delta x} \right] = \rho C_p A \frac{\Delta x}{2} \left[ \frac{T_o - T_0}{\Delta t} \right] \]

Rearranging

\[- \left( \frac{k_2}{\rho C_p} \right) \left( \frac{2\Delta t+1}{(\Delta x)^2} \right) T_o - \left( \frac{k_2}{\rho C_p} \right) \left( \frac{2\Delta t}{(\Delta x)^2} \right) T_1 = T_o\]

Because each of the equations which have been derived contain at least two unknown temperature, none can be solved independently. However, when all the equations in 'n' unknowns results.
If we define

\[
A = \frac{k_1}{\rho C_p} \frac{\Delta t}{(\Delta x)^2}
\]

\[
B = \frac{k_1}{\rho C_p} \frac{\Delta t}{(\Delta x)^2}
\]

\[
C = 1 + A + B
\]

\[
D = 1 + 2x
\]

\[
E = 1 + 2B
\]

the following tridiagonal system of equations is obtained.

\[
\begin{align*}
ET' - 2BT' &= F_0 \\
-AT' + CT' - BT' &= F_1 \\
&\vdots \\
-AT' + CT' - BT' &= F_i \\
&\vdots \\
-AT' + CT' - BT' &= F_s \\
-2AT' + DT' &= F_s
\end{align*}
\]

where

\[
f = \frac{T - 2A}{k_1} \frac{\Delta x}{\Delta t} Q
\]

\[
f = T_i, \quad i = 0, \ldots, s-1
\]

This system of equations is easily solved by Gaussian elimination. Comparison of model-predicted temperatures with an analytical solution to Eq 4.1 showed very good agreement for the case of a slab of initial uniform temperature with
constant surface boundary condition and thermophysical properties.
APPENDIX C - ONE DIMENSIONAL BILLET CASTING HEAT TRANSFER MODEL
IMPLICIT FINITE DIFFERENCE METHOD

C- ONE DIMENSIONAL BILLET CASTING HEAT TRANSFER MODEL
C- -----------------------------------------------
C- IMPLICIT FINITE DIFFERENCE METHOD
C- -----------------------------------------------
C
C- THIS MODEL FITS 6 POLYNOMIALS FOR THE HEATFLUX (KW/SQ.M)
C- HEAT NUMBER SHOULD BE SPECIFIED.
C
C-HEAT FLUX, TEMPERATURES OF NODES, SHELL THICKNESS PROFILE
AND COOLING RATES OF SPECIFIED NODES ARE PLOTTED BY THE MODEL
C
C- *********************************************************
C- * INPUT DATA FILE =5  GENERAL OUTPUT =6 *
C- * OUTPUT TEMPERATURES =7 *
C- * FLUX /DISTANCE OUTPUT =8 *
C- * GENERAL PLOT OUTPUT =9 *
C- *********************************************************
C
C
C- KEY TO SYMBOLS:--
C- -----------------------------------------------
C- CP - SPECIFIC HEAT CAPACITY (J/KG/DEG C)
C- DT - TIME STEP (SEC)
C- DX - NODE SIZE (CM)
C- END - SIMULATION LENGTH (M)
C- K - THERMAL CONDUCTIVITY (W/M/DEG C)
C- MOLD - MOLD LENGTH (M)
C- QDOTX - SURFACE HEAT FLUX (W/M**2)
C- NNODE - NO. OF NODES
C- ROW - STEEL DENSITY(KG/M**3)
C- SPEED - CASTING SPEED (M/MIN)
C- STEEL - STEEL GRADE
C- THICK - BILLET SIZE(M)
C- TLIQ - LIQUIDUS TEMP (DEG C)
C- TPOR - POURING TEMP (DEG C)
C- TSOL - SOLIDUS TEMP (DEG C)
C- T(I) - NODE TEMP (DEG C)
C- -----------------------------------------------

REAL K,MOLD,K1,K2,K3
REAL MOLY,MANGY
REAL ZL(90)
INTEGER STEEL
INTEGER OR1,OR2,OR3,OR4,OR5,OR6
LOGICAL LK

COMMON /C0/ TW(200),NZON,T(100)
COMMON /C1/ TNEW(100),AC(100),BC(100),CC(100),DC(100)
COMMON /C2/ STEEL,NNODE,TLIQ,TSOL
COMMON /C3/ C(50), D(50), E(50), F(50)
COMMON /C4/ S(150), SIGMA(150), AA(150), BB(150)
COMMON /C5/ YF(200), YD(200), WT(200)
COMMON /C6/ P1(50), P2(50), P3(50), P4(50), P5(50), P6(50)
COMMON /C7/ KU1, KU2, KU3, KU4, KU5, KU6
COMMON /C8/ G1(50), G2(50), G3(50), G4(50)
COMMON /C9/ H1(50), H2(50), H3(50), H4(50)
COMMON /C10/ ZA(50), ZB(50), ZC(50), ZD(50), ZE(50), ZF(50)
COMMON /C11/ YF(200), YD(200), WT(200)
COMMON /C12/ T1, T2, T3, T4, T5
COMMON /C13/ TNNODE(300), SSOLID(300), SLIQUID(300), QSCALE(300)
COMMON /C14/ DISREV(300), DISSCA(300), NSTEPS
COMMON /C15/ ABC(5), BCD(5), CDE(5), DEF(5), EFG(11)

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READ(5, 1)(CDE(I), I=1, 5)
READ(5, 1)(DEF(I), I=1, 5)
READ(5, 1)(EFG(I), I=1, 5)

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READ(5, 3) ROW
READ(5, 4) MOLD
READ(5, 5) CARBON, SULFUR, PHOS, GMN, SI
READ(5, 6) CROME, YMOLY, COPPER, SICKLE
READ(5, 7) SUPER
READ(5, 9) N1, N2, N3, N4, N5, N6
READ(5, 10)(C(I), D(I), I=1, N1)
READ(5, 10)(E(I), F(I), I=1, N2)
READ(5, 10)(G1(I), H1(I), I=1, N3)
READ(5, 10)(G2(I), H2(I), I=1, N4)
READ(5, 10)(G3(I), H3(I), I=1, N5)
READ(5, 10)(G4(I), H4(I), I=1, N6)
READ(5, 11) T1, T2, T3, T4, T5

1 FORMAT(5A4)
2 FORMAT(I5, 2X, F5.4, 2X, F5.3, 2X, F3.1, 2X, F6.5, 2X, I3)
3 FORMAT(F6.0)
4 FORMAT(F6.4)
5 FORMAT(F6.3, 1X, F6.3, 1X, F6.3, 1X, F6.3, 1X, F6.3)
6 FORMAT(F6.3, 1X, F6.3, 1X, F6.3, 1X, F6.3)
7 FORMAT(F4.1)
9 FORMAT(I2, 1X, I2, 1X, I2, 1X, I2, 1X, I2)
10 FORMAT(F5.2, F6.1)
11 FORMAT(F5.2, F5.2, F5.2, F5.2, F5.2)

C
C - SIMULATION DISTANCE IS CALCULATED
C
TMOLD=0.8000
DIFF=MOLD-TMOLD
DLEVEL=SLEVEL-DIFF

MOLD=TMOLD
SLEVEL=DLEVEL
END=MOLD-SLEVEL

DSTEP=(MOLD*100)/20.0
ENDCM1=22.0-((SLEVEL*100)/DSTEP)
ENDCM2=22.0
ENDCM3=ENDCM2+0.5

LIQUIDUS/SOLIDUS/POURING TEMPERATURES ARE CALCULATED ---

TLIQ=1540.0-59.2*CARBON-22.5*(CARBON**0.5)
1-31.2*(SULFUR+PHOS)-11.5*SI-3.6*GMN
2-3.8*SICKLE-1.8*CROME-2.3*YMOLY-4.3*COPPER

TSOL=TFEC(CARBON)-(20.5*SI+6.0*GMN+500*PHOS+700*SULFUR)

TPOR=TLIQ+SUPER

PERTINENT INFORMATION IS PRINTED --------

WRITE(6,80)STEEL
80 FORMAT('HEAT FLOW MODEL TEMPERATURE PREDICTIONS',15)
WRITE(6,81)(EFG(I),I=1,5)
81 FORMAT('MOLD WATER ',5A4)
WRITE(6,82)SPEED
82 FORMAT('CASTING SPEED = ',F5.2,4X,'M./MIN.')
WRITE(6,83)SUPER
83 FORMAT('SUPERHEAT = ',F4.1,3X,'DEG C')
WRITE(6,84)TPOR
84 FORMAT('POURING TEMP. = ',F5.0,4X,'DEG. C.')
WRITE(6,85)THICK
85 FORMAT('BILLETT SIZE = ',F5.4,4X,'M.')
WRITE(6,86)MOLD
86 FORMAT('MOLD LENGTH = ',F6.4,3X,'M.')
WRITE(6,87)SLEVEL
87 FORMAT('MENISCUS LEVEL = ',F6.5,3X,'M.')
WRITE(6,88)END
88 FORMAT('SIMULATION LENGTH= ',F6.4,3X,'M.')

MENTS(CARBON)

WRITE(6,89)CARBON,SULFUR,PHOS,GMN,SI
89 FORMAT('COMPOSITION OF STEEL : CARBON',9X,'=',F6.3,
1/25X,'SULFUR',9X,'=',F6.3,,'PHOSPHOROUS',4X,'=',F6.3,
1/25X,'MANGANESE',6X,'=',F6.3,,'SILICON',8X,'=',F6.3,,'NICKLE',9X,'=',F6.3,,'CROMO',7X,'=',F6.3,,'MOLYBDYNUM',5X,'=',F6.3,,'COPPER',9X,'=',F6.3,,'M./MIN.')
1 'SOLIDUS TEMPERATURE FOR PURE FE-C ALLOY=',F6.1)
WRITE(6,90)TLIQ,TSOL
90 FORMAT('//,5X,'MODEL PARAMETERS : LIQUIDUS TEMP. = ',F5.0,4
- 'DEG. C.',/25X,'SOLIDUS TEMP. = ',F5.0,4X,'DEG. C.')
WRITE(6,91)NNODE
91 FORMAT(25X,'NO. OF NODES = ',I3)
C
C- NODE SIZE IS CALLED -
C
DX=THICK/(FLOAT(NNODE-1)*2.)
SIZE=100.*DX
C
WRITE(6,92)SIZE,DT
92 FORMAT(25X,'NODE SIZE = ',F7.5,2X,'CM.',/25X,'TIME STEP = ',F5.2,4X,'SEC.',//)
C
C- INPUT HEAT FLUX DATA IS FITTED WITH POLYNOMIALS -------
C
WRITE(6,100)
100 FORMAT//(,'TIME',3X,'HEATFLUX',3X,'COMPUTED',
13X,'%ERROR',3X,'COEFFICIENTS OF',7X,'OR OF')
WRITE(6,101)
101 FORMAT(' ',3X,' ',3X,' ',3X,' ',3X,' ',3X,' ',3X,' ',3X,' ',8X, '--',/
C
CALL CURFIT(N1,C,D,P1,KU1,ZA,ZAE,OR1)
CALL CURFIT(N2,E,F,P2,KU2,ZB,ZBE,OR2)
CALL CURFIT(N3,G1,H1,P3,KU3,ZC,ZCE,OR3)
CALL CURFIT(N4,G2,H2,P4,KU4,ZD,ZDE,OR4)
CALL CURFIT(N5,G3,H3,P5,KU5,ZE,ZEE,OR5)
CALL CURFIT(N6,G4,H4,P6,KU6,ZF,ZFE,OR6)
C
WRITE(6,222)T1,T2,T3,T4,T5
222 FORMAT//(,'TIME BELOW MENISCUS WHERE POLYNOMIALS ARE DIFFER
1',/,'T1=',F4.1,3X,'T2=',F4.1,3X,'T3=',F4.1
1,3X,'T4=',F4.1,3X,'T5=',F4.1,//)
C
WRITE(6,233)
233 FORMAT('TIME BELOW',5X,'POSITION OF',3X,'SHELL(CM)',2X,
1 'DISTANCE(CM)',4X,'SURFACE',6X,'HEATFLUX',/,
1 'MENISCUS(SEC)',2X,'LIQUIDUS(CM)',2X,'THICKNESS',2X,
1 'BELOW MENISCUS',2X,'TEMP(DEC C)',2X,'(KW/M*M)',/,
1 '----',3X,'---',2X,'-',2X,
1 '----',2X,'--',2X,'- ----',/)
C
C- HEAT FLUX POINTS ARE REPRESENTED ON THIS PLOT-----
C
CALL AXCTRL('XORIGIN',0.0)
CALL AXCTRL('YORIGIN',ENDCM2)
C
WWW=((100.0*SPEED)/60.0)/4.0
DO 300 I=1,N1
CWWW=ENDCM1-C(I)*WWW
DWWW=(D(I)-500.0)/250.0
CALL SYMBOL(DWWW,CWWW,0.28,11,0.0,-1)
300 CONTINUE

C
DO 301 I=2,N2
EWWW=ENDCM1-E(I)*WWW
FWWW=(F(I)-500.0)/250.0
CALL SYMBOL(FWWW,EWWW,0.28,11,0.0,-1)
301 CONTINUE

C
DO 302 I=2,N3
G1WWW=ENDCM1-G1(I)*WWW
IF(G1WWW.LE.2.0)GO TO 306
H1WWW=(H1(I)-500.0)/250.0
CALL SYMBOL(H1WWW,G1WWW,0.28,11,0.0,-1)
302 CONTINUE

C
DO 303 I=2,N4
G2WWW=ENDCM1-G2(I)*WWW
IF(G2WWW.LE.2.0)GO TO 306
H2WWW=(H2(I)-500.0)/250.0
CALL SYMBOL(H2WWW,G2WWW,0.28,11,0.0,-1)
303 CONTINUE

C
DO 304 I=2,N5
G3WWW=ENDCM1-G3(I)*WWW
IF(G3WWW.LE.2.0)GO TO 306
H3WWW=(H3(I)-500.0)/250.0
CALL SYMBOL(H3WWW,G3WWW,0.28,11,0.0,-1)
304 CONTINUE

C
DO 305 I=2,N6
G4WWW=ENDCM1-G4(I)*WWW
IF(G4WWW.LE.2.0)GO TO 306
H4WWW=(H4(I)-500.0)/250.0
CALL SYMBOL(H4WWW,G4WWW,0.28,11,0.0,-1)
305 CONTINUE

C
306 CONTINUE
C
C- Distance, time and node temperatures are initialized -----
C
NSTEP=1
QTOTAL=0.
TOTRAD=0.
DIST=0.
TIME=0.
DTZ=DT
IF=0

C
DO 110 I=1,NNODE
T(I)=TPOR
CONTINUE
C    WRITE(7,1103)DIST,TIME
    WRITE(7,1102)(I,T(I),I=1,NNODE)
C
C START OF THE LOOP @@@@@@@@@@@
C@@@@@@@@@@
C C 5000 XDIST=DIST
    XTIME=TIME
    CALL POS(TIME,IF,DTZ,DT)
    DIST=TIME*SPEED/60.
    XLAM=DTZ/(DX*DX)
C
C IF(DIST.GT.END)GO TO 9999
C
C THE TRIDIAGONAL MATRIX IS CONSTRUCTED -------
C DO 230 I=1,NNODE
    DC(I)=T(I)
    IF(I.EQ.1)GO TO 180
    IF(I.EQ.NNODE)GO TO 190
C INTERIOR NODE
    K1=K(I)
    K2=K(I-1)
    K3=K(I+1)
    IF(T(I-1).GE.TLIQ)K1=K2
    IF(T(I).GE.TLIQ)K3=K1
    A=(K1+K2)*XLAM/(2.*ROW*CP(I))
    B=(K1+K3)*XLAM/(2.*ROW*CP(I))
    AC(I)=-A
    BC(I)=1.+A+B
    CC(I)=-B
    GO TO 230
C MIDPLANE HALF NODE
180 K1=K(1)
    K2=K(2)
    IF(T(1).GE.TLIQ)K2=K1
    B=(K1+K2)*XLAM/(2.*ROW*CP(1))
    AC(I)=0.
    BC(I)=1.+2.*B
    CC(I)=-2.*B
    GO TO 230
C SURFACE HALF NODE

188

C
190 K1=K(NNODE)
   K2=K(NNODE)
   A=(K1+K2)*XLAM/(2.*ROW*CP(NNODE))
   AC(I)=-2.*A
   BC(I)=1.+2.*A
   CC(I)=0.
   QNOWW=QDOTX(IZ,NNODE,TIME)
   QTOTAL=QTOTAL+QNOWW*DTZ
   DC(I)=DC(I)-4.*A*(DX/(K1+K2))*QNOWW

C 230 CONTINUE

C- THE TRIDIAGONAL MATRIX IS SOLVED FOR THE NEW
C- TEMPERATURE DISTRIBUTION.
C- THE NEW TEMPERATURES ARE ADJUSTED TO COMPENSATE
C- FOR LATENT HEAT RELEASE MISSED DUE TO THE
C- DISCRETE TIME STEP.
C
   CALL TRIDAG(1,NNODE)
   DO 1200 J=1,NNODE
       CALL CHECK(J,TNEW(J))
       T(J)=TNEW(J)
   1200 CONTINUE

C-DISTANCE AND FLUX UNITS ARE CHANGED TO CM AND KILO WATTS
C
   DISTCM=DIST*100.
   QNOWKW=QNOWW/1000.0
C
C- TO CALCULATE SHELL THICKNESS AT EACH TIME STEP ------
C
   NNNODE=NNODE-1
   IF(T(NNODE).LT.TSOL) GO TO 999
   SHELL=0
   GO TO 997
999 SHELL=SIZE/2.0
   NNNODE=NNODE-1
   DO 998 J=1,NNNODE
       IF(T(NNODE-J).GT.TSOL)GO TO 997
       SHELL=SHELL+SIZE
   998 CONTINUE

C- TO CALCULATE POSITON OF LIQUIDUS --
C
997 IF(T(NNODE).LT.TLIQ) GO TO 996
   LIQUID=0
   GO TO 994
996 LIQUID=SIZE/2.0
   DO 995 J=1,NNNODE
       IF(T(NNODE-J).GT.TLIQ)GO TO 994
       LIQUID=LIQUID+SIZE
   995 CONTINUE
C-RELEVENT OUTPUT IS COLLECTED IN FILE 6-----
C
994 WRITE(6,991)TIME,LIQUID,SHELL,DISTCM,T(NNODE),QNOWKW
C
C-THE ALL TEMPERATURE MATRIX IS GENERATED--
C-ALL OTHER PLOTTABLE PARAMETERS ARE SCALED AND STORED
C
DO 1101 I=1,NNODE
   TALL(NSTEP,I)=T(I)
1101 CONTINUE
C
DISSCA(NSTEP)=DISTCM/4.0
QSCALE(NSTEP)=(QNOWKW-500.0)/250.0
TNNODE(NSTEP)=(T(NNODE)-1000.0)/50.0
SSOLID(NSTEP)=25.0+SHELL*10.0
SLIQID(NSTEP)=25.0+LIQUID*10.0
TNNODE(NSTEP)=44.0+((T(NNODE)-1000.0)/50.0)
C
C-NEW---
C-TEMPERATURE DISTRIBUTION IS PRINTED IN FILE 7--------
C
WRITE(7,1103)DISTCM,TIME
1103 FORMAT(///,5X,'TEMPERATURE DISTRIBUTION AT',F8.2,' CM OR ',
       -F8.2,' SECONDS BELOW MENISCUS')
C
WRITE(7,1102)(I,T(I),1=1,NNODE)
1102 FORMAT(10('  T(' ,I  3,' ) = ' ,F5.0))
C
C-HEAT FLUX /TIME IS PRINTED IN FILE 8--------
C
WRITE(8,1001)QNOWKW,TIME
1001 FORMAT(F12.2,',',F8.2)
C
HEAT FLUX AND TOTAL HEAT REMOVED ARE PRINTED AFTER--------
C- PRINTING THE TEMPERATURE PROFILE IN FILE 7----
C
321 WRITE(7,323)QNOWKW,QTOTAL
323 FORMAT(5X,'HEAT FLUX = ',F11.2,' W/M*M',/,5X,'TOTAL HEAT REMOVED IN ZONE = ',F12.2,' J/M*M')
C
NSTEP=NSTEP+1
GO TO 5000
C
C@@@ END OF LOOP @@@@@
C
9999 NSTEPS=NSTEP-1
WRITE(6,8888)NSTEPS
8888 FORMAT('TOTAL NUMBER OF TIMES THE MODEL CALCULATED THE HEAT
       1,' FLUX PROFILE=',I4)
C
CALL CREATE(TIME)
SUBROUTINE TRIDAG(IF,L)

SUBROUTINE TO SOLVE TRIDIAGONAL MATRIX FOR
THE NEW TEMPERATURE DISTRIBUTION

COMMON /C1/ V(100),AC(100),BC(100),CC(100),DC(100)
DIMENSION BETA(101),GAMMA(101)
BETA(IF)=BC(IF)
GAMMA(IF)=DC(IF)/BETA(IF)
IFP1=IF+1
DO 10 I=IFP1,L
   BETA(I)=BC(I)-AC(I)*CC(I-1)/BETA(I-1)
   GAMMA(I)=(DC(I)-AC(I)*GAMMA(I-1))/BETA(I)
10 CONTINUE
V(L)=GAMMA(L)
LAST=L-IF
DO 20 KT=1,LAST
   I=L-KT
   V(I)=GAMMA(I)-CC(I)*V(I+1)/BETA(I)
20 CONTINUE
RETURN
END

SUBROUTINE CHECK(J,TP)

SUBROUTINE TO COMPENSATE FOR LATENT HEAT RELEASE
MISSED DUE TO DISCRETE TIME STEP

COMMON /C0/ TW(200),NZON,T(100)
COMMON /C2/ STEEL,NNODE,TL,Ts
IF(TP.GT.T(J))GO TO 50
IF(TP.GT.TL)GO TO 90
IF(TP.LE.TS)GO TO 10
IF(T(J).LE.TL)GO TO 90
CPL=CP(J)
T(J)=TP
CPM=CP(J)
TP=TL-CPL/CPM*(TL-TP)
GO TO 90
10 IF(T(J).LE.TS)GO TO 90
   IF(T(J).GE.TL)GO TO 20
   CPM=CP(J)
   T(J)=TP
   CPS=CP(J)
   TP=TS-CPM/CPS*(TS-TP)
   RETURN
20 CPL=CP(J)
   TOLD=T(J)
   T(J)=(TL+TS)/2.
CPM=CP(J)
T(J)=TP
CPS=CP(J)
A=CPL*(TOLD-TL)+CPM*(TL-TS)
B=CPS*(TS-TP)
IF(A.LT.B)GO TO 30
TP=TL-CPL/CPM*(TL-TP)
RETURN
30 TP=TS+CPM/CPS*(TL-TS)-CPL/CPS*(TL-TP)
GO TO 90
50 IF(TP.LE.TS)GO TO 90
IF(TP.GT.TL)GO TO 60
IF(T(J).GE.TS)GO TO 90
TP=TL-CPL/CPM*(TL-TP)
RETURN
60 IF(T(J).GE.TL)GO TO 90
IF(T(J).LE.TS)GO TO 70
CPM=CP(J)
T(J)=TP
CPL=CP(J)
TP=TL+CPM/CPL*(TP-TL)
GO TO 90
70 TOLD=T(J)
CPS=CP(J)
T(J)=(TL+TS)/2.
CPM=CP(J)
T(J)=TP
CPL=CP(J)
A=CPS*(TOLD-TS)+CPM*(TS-TL)
B=CPL*(TL-TP)
IF(A.LE.B)GO TO 80
TP=TL+CPS/CPL*(TP-TS)+CPM/CPL*(TS-TL)
GO TO 90
80 TP=TS+CPS/CPM*(TP-TS)
90 RETURN
END

C
FUNCTION QDOTX(I2,I,I,TIME)
C
C- SUBPROGRAM TO CALCULATE SURFACE HEAT FLUX -----
C
COMMON /C0/ TW(200),NZON,T(100)
COMMON /C3/ C(50),D(50),E(50),F(50)
COMMON /C4/ S(150),SIGMA(150),AA(150),BB(150)
COMMON /C5/ YF(200),YD(200),WT(200)
COMMON /C6/ P1(50),P2(50),P3(50),P4(50),P5(50),P6(50)
COMMON /C7/ KU1,KU2,KU3,KU4,KU5,KU6
COMMON /C8/ G1(50),G2(50),G3(50),G4(50)
COMMON /CC8/ H1(50),H2(50),H3(50),H4(50)
COMMON /C11/ T1,T2,T3,T4,T5

C
C- MOLD HEAT FLUX IS CALCULATED HERE
C
10 IF(TIME.GT.T1)GO TO 1
   QDOTX=0
   DO 11 J=1,KU1
   QDOTXX=1000*(P1(J)*(TIME**(J-1)))
11   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   1 IF(TIME.GT.T2)GO TO 2
   QDOTX=0
   DO 12 J=1,KU2
   QDOTXX=1000*(P2(J)*(TIME**(J-1)))
12   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   2 IF(TIME.GT.T3)GO TO 3
   QDOTX=0
   DO 13 J=1,KU3
   QDOTXX=1000*(P3(J)*(TIME**(J-1)))
13   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   3 IF(TIME.GT.T4)GO TO 4
   QDOTX=0
   DO 14 J=1,KU4
   QDOTXX=1000*(P4(J)*(TIME**(J-1)))
14   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   4 IF(TIME.GT.T5)GO TO 5
   QDOTX=0
   DO 15 J=1,KU5
   QDOTXX=1000*(P5(J)*(TIME**(J-1)))
15   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   5 QDOTX=0
   DO 16 J=1,KU6
   QDOTXX=1000*(P6(J)*(TIME**(J-1)))
16   QDOTX=QDOTX+QDOTXX
   RETURN
   C

   RETURN
   END
   C

   FUNCTION CP(I)
   C-
   C-
   C- SUBPROGRAM TO CALCULATE SPECIFIC HEAT CAPACITY -------
   C-
   COMMON /C0/ TW(200),NZON,T(100)
   COMMON /C2/ STEEL,NODE,TLIQ,TSOL
   C
   CP=1000*(0.540+(0.0000941*T(I)))
   C
   IF(T(I).LT.TLIQ)GO TO 1
GO TO 11
C
1 IF(T(I).LT.TSOL) GO TO 11
CPP=CP
CP=CPP+((1000*272.09)/(TLIQ-TSOL))
C
11 WRITE(15,10)T(I),CP
10 FORMAT('TEMPERATURE=',F6.1,2X,F12.2)
C
11 RETURN
END
C
REAL FUNCTION K(I)
C
C SUBPROGRAM TO CALCULATE THERMAL CONDUCTIVITY
C
COMMON /C0/ TW(200),NZON,T(100)
COMMON /C2/ STEEL,NNODE,TLIQ,TSOL
C
K=1000*(0.017+(0.000012*T(I)))
C
IF(T(I).LT.TLIQ)GO TO 12
WK=K
K=7.0*WK
C
12 RETURN
END
C
SUBROUTINE POS(A,I,B,C)
C
C SUBROUTINE TO DETERMINE NEW TIME
C
A=A+B
I=I+1
C
RETURN
END
C
SUBROUTINE CURFIT(N,X,Y,P,KU,Z,Z1,NUMBER)
C-
C THIS SUBROUTINE FITS A POLYNOMIAL TO THE HEAT FLUX / TIME
C BELOW THE MENISCUS DATA -THIS WILL BE USED IN MOLD
C- HEAT FLUX ESTIMATIONS AT EACH TIME STEP
C
DIMENSION X(100),Y(100),P(50)
DIMENSION Z(50),Z1(50),ZZ(50)
COMMON /C4/ S(150),SIGMA(150),AA(150),BB(150)
COMMON /C5/ YF(200),YD(200),WT(200)
C
LOGICAL LK
LK=.FALSE.
NWT=0

NUMBER=N-2
IF(NUMBER.GE.40)NUMBER=40

CALL OLSF (NUMBER,N,X,Y, YF, YD, WT, NWT, S1, SIGMA, AA, BB, SS, LK, P)

KU=NUMBER+1

DO 8 I=1,N
Z(I)=P(1)
  DO 6 J=2,KU
    ZZ(I)=P(J)*(X(I)**(J-1))
    Z(I)=ZZ(I)+Z(I)
    CONTINUE
  Z1(I)=(Z(I)-Y(I))/Y(I)*100.0
8 CONTINUE

WRITE(6,10) NUMBER
10 FORMAT(60X,'  ',1X,I2,1X,'  ',/)
WRITE(6,7)(X(I),Y(I),Z(I),Z1(I),1,P(I),1=1,KU)
KU=KU+1
WRITE(6,9)(X(I),Y(I),Z(I),Z1(I),I=KU,N)

FUNCTION TFEC(C)
IF(C.GE.0.1)GO TO 100
TFEC=-(C*410.0)+1534.0
RETURN
100 IF(C.GE.0.16)GO TO 200
TFEC=-(0.3333*C)+1493.3333
RETURN
200 TFEC=-(182.10526*C)+1522.1368
RETURN
END

SUBROUTINE CREATE(TOTIME)

COMMON /C2/ STEEL, NNODE, TLIQ, TSOL
COMMON /C12/ TALL(300, 100), OUT(300), SLOPE(300), 1, TPOR, DT, MOLD, END, SLEVEL, ENDCM1, ENDCM2, ENDCM3, DSTEP, TISTEP
COMMON /C13/ TNNODE(300), SSOLID(300), SLIQID(300), QSCALE(300)
COMMON /C14/ DISREV(300), DISSCA(300), NSTEPS
COMMON /C15/ ABC(5), BCD(5), CDE(5), DEF(5), EFG(11)
CALL DASHLN(0.2,0.2,0.2,0.2)

DISTANCE BELOW THE MENISCUS IS SCALED

DO 100 I=1,NSTEPS
  DISREV(I)=ENDCM1-DISSCA(I)
100 CONTINUE

ENDCM=(END*100)/DSTEP
TSTEP=TOTIME/ENDCM
ENDCM=ENDCM-1.0
ENDCMM=ENDCM
EMENSC=ENDCM1+0.25
N1STEP=NSTEPS-1

HEAT FLUX PROFILE IS PLOTTED *

CALL AXCTRL('DIGITS',1)
CALL AXCTRL('XORIGIN',0.0)
CALL AXCTRL('YORIGIN',ENDCM2)
CALL AXCTRL('SIDE',-1)
CALL AXPLOT(';',270.0,20.0,0.0,DSTEP)
CALL SYMBOL(-1.0,7.0,0.42,'DISTANCE DOWN THE MOLD (CM)' Q,90.0,31)

CALL AXCTRL('SIDE',+1)
CALL AXCTRL('XORIGIN',21.0)
CALL AXCTRL('YORIGIN',ENDCM1)
CALL AXPLOT(';',270.0,ENDCM,0.0,TISTEP)
CALL WHERE(XX,YY)
CALL PLOT(XX,YY,3)
CALL PLOT(XX,2.0,2)
CALL PLOT(0.0,0.0,3)
CALL SYMBOL(22.35,7.0,0.42,'TIME BELOW THE MENISCUS(SEC)' Q,90.0,28)

CALL AXCTRL('XORIGIN',0.0)
CALL AXCTRL('YORIGIN',2.0)
CALL AXCTRL('SIDE',-1)
CALL AXPLOT(';',0.0,20.0,50.0,25.0)
CALL SYMBOL(5.5,0.65,0.42,'MOLD HEAT FLUX(KW/SQ.M)(X10)' Q,0.0,28)

CALL PLOT(0.0,ENDCM2,3)
CALL PLOT(21.0,ENDCM2,2)
CALL PLOT(21.0,2.0,3)
CALL PLOT(20.0,2.0,2)
CALL PLOT(0.0,ENDCM1,3)
CALL PLOT(21.0,ENDCM1,4)
CALL PLOT(21.0,ENDCM1,3)
CALL PLOT(21.0,ENDCM2,2)
CALL PLOT(0.0,2.0,3)
CALL SYMBOL(17.0, EMENS C, 0.42, 'MENISCUS', 0.0, 8)

CALL PLOT(QSCALE(1), DISREV(1), 3)
DO 200 I=1, N1STEP
CALL PLOT(QSCALE(I), DISREV(I), 2)

CONTINUE

CALL PSYM(12.0, 10.0, 0.42, ABC, 0.0, 20, 22)
CALL PSYM(12.0, 9.0, 0.42, BCD, 0.0, 20, 22)
CALL PSYM(12.0, 8.0, 0.42, CDE, 0.0, 20, 22)
CALL PSYM(12.0, 7.0, 0.42, DEF, 0.0, 20, 22)
CALL PSYM(12.0, 6.0, 0.42, EFG, 0.0, 20, 22)

CALL PSYM(6.5, ENDCM3, 0.56, 'HEAT FLUX PROFILE', 0.0, 17, 22)

SHELL THICKNESS PROFILE IS PLOTTED**

CALL AXCTRL('DIGITS', 1)
CALL AXCTRL('XORIGIN', 25.0)
CALL AXCTRL('YORIGIN', ENDCM2)
CALL AXCTRL('SIDE', -1)
CALL AXPLOT(', 270.0, 20.0, 0.0, DSTEP)
CALL SYMBOL(24.0, 7.0, 0.42, 'DISTANCE DOWN THE MOLD (CM) Q, 90.0, 31)

CALL AXCTRL('SIDE', +1)
CALL AXCTRL('XORIGIN', 40.0)
CALL AXCTRL('YORIGIN', ENDCM1)
CALL AXPLOT(', 270.0, ENDCM, 0.0, TISTEP)
CALL WHERE(XX, YY)
CALL PLOT(XX, YY, 3)
CALL PLOT(XX, 2.0, 2)
CALL PLOT(0.0, 0.0, 3)
CALL SYMBOL(41.35, 7.0, 0.42, 'TIME BELOW THE MENISCUS(SEC) Q, 90.0, 28)

CALL AXCTRL('XORIGIN', 25.0)
CALL AXCTRL('SIDE', -1)
CALL AXCTRL('YORIGIN', 2.0)
CALL AXPLOT(', 0.0, 14.0, 0.0, 1.0)
CALL SYMBOL(29.0, 0.65, 0.42, 'SHELL THICKNESS(MM) Q, 0.0, 19)
CALL PLOT(SSOLID(1), DISREV(1), 3)

DO 300 I=1, N1STEP
IPLUS=I+1
IF(I.EQ.N1STEP) GO TO 301
IF(SSOLID(IPLUS).GT.SSOLID(I)) GO TO 299
GO TO 300

CALL PLOT(SSOLID(IPLUS), DISREV(IPLUS), 2)

CONTINUE
CALL PLOT(SSOLID(N1STEP),2.0,2)
CALL PLOT(0.0,0.0,3)

CALL PSYM(31.0,20.0,0.42,ABC,0.0,20,22)
CALL PSYM(31.0,19.0,0.42,BCD,0.0,20,22)
CALL PSYM(31.0,18.0,0.42,CDE,0.0,20,22)
CALL PSYM(31.0,17.0,0.42,DEF,0.0,20,22)
CALL PSYM(31.0,16.0,0.42,EFG,0.0,20,22)

CALL PSYM(31.0,20.0,0.42,ABC,0.0,20,22)
CALL PSYM(31.0,19.0,0.42,BCD,0.0,20,22)
CALL PSYM(31.0,18.0,0.42,CDE,0.0,20,22)
CALL PSYM(31.0,17.0,0.42,DEF,0.0,20,22)
CALL PSYM(31.0,16.0,0.42,EFG,0.0,20,22)

CALL PSYM(27.0,ENDCM3,0.56,'SHELL THICKNESS PROFILE',0.0,23)

CALL PLOT(25.0,ENDCM2,3)
CALL PLOT(40.0,ENDCM2,2)
CALL PLOT(40.0,2.0,3)
CALL PLOT(39.0,2.0,2)
CALL PLOT(25.0,ENDCM1,3)
CALL PLOT(30.0,ENDCM1,4)
CALL PLOT(40.0,ENDCM1,3)
CALL PLOT(40.0,ENDCM2,2)
CALL PLOT(0.0,0.0,3)

CALL SYMBOL(26.0,EMENSC,0.42,'MENISCUS',0.0,8)

C TEMPERATURES OF ALL NODES ARE PLOTTED

CALL AXCTRL('DIGITS',1)
CALL AXCTRL('XORIGIN',44.0)
CALL AXCTRL('YORIGIN',ENDCM2)
CALL AXCTRL('SIDE',-1)
CALL AXPLOT(';',270.0,20.0,0.0,DSTEP)
CALL SYMBOL(43.0,7.0,0.42,'DISTANCE DOWN THE MOLD (CM) Q,90.0,31)

CALL AXCTRL('SIDE',+1)
CALL AXCTRL('XORIGIN',61.0)
CALL AXCTRL('YORIGIN',ENDCM1)
CALL AXPLOT(';',270.0,ENDCM,0.0,TISTEP)
CALL WHERE(xx,yy)
CALL PLOT(xx,yy,3)
CALL PLOT(xx,2.0,2)
CALL PLOT(0.0,0.0,3)
CALL SYMBOL(62.35,7.0,0.42,'TIME BELOW THE MENISCUS(SEC)' Q,90.0,28)

CALL AXCTRL('XORIGIN',44.0)
CALL AXCTRL('SIDE',-1)
CALL AXCTRL('YORIGIN',2.0)
CALL AXPLOT(';',0.0,16.0,800.0,50.0)
CALL SYMBOL(48.0,0.65,0.42,'TEMPERATURE OF NODES(DEG.C)' Q,0.0,27)
LIQUIDUS AND SOLIDUS LINES ARE DRAWN *

TLIQX = 44.0 + ((TLIQ - 800) / 50.0)
TSOLX = 44.0 + ((TSOL - 800) / 50.0)
CALL PLOT(TLIQX, 2.0, 3)
CALL PLOT(TLIQX, ENDCM1, 2)
CALL PLOT(TSOLX, ENDCM1, 2)
CALL PLOT(TSOLX, 2.0, 2)

- TEMPERATURES OF INDIVIDUAL NODES ARE PICKED UP AND PLOTTED **

DO 500 INODE = 85, NNODE

OUT(1) = 44.0 + (((TALL(1, INODE) - 800.0) / 50.0))
CALL PLOT(OUT(1), DISREV(1), 3)

DO 400 JTIMES = 1, N1STEP
OUT(JTIMES) = 44.0 + (((TALL(JTIMES, INODE) - 800.0) / 50.0))
CALL PLOT(OUT(JTIMES), DISREV(JTIMES), 2)
CONTINUE

CALL PSYM(45.0, 20.0, 0.42, ABC, 0.0, 20, 22)
CALL PSYM(45.0, 19.0, 0.42, BCD, 0.0, 20, 22)
CALL PSYM(45.0, 18.0, 0.42, CDE, 0.0, 20, 22)
CALL PSYM(45.0, 17.0, 0.42, DEF, 0.0, 20, 22)
CALL PSYM(45.0, 16.0, 0.42, EFG, 0.0, 20, 22)
CALL SYM(57.0, EMENSC, 0.42, 'MENISCUS', 0.0, 8)

COOLING RATES OF ALL NODES ARE PLOTTED **

CALL AXCTRL('XORIGIN', 65.0)
CALL AXCTRL('YORIGIN', ENDCM2)
CALL AXCTRL('SIDE', -1)
CALL AXPLOT(';', 270.0, 20.0, 0.0, DSTEP)
CALL SYMBOL(64.0, 7.0, 0.42, 'DISTANCE DOWN THE MOLD (CM)', 90.0, 31)
CALL AXCTRL('SIDE',+1)
CALL AXCTRL('XORIGIN',91.0)
CALL AXCTRL('YORIGIN',ENDCM1)
CALL AXPLOTC(';',270.0,ENDCM,0.0,TISTEP)
CALL WHERE(XX,YY)
CALL PLOT(XX,YY,3)
CALL PLOT(XX,2.0,2)
CALL PLOT(0.0,0.0,3)
CALL SYMBOL(92.35,7.0,0.42,'TIME BELOW THE MENISCUS(SEC)' Q,90.0,28)

CALL AXCTRL('SIDE',-1)
CALL AXCTRL('XORIGIN',70.0)
CALL AXCTRL('YORIGIN',2.0)
CALL AXPLOTC(';',0.0,20.0,0.0,5.0)
CALL SYMBOL(73.0,0.65,0.42,'COOLING RATES (DEG.PER.SEC)' Q,0.0,27)

CALL AXCTRL('XORIGIN',65.0)
CALL AXPLOTC(';',0.0,5.0,-25.0,5.0)

C-SLOPES (COOLING RATES) ARE CALCULATED *

DO 1900 INODE=80,NNODE

IF(INODE.EQ.80)GO TO 1899
IF(INODE.EQ.90)GO TO 1899
IF(INODE.EQ.NNODE)GOTO 1899

GO TO 1900

1899 WRITE(14,127)INODE
127 FORMAT(1X,' ',14,' ')

DO 1800 JTIME=1,NSTEPS

IF(JTIME.GT.1)GO TO 120
SLOPE(1)=(((TPOR-TALL(1,INODE))/DT)/5.0)+70.0
GO TO 121

120 JMINUS=JTIME-1
SLOPE(JTIME)=(((TALL(JMINUS,INODE)-TALL(JTIME,INODE))/DT)
/5.0)+70.0

121 IF(SLOPE(JTIME).GT.90.0)GO TO 1705
IF(SLOPE(JTIME).LT.65.0)GO TO 1706

1705 SLOPE(JTIME)=90.0
GO TO 1707

1706 SLOPE(JTIME)=65.0

WRITE(14,129)SLOPE(JTIME),JTIME,IN
129 FORMAT(F5.1,2X,I3,2X,'INODE=',I3)

CONTINUE
CALL PLOT(SLOPE(1),DISREV(1),3)

DO 1850 JTIME=1,N1STEP
    JNEXT=JTIME+1
    IF(JTIME.EQ.N1STEP) GO TO 1851
    IF((SLOPE(JNEXT)-SLOPE(JTIME)).GT.3.0) GO TO 1850
    IF((SLOPE(JNEXT)-SLOPE(JTIME)).LT.-3.0) GO TO 1850
    IF(INODE.EQ.90) GO TO 1849
    CALL PLOT(SLOPE(JNEXT),DISREV(JNEXT),2)
GO TO 1850

1849 CALL PLOT(SLOPE(JNEXT),DISREV(JNEXT),4)
1850 CONTINUE

CALL PLOT(0.0,0.0,3)

CONTINUE

CALL PSYM(72.0,ENDCM3,0.56,'COOLING RATES OF NODES',0.0,22,
CALL PSYM(82.0,10.0,0.42,'ABC',0.0,20,22)
CALL PSYM(82.0,9.0,0.42,'BCD',0.0,20,22)
CALL PSYM(82.0,8.0,0.42,'CDE',0.0,20,22)
CALL PSYM(82.0,7.0,0.42,'DEF',0.0,20,22)
CALL PSYM(82.0,6.0,0.42,'EFG',0.0,20,22)

CALL PLOT(65.0,ENDCM2,3)
CALL PLOT(91.0,ENDCM2,2)
CALL PLOT(91.0,2.0,3)
CALL PLOT(90.0,2.0,2)

CALL PLOT(70.0,ENDCM1,3)
CALL PLOT(70.0,2.0,2)
CALL PLOT(0.0,0.0,3)

CALL PLOT(65.0,ENDCM1,3)
CALL PLOT(91.0,ENDCM1,4)
CALL PLOT(91.0,ENDCM1,3)
CALL PLOT(91.0,ENDCM2,2)
CALL PLOT(0.0,0.0,3)

CALL SYMBOL(66.0,EMENSC,0.42,'MENISCUS',0.0,8)
22 CALL PLOTND

RETURN
END
APPENDIX D - TWO-DIMENSIONAL UN-STEADY STATE MENISCUS SOLIDIFICATION MODEL

C ******************************************************
C 6=-6  (FINAL OUTPUT)
C 7=-7  (TO CHECK HOW LATENT HEAT IS LIBERATED IN S/R ESTMAT)
C 9=-9  (GIVES THE PLOTTER OUTPUT)
C 10=-10 (TEMPERATURES IN THE HALF TIME STEPS ONLY)
C 1=-1  2=-2  3=-3 AND 11=-1 12=-2 13=-3 ARE ONLY
C TO GIVE PLOTTER REQUIRED INFORMATION-NEED NEVER BE PRINTED
C
-------------------------------------
ALL UNITS ARE C.G.S
-------------------------------------
C
THIS PROGRAM USES HEAT FLUX VALUES ....CAL/(SQ.CM)(SEC)
C
**** DOUBLE PRECISION
C
**** FE-C DIAGRAM IS INCORPORATED
C
**** THERMAL CONDUCTIVITY AND SPECIFIC HEAT ARE VARIED WITH TEMPERATURE
C
**** ALL NODES ARE CONSIDERED AT ANY TIME IN TRIDAG ****
C
C
THIS IS A TWO-DIMENSIONAL UNSTEADY STATE HEAT TRANSFER MODEL*
C FOR SOLIDIFICATION AT THE MENISCUS OF THE LIQUID STEEL POOL *
C IN A CONTINUOUS CASTING MOLD.IT IS ASSUMED THAT THE MENISCUS*
C IS STAGNANT FOR A VERY SHORT TIME.THE SOLUTION OF THE SIMUL-*
C TANTEOUS EQUATIONS DEVELOPED FROM HEAT BALANCES IS DONE BY *
C FINITE-DIFFERENCE APPROXIMATIONS AND EMPLOYING THE ALTERNAT-*
CING DIRECTION METHOD OVER SUCCESSIVE TIME STEPS.
C
AT TIME=0.0 ALL THE NODES ARE SET EQUAL TO POURING TEMPERAT-*
CURES.THE FOLLOWING BOUNDARY CONDITIONS ARE APPLIED
C
(1) X=0 Z=0 TO Z2...HEAT IN=-(QMOLD*AREA OF NODE)
(2) X=X2 Z=0 TO Z2...HEAT IN=0
(3) Z=0 X=0 TO X2...HEAT IN=RADIATION+CONVECTION LOSS
(4) Z=Z2 X=0 TO X2...HEAT IN=0
C
-------- NOMENCLATURE --------
C AK    =THERMAL CONDUCTIVITY OF STEEL......(CAL/CM*SEC*DEG C)
C AKL   =THERMAL CONDUCTIVITY OF LIQUID STEEL
C AKS   =THERMAL CONDUCTIVITY OF SOLID STEEL
C * AKMU = THERMAL CONDUCTIVITY OF STEEL IN THE MUSHY ZONE *
C * BETA = INTERMEDIATE SOLUTION VECTOR USED IN S/R TRIDAG *
C * CP = SPECIFIC HEAT ...................................... (CAL/GM*DEG C) *
C * CPLIQ = SPECIFIC HEAT OF LIQUID *
C * CPSOL = SPECIFIC HEAT OF SOLID STEEL *
C * CPMU = SPECIFIC HEAT IN THE MUSHY ZONE *
C * DBOT = SUB DIAGNOL COEFFICIENT VECTOR USED IN S/R TRIDAG *
C * D = DIAGNOL COEFFICIENT VECTOR USED IN S/R TRIDAG *
C * DTOP = SUPER DIAGNOL COEFFICIENT VECTOR USED IN S/R TRIDAG *
C * DT = TIME STEP (SEC) *
C * DX(CM) = WIDTH OF NODE IN X-D/N = X1/M1 (CONSTANT) AND X2 = DX*M2 *
C * DZ(CM) = WIDTH OF NODE IN Z-D/N = Z1/N1 (VARIATES) *
C * END = SIMULATION TIME (SEC) *
C * FSLANT = VIEW FACTOR FOR THE TRIANGULER NODES *
C * FHORIZ = VIEW FACTOR FOR FLAT BOUNDRU NODES ON THE MENISCUS *
C * GAMMA = INTERMEDIATE SOLUTION VECTOR USED IN S/R TRIDAG *
C * HEAT = LATENT HEAT RELEASE (CAL/GM) *
C * M1 = NO. OF NODES IN X-D/N IN MENISCUS *
C * M2 = NO. OF NODES IN X-D/N AFTER MENISCUS *
C * N1 = NO. OF NODES IN Z-D/N IN MENISCUS *
C * N2 = NO. OF NODES IN Z-D/N AFTER MENISCUS *
C * QMOLD = MOLD HEAT FLUX .......... CAL/(SQ.CM)*SEC *
C * R = RIGHT HAND SIDE OF THE LINEAR SIMULTANEOUS EQUATIONS *
C * ROW = DENSITY OF STEEL ............ (GM/CUBIC CM) *
C * ROWL = DENSITY OF LIQUID STEEL *
C * ROWS = DENSITY OF SOLID STEEL *
C * ROWMU = DENSITY OF STEEL IN THE MUSHY ZONE *
C * TT = TEMPERATURE OF STEEL ....................... (DEG C) *
C * TLIQID= LIQUIDUS TEMPERATURE *
C * TPRIME = SOLUTION VECTOR EMPLOYED IN S/R'S 'TRIDAG', 'SOLVE' *
C * TOLD = ALL TEMPERATURES FROM PREVIOUS TIME STEP ARE STORED *
C * TPOUR = POURING TEMPERATURE *
C * TS = TEMPERATURE OF STEEL AFTER ONE HAFF TIME STEP *
C * TSOLID = SOLIDUS TEMPERATURE *
C * SUHEAT = SUPER HEAT IN THE STEEL *
C * IMPLICIT REAL*8 (A-H,O-Z) *
LOGICAL LK
C
COMMON /C1/ TT(75,100),TS(75,100)
COMMON /C2/ D2(75)
COMMON /C3/ AK(75,100),CP(75,100),ROW(75,100)
COMMON /C4/ SOLID(75,100)
COMMON /C5/ DMID(7600),DSTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C6/ BETA(7600),GAMMA(7600),TPRIME(7600)
COMMON /C7/ N1,N2,M1,M2,Z1,Z2,X1,X2,N10,N12,M10,M12
COMMON /C8/ ROWS,ROWL
COMMON /C9/ NTIMES,NTIME,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ PSLANT,FHORIZ,TAMB
COMMON /C14/ NTOTAL,MTOTAL,NX
COMMON /C15/ TFORC(15),TFORCP(15),NFORC,NSFORCP
COMMON /C16/ AKD1(15),AKD2(15),AKD3(15),AKD4(15),AKD5(15)
COMMON /C17/ CPD1(15),CPD2(15),CPD3(15),CPD4(15),CPD5(15)
COMMON /C18/ YK(15),YCP(15),PK(15),PCP(15),ORDERK,ORDERC,
1KK,KCP
COMMON /C19/ C1,C2,C3,C4,C5
COMMON /C20/ SHELLF(75),XMINSC(75),DIST(75)
COMMON /C21/ FS(75,100),FRACTN,NREPET

C
CALL PLCTRL('METR',1)
CALL READ
CALL XANDY
CALL SHAPE(M1,N1,89,61)
1 CALL START
C*************************************************************************
2 DO 8 NTIME=1,NREPET
3 IF(MTIMES.EQ.0)GO TO 4
4 CALL OUTPUT(6)
C********************************************************************************
5 CALL SOLVE(83,85)
C********************************************************************************
6 TIME=NTIME*END
7 CALL MSHAPE(N1)
8 CALL MENISC
9 CALL PROFLE(TIME)
10 CALL SHELL(N1)
C********************************************************************************
8 CONTINUE
C*************************************************************************
WRITE(6,100)
100 FORMAT(////////////////////////////////////////////////////,'THE FINAL RESULT',/)
CALL OUTPUT(6)
CALL PLOTND
9 STOP
END
SUBROUTINE READ

IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION ABC(6),BCD(6),CDE(6),DEF(6),EFG(6),FGH(6)
COMMON /C7 / N1,N2,M1,M2,Z1,Z2,X1,X2,N10,N12,M10,M12
COMMON /C8 / ROWS,ROWL
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FHORIZ,TAMB
COMMON /C15/ TFORK(15),TFORCP(15),NFORK,NFORCP
COMMON /C16/ AKD1(15),AKD2(15),AKD3(15),AKD4(15),AKD5(15)
COMMON /C17/ CPD1(15),CPD2(15),CPD3(15),CPD4(15),CPD5(15)
COMMON /C19/ C1,C2,C3,C4,C5
COMMON /C21/ FS(75,100),FRACTN,NREPET

READ(5,1)(ABC(I),I=1,6)
READ(5,1)(BCD(I),I=1,6)
READ(5,1)(CDE(I),I=1,6)
READ(5,1)(DEF(I),I=1,6)
READ(5,1)(EFG(I),I=1,6)
READ(5,1)(FGH(I),I=1,6)

READ(5,500) DT,NTIMES,NREPET
READ(5,501) CARBON,QMOLD,SUHEAT,FRACTN
READ(5,502) HEAT,ROWL,ROWS,TAMB,FSLANT,FHORIZ
READ(5,503) N1,N2,M1,M2
READ(5,504) Z1,Z2,X1

READ(5,505)NFORK,NFORCP
READ(5,506)C1,C2,C3,C4,C5
DO 100 I=1,NFORK
  100 READ(5,507)TFORK(I),AKD1(I),AKD2(I),AKD3(I),AKD4(I),AKD5(I)
DO 200 I=1,NFORCP
  200 READ(5,507)TFORCP(I),CPD1(I),CPD2(I),CPD3(I),CPD4(I)
  1,CPD5(I)

1 FORMAT(6A4)

500 FORMAT(F10.5,I4,6X,I4)
501 FORMAT(4F10.5)
502 FORMAT(6F10.6)
503 FORMAT(I4,6X,I4,6X,I4,6X,I4)
504 FORMAT(3F10.5)

505 FORMAT(I2,1X,I2)
506 FORMAT(7X,F4.2,2X,F4.2,2X,F4.2,2X,F4.2,2X,F4.2)
507 FORMAT(F6.1,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3)

WRITE(11,1)(ABC(I),I=1,6)
WRITE(11,1)(BCD(I),I=1,6)
SUBROUTINE SHAPE MAKES SURE THAT M1=N1

SUBROUTINE SHAPE(M1,N1,*,*)
IMPLICIT REAL*8 (A-H,O-Z)
IF(M1-N1) 800,802,800
800 WRITE(6,801)
801 FORMAT(1HO,2OH M1=N1 NOT EQUAL )
RETURN 1
802 RETURN 2
END

SUBROUTINE START INITIATES VARIOUS PARAMETERS

DIMENSION DOOO(75)
********TIME IS INITIALLED
TIME=0.0D0
END=NTIMES*DT
THEEND=NREPET*END
MTIMES=0

******DEFINITION OF THE GRID

WRITE(11,1)(CDE(I),I=1,6)
WRITE(11,1)(DEF(I),I=1,6)
WRITE(11,1)(EFG(I),I=1,6)
WRITE(11,1)(FGH(I),I=1,6)
RETURN
END
NTOTAL=N1+N2
MTOTAL=M1+M2
N10=N1-1
N12=N1+1
M10=M1-1
M12=M1+1
DX=X1/FLOAT(M1)
X2=DX*FLOAT(M2)
IF(MTOTAL.GE.23) GO TO 100
NX=MTOTAL
GO TO 200
100 NX=23

C********** DEFINITION OF THE MENISCUS
C
200 DO 300 N=1,N1
300 DZ(N)=DSQRT(Z1**2/X1*(X1-DX*FLOAT(N-1)))
A-DSQRT(Z1**2/X1*(X1-DX*FLOAT(N)))
C
DO 400 N=N1,NTOTAL
400 DZ(N)=Z2/FLOAT(N2)
DIST(1)=DZ(1)
DO 500 N=2,NTOTAL
500 DIST(N)=DIST(N-1)+DZ(N)
C
DO 600 N=1,NTOTAL
DO00=20.0D0-(5.0D0*DIST(N))
DIST(N)=DO00
600 CONTINUE

C ******** LIQUIDUS, SOLIDUS, POURING TEMPERATURES ARE CALCULATED
C
TLIQID=TLIQ(CARBON)
C
TSOLID=TSOL(CARBON)
C
TPOUR=TLIQID+SUHEAT
C
CALL INPUT
C
C THERMAL CONDUCTIVITY & SPECIFIC HEAT ARE VARIED WITH TEMP.
C
CC1=DABS(CARBON-C1)
CC2=DABS(CARBON-C2)
CC3=DABS(CARBON-C3)
CC4=DABS(CARBON-C4)
CC5=DABS(CARBON-C5)
C
IF(CC1.GT.CC2)GO TO 111
DO 1 I=1,NFORK
1 YK(I)=AKD1(I)
DO 2 I=1,NFORCP
2 YCP(I)=CPD1(I)
   GO TO 555
C
111 IF(CC2.GT.CC3)GO TO 222
   DO 3 I=1,NFORK
3 YK(I)=AKD2(I)
   DO 4 I=1,NFORCP
4 YCP(I)=CPD2(I)
   GO TO 555
C
222 IF(CC3.GT.CC4)GO TO 333
   DO 5 I=1,NFORK
5 YK(I)=AKD3(I)
   DO 6 I=1,NFORCP
6 YCP(I)=CPD3(I)
   GO TO 555
C
333 IF(CC4.GT.CC5)GO TO 444
   DO 7 I=1,NFORK
7 YK(I)=AKD4(I)
   DO 8 I=1,NFORCP
8 YCP(I)=CPD4(I)
   GO TO 555
C
444 DO 9 I=1,NFORK
9 YK(I)=AKD5(I)
   DO 10 I=1,NFORCP
10 YCP(I)=CPD5(I)
C
555 WRITE(6,11)
11 FORMAT(//,'TEMP',3X,'TH.CONDC',3X,'COMPUTED',
         13X,'%ERROR',3X,'COEFFICIENTS OF',7X,'ORDER OF')
   WRITE(6,12)
12 FORMAT(  
1'(',C'),2X,  ',3X,'TH.COND',12X,
1'POLYNOMIAL',11X,'THE POLYNOMIAL'
1'/,'-----',3X,'-----',3X,'-----',3X,
1'-----',3X,'-----',8X,'-----',/)
C
   CALL CURFIT(NFORK,TFORK,YK,PK,KK,ORDERK)
C
   WRITE(6,13)
13 FORMAT(//,'TEMP',3X,'SP.HEAT ',3X,'COMPUTED',
         13X,'%ERROR',3X,'COEFFICIENTS OF',7X,'ORDER OF')
   WRITE(6,14)
14 FORMAT(  
1'(',C'),2X,  ',3X,'SP.HEAT',12X,
1'POLYNOMIAL',11X,'THE POLYNOMIAL'
1'/,'-----',3X,'-----',3X,'-----',3X,
1'-----',3X,'-----',8X,'-----',/)
C
   CALL CURFIT(NFORCP,TFORCP,YCP,PCP,KCP,OEDERC)
TEMPERATURES & THERMO-PHYSICAL PROPERTIES ARE INITIATED

DO 800 N=1,NTOTAL
DO 700 M=1,MTOTAL
L=0
TT(N,M)=TPOUR
TS(N,M)=TPOUR
SOLID(N,M)=0.0D0
FS(N,M)=0.0D0
AK(N,M)=7*(AKSOL(TPOUR))
CP(N,M)=CPSOL(TPOUR)
ROW(N,M)=ROWL
700 CONTINUE
800 CONTINUE

RETURN
END

SUBROUTINE WRITE PRINTS PERTINENT INFORMATION IN FILE 6

SUBROUTINE INPUT

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C2 / DZ(75)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C7 / N1,N2,M1,M2,Z1,Z2,X1,X2,N10,N12,M10,M12
COMMON /C8 / ROWS,ROWL
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FHORIZ,TAMB
COMMON /C14/ NTOTAL,MTOTAL,NX
COMMON /C21/ FS(75,100),FRACTN,NREPET

WRITE(6,500)CARBON
500 FORMAT(5X,'HEAT FLOW MODEL TEMPERATURE PREDICTIONS'
-'/,5X,'FOR SOLIDIFICATION OF A PURE IRON-C ALLOY'
-'/,5X,'WEIGHT % OF CARBON IN THE STEEL : ',F6.3
-'/,4X,'------------------------------------------'
-'/,4X,'------------------------------------------'
-'/,4X,'------------------------------------------'
-'/,4X,'------------------------------------------'

WRITE(6,502)TLIQID,TSOLID
502 FORMAT(5X,'MODEL PARAMETERS : LIQUIDUS TEMP. : '
-'/,F5.0,4X
-'/,5X,'DEG C' ,'/,5X,'SOLIDUS TEMP : '
-'/,F5.0,4X,'DEG C'

WRITE(6,503)SUHEAT
503 FORMAT(25X,'SUPERHEAT : ',F5.0,4X,'DEG C'

WRITE(6,504)TPOUR
504 FORMAT(25X,'POURING TEMP. : ',F5.0,4X,'DEG C'

WRITE(6,505)TAMB
505 FORMAT(25X,'AMBIENT TEMP : ',F5.0,4X,'DEG C')
WRITE(6,506)QMOLD
506 FORMAT(23X,'MOLD HEAT FLUX :',F8.2,1X
1,'CAL/SEC*SQ.CM')
WRITE(6,508)FRACTN
508 FORMAT(18X,'RIGIDITY CRITERION IS >',F3.1,1X
1,'FRACTION OF SOLID')
WRITE(6,511)HEAT
511 FORMAT(10X,'LATENT HEAT OF SOLIDIFICATION :',F10.5,4X
1,'CAL/GM',/)
WRITE(6,512)N1,N2
512 FORMAT(/,5X,'DEFINITION OF THE CONTINUUM : N1: ',I4,/
-5X,'----------------------: N2: ',I4)
WRITE(6,513)M1,M2,Z1,Z2,X1,X2
513 FORMAT(38X,'M1: ',I4,/,38X
1,'M2: ',I4,/
1,38X,'Z1: ',F6.4,/,38X,'Z2: ',F6.4,/,38X,'X1: ',F6.4,/,38X
1,'X2: ',F6.4,/) WRITE(6,514)DX
514 FORMAT(38X,'DX: ',F10.7)
DO 516 N=1,N1
WRITE(6,515)N,DZ(N)
515 FORMAT(34X,'DZ(',I4,'):',F10.7)
516 CONTINUE
C
WRITE(6,517)
517 FORMAT(/,5X,'TIME STEPS EMPLOYED IN THE PROGRAM :',/
-5X,'---------------------:')
WRITE(6,518)DT
518 FORMAT(31X,'TIME STEP:',F10.8)
WRITE(6,519)END
519 FORMAT(19X,'TOTAL SIMULATION TIME:',F10.8,/) C
WRITE(6,520)FSLANT,FHORIZ
520 FORMAT(9X,'VIEW FACTOR FOR INCLINED NODES :',F5.3,/
1,7X,'VIEW FACTOR FOR HORIZONTAL NODES :',F5.3,///
1,'DETAILS OF THE POLYNOMIALS FITTED TO THE THERMAL
1CONDUCTIVITY'
1,/,8X,'AND SPECIFIC HEAT DATA OBTAINED FROM LITERATURE',/
1,'-----------------------------------------------' C
RETURN END
C SUBROUTINE SOLVE ACTUALLY DEVELOPS COEFFICIENT ARRAYS FOR THE
C THE GRID AND CALLS TRIDAG TO SOLVE THEM
C
C SUBROUTINE SOLVE(*,*)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C1/ TT(75,100),TS(75,100)
**C**

C******* COMPUTE TEMPERATURES OVER THE FIRST HALF TIME STEP

C******* IMPLICIT IN THE Z-DIRECTION

C

DO 200 N=1,NTOTAL
   DO 300 M=1,MTOTAL
      CALL FIND(N,M,1)
   300 CONTINUE
200 CONTINUE
   CALL TRIDAG(1,L)
   L0=1
   DO 400 N=1,NTOTAL
      DO 402 M=1,MTOTAL
         IF(TS(N,M).EQ.0.0D0) GO TO 401
         TT(N,M)=TPRIME(L0)
         L0=L0+1
         GO TO 402
      401 TT(N,M)=0.0D0
   402 CONTINUE
400 CONTINUE

C

WRITE(10,89)
89 FORMAT(//,'AFTER THE FIRST HALF TIME STEP')

C

WRITE(10,101)TIME
101 FORMAT(1H0,10H TIME =,F10.7)
   WRITE(10,102)
102 FORMAT(1H0,5H T-1 ,5H T-2 ,5H T-3 ,5H T-4 ,5H T-5
A,5H T-6,5H T-7
A,5H T-8 ,5H T-9 ,5H T-10,5H T-11,5H T-12,5H T-13
A,5H T-14,5H T-15
A H T-16,5H T-17,5H T-18,5H T-19,5H T-20,5H T-21
A,5H T-22,5H T-23)

C

DO 104 N=1,NTOTAL
   WRITE(10,103) (TT(N,J),J=1,NX)
103 FORMAT(23F5.0)
104 CONTINUE

C

WRITE(10,105)
105 FORMAT(1H0,5H F-1 ,5H F-2 ,5H F-3 ,5H F-4 ,5H F-5
A,5H F-6 ,5H F-7
A,5H F-8, 5H F-9, 5H F-10, 5H F-11, 5H F-12, 5H F-13
A,5H F-14, 5H F-15, 5
A, 5H F-16, 5H F-17, 5H F-18, 5H F-19, 5H F-20, 5H F-21
A, 5H F-22, 5H F-23)
C
DO 107 N=1, NTOTAL
WRITE (10, 106) (FS(N,J), J=1,NX)
106 FORMAT (23F5.3)
107 CONTINUE
C
L=0
C
C****** Compute temperatures at the end of a whole time step
C****** Implicit in x-direction
C
DO 700 M=1, MTOTAL
DO 500 N=1, NTOTAL
CALL FIND(N,M,0)
500 CONTINUE
700 CONTINUE
CALL TRIDAG(1,L)
L1 = 1
DO 600 M=1, MTOTAL
DO 602 N=1, NTOTAL
IF(TT(N,M).EQ.0.0D0) GO TO 601
TS(N,M) = TPRIME(L1)
L1 = L1 + 1
GO TO 602
601 TS(N,M) = 0.0D0
602 CONTINUE
600 CONTINUE
L=0
WRITE (10, 79)
79 FORMAT (/,'AFTER THE WHOLE TIME STEP')
WRITE (10, 101) TIME
WRITE (10, 102)
C
DO 201 N=1, NTOTAL
WRITE (10, 103) (TS(N,J), J=1,NX)
201 CONTINUE
C
WRITE (10, 105)
C
DO 202 N=1, NTOTAL
WRITE (10, 106) (FS(N,J), J=1,NX)
202 CONTINUE
C
C****** Reset all thermo physical properties for each node
C
DO 222 M=1, MTOTAL
DO 222 N=1, NTOTAL
CALL CHECK(N,M,TS(N,M))
C SUBROUTINE CHECK GIVES THE RIGHT THERMO-PHYSICAL PROPERTIES
C AS PER THEIR TEMPERATURES

SUBROUTINE CHECK(N,M,TNODE)

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C3 / AK(75,100),CP(75,100),ROW(75,100)
COMMON /C8 / ROWS,ROWL
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C21/ FS(75,100),FRACTN,NREPET

IF(TNODE.GT.0.0D0) GO TO 10
RETURN

10 CONTINUE

IF(TNODE.LT.TLIQID)GO TO 1
CP(N,M)=CPSOL(TNODE)
ROW(N,M)=ROWL
AK(N,M)=7*(AKSOL(TNODE))
GO TO 3

1 IF(TNODE.LT.TSOLID)GO TO 2
CP(N,M)=CPSOL(TNODE)
ROW(N,M)=ROWS+ROWL)/2.0D0
AK(N,M)=((1+(6*((1-0.5*FS(N,M))**2)))*AKSOL(TNODE)
GO TO 3

2 CP(N,M)=CPSOL(TNODE)
ROW(N,M)=ROWS
AK(N,M)=AKSOL(TNODE)

3 RETURN
END

C SUBROUTINE OUTPUT PrinterS OUT TIME TEMPERATURES IN FILE 6 OR 7
C AS DESIRED

SUBROUTINE OUTPUT(KFILE)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C1/ TT(75,100),TS(75,100)
COMMON /C2/ D2(75)
COMMON /C5/ DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9/ MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C14/ NTOTAL,MTOTAL,NX
COMMON /C20/ SHELLF(75),XMINSC(75),DIST(75)
COMMON /C21/ FS(75,100),FRACTN,NREPET
WRITE(KFILE,100)TIME
100 FORMAT(1HO,10H TIME = ,F10.7)
WRITE(KFILE,1000)
1000 FORMAT(1HO,5H T-1 ,5H T-2 ,5H T-3 ,5H T-4
A,5H T-5 ,5H T-6 ,5H T-7
A,5H T-8 ,5H T-9 ,5H T-10,5H T-11,5H T-12
A,5H T-13,5H T-14,5H T-15,5
AH T-16,5H T-17,5H T-18,5H T-19,5H T-20
A,5H T-21,5H T-22,5H T-23)
C
DO 200 N=1,NTOTAL
WRITE(KFILE,2000) (TS(N,J),J=1,NX)
2000 FORMAT(23F5.0)
200 CONTINUE
C
WRITE(KFILE,3000)
3000 FORMAT(1HO,5H F-1 ,5H F-2 ,5H F-3 ,5H F-4
A,5H F-5 ,5H F-6 ,5H F-7
A,5H F-8 ,5H F-9 ,5H F-10,5H F-11,5H F-12
A,5H F-13,5H F-14,5H F-15,5
AH F-16,5H F-17,5H F-18,5H F-19,5H F-20
A,5H F-21,5H F-22,5H F-23)
C
DO 300 N=1,NTOTAL
WRITE(KFILE,4000) (FS(N,J),J=1,NX)
4000 FORMAT(23F5.3)
300 CONTINUE
C
RETURN
END
C
SUBROUTINE FIND DESIGNATES THE TYPE OF NODE AND FORMULATES THE
C COEFFICIENT ARRAYS NEEDED FOR TRIDAG MATRIX
C-----------------------------------------------
C
SUBROUTINE FIND(N,M,KSTEP)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C1/ TT(75,100),TS(75,100)
COMMON /C2/ D2(75)
COMMON /C3/ AK(75,100),CP(75,100),ROW(75,100)
COMMON /C5/ DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C7/ N1,N2,M1,M2,Z1,Z2,X1,X2,N10,N12,M10,M12
COMMON /C9/ MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FLORIZ,TAMB
COMMON /C14/ NTOTAL,MTOTAL,NX

****** TO FIND THE TYPE OF NODE

IF(N-1)1,1,100

1 IF(M-M10) 1000,1000,2
2 IF(M-M12) 1100,1200,3
3 IF(M-MTOTAL) 1300,1400,1400

100 IF(N-N10)10,200,300

10 MC1=M1-N
MC2=MC1+2
11 IF(M-1) 1000,1000,11
12 IF(M-MC1) 1000,1000,12

12 IF(N.GT.2)GO TO 15

13 IF(M-MC2)1500,1600,13
14 IF(M-MTOTAL)1700,1800,1800

15 CONTINUE

16 IF(M-MTOTAL) 2000,2100,2100

200 CONTINUE

21 IF(M-MTOTAL) 2100,2100,2100

22 IF(M-MTOTAL) 2200,2300,32

300 IF(N-N12)31,400,500

31 IF(M-2) 2200,2300,32
32 IF(M-MTOTAL) 2000,2100,2100

400 CONTINUE

41 IF(M-2) 2400,2500,41

500 IF(N-NTOTAL) 51,600,600

51 IF(M-2) 2600,2500,52
52 IF(M-MTOTAL) 2000,2100,2100

600 CONTINUE

61 IF(M-MTOTAL) 2900,3000,3000

****** TO CALCULATE THE MATRIX DIAGNOLS FOR THE NODE
C
1000 IF(KSTEP.EQ.1) GO TO 1001
   CALL DUMMY(TT(N,M),0,δ99)
1001 CALL DUMMY(TS(N,M),1,δ99)
C
1100 IF(KSTEP.EQ.1) GO TO 1101
   CALL TOPTRI(TT(N,M),TT(N,M+1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N+1,M),AK(N,M+1),DZ(N),0,δ99,N,M
1101 CALL TOPTRI(TS(N,M),TS(N+1,M),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N+1,M),AK(N,M+1),DZ(N),1,δ99,N,M
C
1200 IF(KSTEP.EQ.1) GO TO 1201
   CALL TBONE(TT(N,M),TT(N,M+1),TT(N,M-1),ROW(N,M)
   1,CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N,M-1),AK(N+1,M),DZ(N),0,δ99,N,M
1201 CALL TBONE(TS(N,M),TS(N+1,M),TS(N+1,M)
   1,ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N,M-1),AK(N+1,M),DZ(N),1,δ99,N,M
C
1300 IF(KSTEP.EQ.1) GO TO 1301
   CALL TB(TT(N,M),TT(N,M+1),TT(N,M-1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N,M-1),AK(N+1,M),DZ(N),0,δ99,N,M
1301 CALL TB(TS(N,M),TS(N+1,M),TS(N+1,M)
   1,ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N,M-1),AK(N+1,M),DZ(N),1,δ99,N,M
C
1400 IF(KSTEP.EQ.1) GO TO 1401
   CALL TLCORN(TT(N,M),TT(N,M-1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N+1,M),AK(N,M-1),DZ(N),0,δ99,N,M
1401 CALL TLCORN(TS(N,M),TS(N+1,M),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N+1,M),AK(N,M-1),DZ(N),1,δ99,N,M
C
1500 IF(KSTEP.EQ.1) GO TO 1501
   CALL TRIANG(TT(N,M),TT(N,M+1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N+1,M),DZ(N),0,δ99,N,M
1501 CALL TRIANG(TS(N,M),TS(N+1,M),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N,M+1),AK(N+1,M),DZ(N),1,δ99,N,M
C
1600 IF(KSTEP.EQ.1) GO TO 1601
   CALL INONE(TT(N,M),TT(N,M+1),TT(N,M-1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N-1,M),AK(N+1,M),AK(N,M+1),AK(N,M-1)
   1,DZ(N-1),DZ(N),0,δ99,N,M
1601 CALL INONE(TS(N,M),TS(N+1,M),TS(N-1,M)
   1,ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N-1,M),AK(N+1,M),AK(N,M+1),AK(N,M-1)
   1,DZ(N-1),DZ(N),1,δ99,N,M
C
1700 IF(KSTEP.EQ.1) GO TO 1701
   CALL INTO(TT(N,M),TT(N,M+1),TT(N,M-1),ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N-1,M),AK(N+1,M),AK(N,M+1),AK(N,M-1)
   1,DZ(N-1),DZ(N),0,δ99,N,M
1701 CALL INTO(TS(N,M),TS(N+1,M),TS(N-1,M)
   1,ROW(N,M),CP(N,M)
   1,AK(N,M),AK(N-1,M),AK(N+1,M),AK(N,M+1),AK(N,M-1)
1, DZ(N-1), DZ(N), 1, δ99, N, M)
C
1800 IF(KSTEP.EQ.1) GO TO 1801
CALL RBONE(TT(N,M), TT(N,M-1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M-1), DZ(N-1), DZ(N), 0, δ99,
1801 CALL RBONE(TS(N,M), TS(N-1,M), TS(N+1,M)
1, ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M-1), DZ(N-1), DZ(N), 1, δ99,
C
1900 IF(KSTEP.EQ.1) GO TO 1901
CALL INNEXT(TT(N,M), TT(N,M+1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N+1,M), AK(N-1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 0, δ99, DZ(N-2), N, M)
1901 CALL INNEXT(TS(N,M), TS(N-1,M), TS(N+1,M)
1, ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 1, 599, DZ(N-2), N, M)
C
2000 IF(KSTEP.EQ.1) GO TO 2001
CALL IN(TT(N,M), TT(N,M+1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 0, δ99, N, M)
2001 CALL IN(TS(N,M), TS(N+1,M), TS(N-1,M)
1, ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 1, δ99, N, M)
C
2100 IF(KSTEP.EQ.1) GO TO 2101
CALL RB(TT(N,M), TT(N,M-1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N+1,M), AK(N-1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 0, δ99, N, M)
2101 CALL RB(TS(N,M), TS(N+1,M), TS(N-1,M)
1, ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 1, δ99, N, M)
C
2200 IF(KSTEP.EQ.1) GO TO 2201
CALL BOTTRI(TT(N,M), TT(N,M+1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N+1,M), AK(N-1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 0, δ99, N, M)
2201 CALL BOTTRI(TS(N,M), TS(N+1,M), TS(N-1,M), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N+1,M), AK(N,M+1), DZ(N-1), DZ(N), 1, δ99, N, M)
C
2300 IF(KSTEP.EQ.1) GO TO 2301
CALL INBOT(TT(N,M), TT(N,M+1), TT(N,M-1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 0, δ99, DZ(N-2), N, M)
2301 CALL INBOT(TS(N,M), TS(N+1,M), TS(N-1,M)
1, ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), AK(N,M-1)
1, DZ(N-1), DZ(N), 1, δ99, DZ(N-2), N, M)
C
2400 IF(KSTEP.EQ.1) GO TO 2401
CALL LBONE(TT(N,M), TT(N,M+1), TT(N,M+1), ROW(N,M), CP(N,M)
1, AK(N,M), AK(N-1,M), AK(N+1,M), AK(N,M+1), DZ(N-1), DZ(N), 0
1, δ99, DZ(N-2), N, M)
2401 CALL LBONE(TS(N,M), TS(N+1,M), TS(N-1,M), ROW(N,M), CP(N,M)
C SUBROUTINE TRIDAG SOLVES THE SYSTEM OF LINEAR SIMULTANEOUS EQUATIONS HAVING A TRIDIAGONAL COEFFICIENT MATRIX. THE EQUATIONS ARE NUMBERED FROM 'NFIRST' THROUGH 'NLAST' AND THEIR SUBDIAGONAL, MAIN DIAGONAL AND SUPERDIAGONAL COEFFICIENTS ARE STORED IN ARRAYS 'DBOT', 'D' AND 'DTOP'. THE COMPUTED SOLUTION VECTOR
SUBROUTINE TRIDAG(NFIRST,NLAST)
   IMPLICIT REAL*8 (A-H,0-Z)
   COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
   COMMON /C6 / BETA(7600),GAMMA(7600),TPRIME(7600)
   
   C******** COMPUTE INTERMEDIATE ARRAYS BETA AND GAMMA
   BETA(NFIRST)=DMID(NFIRST)
   GAMMA(NFIRST)=R(NFIRST)/BETA(NFIRST)
   NEXT=NFIRST+1
   DO 100 I=NEXT,NLAST
      BETA(I)=DMID(I)-DBOT(I)*DTOP(I-1)/BETA(I-1)
      GAMMA(I)=(R(I)-DBOT(I)*GAMMA(I-1))/BETA(I)
   100 CONTINUE
   
   C******** COMPUTE FINAL SOLUTION VECTOR
   TPRIME(NLAST)=GAMMA(NLAST)
   LAST=NLAST-NFIRST
   DO 200 K=1,LAST
      J=NLAST-K
      TPRIME(J)=GAMMA(J)-DTOP(J)*TPRIME(J+1)/BETA(J)
   200 CONTINUE
   
   RETURN
END

SUBROUTINE DUMMY(T,KSTEP,*)
   IMPLICIT REAL*8 (A-H,0-Z)
   COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
   COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
   IF(KSTEP.EQ.1)GO TO 100
   C******************* FIRST HALF TIME STEP
   T=0.0D0
   GO TO 200
   
   C******************* NEXT HALF TIME STEP
   100 T=0.0D0
   
   200 RETURN

END

SUBROUTINE IN(T,TLATER,TBEFOR,ROW,CP1,AK,AKTOP,AKBOT,AKRIG,AKLEF,DZ0,DZ1,KSTEP,*,N,M)
   IMPLICIT REAL*8 (A-H,0-Z)
   COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
   COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD

L=L+1
VOL=DX*((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=DX*(AK+AKTOP)/(2*DZ0)
C=DX*(AK+AKBOT)/(2*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(DZ0+DZ1)*(AK+AKLEF)/(4*DX)

IF(KSTEP.EQ.1)GO TO 100
****** FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)

GO TO 200
****** NEXT HALF TIME STEP
100 DMID(L)=A+D+E
DTOP(L)=-D
DBOT(L)=-E
R(L)=(T*(A-B-C))+(C*TLATER)+(B*TBEFOR)

200 RETURN

END

SUBROUTINE INONE(T,TLATER,TBEFOR,ROW,CP
1,AK,AKTOP,AKBOT,AKRIG,AKLEF,DZ0,DZ1,KSTEP,*,N,M)

IMPLICIT REAL*8 (A-H,0-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD

L=L+1
VOL=DX*((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=(3*DX*(AK+AKTOP))/(5*DZ0)
C=DX*(AK+AKBOT)/(2*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(3*(DZ0+DZ1)*(AK+AKLEF))/(10*DX)

IF(KSTEP.EQ.1)GO TO 100
****** FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)

GO TO 200
****** NEXT HALF TIME STEP
SUBROUTINE INNEXT(T, TLATER, TBEFOR, ROW, CP, AK, AKTOP, AKBOT, AKRIG, AKLEF, DZ0, DZ1, KSTEP, *, DZT, N, M)

IMPLICIT REAL*8 (A-H, O-Z)
COMMON /C5 / DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9 / MTIMES, NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD

L=L+1
VOL=DX*(((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T, KSTEP, VOL, A, N, M)
B=(3*DX*(AK+AKTOP))/(DZT+(4*DZ0))
C=DX*(AK+AKBOT)/(2*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(3*(DZ0+DZ1)*(AK+AKLEF))/(10*DX)

IF(KSTEP.EQ.1)GO TO 100
C************************ FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)
C
GO TO 200
C************************ NEXT HALF TIME STEP
100 DMID(L)=A+D+E
DTOP(L)=-D
DBOT(L)=-E
R(L)=(T*(A-B-C))+(C*TLATER)+(B*TBEFOR)

200 RETURN 1
END

SUBROUTINE INTOP(T, TLATER, TBEFOR, ROW, CP, AK, AKTOP, AKBOT, AKRIG, AKLEF, DZ0, DZ1, KSTEP, *, N, M)

IMPLICIT REAL*8 (A-H, O-Z)
COMMON /C5 / DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9 / MTIMES, NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD

L=L+1
VOL=DX*(((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=(2*DX*(AK+AKTOP))/(3*DZ0)
C=DX*(AK+AKBOT)/(2*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(DZ0+DZ1)*(AK+AKLEF)/(4*DX)

C
IF(KSTEP.EQ.1)GO TO 100
C************************** FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)
C
GO TO 200
C************************** NEXT HALF TIME STEP
100 DMID(L)=A+D+E
DTOP(L)=-D
DBOT(L)=-E
R(L)=(T*(A-B-C))+(C*TLATER)+(B*TBEFOR)
200 RETURN 1
END

C
SUBROUTINE INBOT(T,TLATER,TBEFOR,ROW,CP
1,AK,AKTOP,AKBOT,AKRIG,AKLEF,DZ0,DZ1,KSTEP,*,DZT,N,M)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
C
L=L+1
VOL=DX*((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=(3*DX*(AK+AKTOP))/(4*(DZ0+DZT))
C=DX*(AK+AKBOT)/(2*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(6*(DZ0+DZ1)*(AK+AKLEF))/(17*DX)
C
IF(KSTEP.EQ.1)GO TO 100
C************************** FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)
C
GO TO 200
C************************** NEXT HALF TIME STEP
100 DMID(L)=A+D+E
DTOP(L)=-D
DBOT(L)=-E
R(L)=(T*(A-B-C))+(C*TLATER)+(B*TBEFOR)
200 RETURN 1
END
SUBROUTINE INLEF(T,TLATER,TBEFOR,ROW,CP,1,AK,AKTOP,AKBOT,AKRIG,AKLEF,DZ0,DZ1,KSTEP,*,N,M)

IMPLICIT REAL*8 (A-H,O-Z)

COMMON /C5/ DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9/ MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD

L=L+1
VOL=DX*((DZ0+DZ1)/2)
A=ROW*CP*VOL/(DZ0)
B=DX*(AK+AKTOP)/(2*DZ0)
C=(DX*(AK+AKBOT))/(2*DZ0)
D=(DZ0+DZ1)*(AK+AKRIG)/(4*DX)
E=(DZ0+DZ1)*(AK+AKLEF)/(3*DX)

IF(KSTEP.EQ.1)GO TO 100

FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D-E))+(D*TLATER)+(E*TBEFOR)

GO TO 200

NEXT HALF TIME STEP
DMID(L)=A+D+E
DTOP(L)=-D
DBOT(L)=-E
R(L)=(T*(A-B-C))+(C*TLATER)+(B*TBEFOR)

RETURN

SUBROUTINE TRIANG(T,TLATER,ROW,CP,1,AK,AKRIG,AKBOT,DZ0,DZ1,KSTEP,*,N,M)

IMPLICIT REAL*8 (A-H,O-Z)

COMMON /C5/ DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9/ MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FHORIZ,TAMB

L=L+1
VOL=DX*(DZ0+DZ1)/4.0D0
A=ROW*CP*VOL/(DT/2.0D0)
AREA=DSQRT(((DZ0+DZ1)/2)**2+DX**2)
HC=(2/(10.0D0**4))*((T-TAMB)**(1/4))
HR=(1.335D0/(10.0D0**12))*FSLANT*(((T+273)**4)-((TAMB+273)**4))

RATIO=((DZ0+DZ1)/(2*DX))*0.017453D0
THETA=DATAN(RATIO)
\begin{verbatim}
B = -H*AREA*(DCOS(THETA))
C = (3*DX*(AK+AKBOT))/(DZ0+(4*DZ1))
D = (5*(DZ0+DZ1)*(AK+AKRIG))/(24*DX)
E = -H*AREA*(DSIN(THETA))

IF(KSTEP.EQ.1)GO TO 100
C************************** FIRST HALF TIME STEP
DMID(L) = A-B+C
DTOP(L) = -C
DBOT(L) = 0.0D0
R(L) = (T*(A+E-D))+(D*TLATER)-(TAMB*(B+E))
GO TO 200
C*************************** NEXT HALF TIME STEP
100 DMID(L) = A-E+D
DTOP(L) = -D
DBOT(L) = 0.0D0
R(L) = (T*(A-C+B))+(C*TLATER)-(TAMB*(B+E))
200 RETURN
1
END

SUBROUTINE TOPTRI(T,TOTHER,ROW,CP
1,AK,AKBOT,AKRIG,DZ1,KSTEP,*N,M)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FHORIZ,TAMB
C
VOL=DX*DZ1*3/8
A = ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
AREA=DSQRT(((DX/2)**2)+((DZ1/2)**2))
HC = (2/(10.0D0**4))*((T-TAMB)**(1/4))
HR = (1.335D0/(10.0D0**12))*FSLANT*(((T+273)**4)-((TAMB+273)**4))
1/(T-TAMB)
H = HR+HC
RATIO = (DZ1/DX)*0.017453D0
THETA = DATAN(RATIO)
B = -H*((AREA*(DCOS(THETA)))+(DX/2))
C = -H*AREA*(DSIN(THETA))
D = (6*DZ1*(AK+AKRIG))/(23*DX)
E = (12*DX*(AK+AKBOT))/(17*DZ1)

IF(KSTEP.EQ.1)GO TO 100
C************************** FIRST HALF TIME STEP
L = L+1
DMID(L) = A-B+E
DTOP(L) = -E
DBOT(L) = 0.0D0
R(L) = (T*(A+C-D))+(D*TLATER)-(TAMB*(B+C))
\end{verbatim}
GO TO 200

C****************************** NEXT HALF TIME STEP

100 L=L+1
    DMID(L)=A-C+D
    DTOP(L)=-D
    DBOT(L)=0.0D0
    R(L)=(T*(A+B-E))+(E*TOTHER)-(TAMB*(B+C))

200 RETURN

END

C

SUBROUTINE BOTTRI(T,TOTHER,ROW,CP
1,AK,AKBOT,AKRIG,DZ0,DZ1,KSTEP,*,N,M)

C

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
COMMON /C13/ FSLANT,FHORIZ,TAMB

C

VOL=DX*(DZ0+(2*DZ1))/8.0D0
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
AREA=DSQRT(((DX/2)**2)+((DZ0/2)**2))
HC=(2/(10.0D0**4))*(T-TAMB)**(1/4)
HR=(1.335D0/(10.0D0**12))*FSLANT*((T+273)**4)-((TAMB+273)**
1/(T-TAMB)
H=HR+HC
RATIO=(DZ0/DX)*0.017453D0
THETA=DATAN(RATIO)
    B=-H*AREA*(DCOS(THETA))
    C=-H*AREA*(DSIN(THETA))
    D=-(QMOLD*DZ1)/2
    E=(6*DX*(AK+AKBOT))/((21*DZ1)+(2*DZ0))
    F=(6*(DZ0+DZ1)*(AK+AKRIG))/(17*DX)

C

IF(KSTEP.EQ.1)GO TO 100
C****************************** FIRST HALF TIME STEP

L=L+1
    DMID(L)=A-B+E
    DTOP(L)=-E
    DBOT(L)=0.0D0
    R(L)=(T*(A+C-F))+(F*TOTHER)-(TAMB*(B+C))+D

C

GO TO 200

C****************************** NEXT HALF TIME STEP

100 L=L+1
    DMID(L)=A-C+F
    DTOP(L)=-F
    DBOT(L)=0.0D0
    R(L)=(T*(A+B-E))+(E*TOTHER)-(TAMB*(B+C))+D

200 RETURN

C

END
SUBROUTINE TB(T, TLATER, TBEFORE, ROW, CP,  
1, AK, AKRIG, AKLEF, AKBOT, DZ1, KSTEP, *, N, M)

IMPLICIT REAL*8 (A-H, O-Z)

COMMON /C5/ DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9/ MTIMES, NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
COMMON /C13/ FSLANT, FHORIZ, TAMB

L = L + 1

VOL = DX * DZ1 / 2.0D0
   A = ROW * CP * VOL / (DT / 2.0D0)
   CALL ESTMAT(T, KSTEP, VOL, A, N, M)

AREA = DX

HC = (2 / (10.0D0 ** 4)) * ((T - TAM) ** (0.25D0))
HR = (1.335D0 / (10.0D0 ** 12)) * FHORIZ * (((T + 273) ** 4) - (T - TAM)) ** (-1 / (T - TAM))
H = HC + HR

B = -H * AREA
C = (2 * DX * (AK + AKBOT)) / (3 * DZ1)
D = DZ1 * (AK + AKRIG) / (4 * DX)
E = DZ1 * (AK + AKLEF) / (4 * DX)

IF (KSTEP .EQ. 1) GO TO 100

C*************** FIRST HALF TIME STEP
DMID(L) = A - B + C
DTOP(L) = -C
DBOT(L) = 0.0D0
R(L) = (T * (A - D - E)) + (D * TLATE) + (E * TBEFORE) - (B * TAM)

GO TO 200

C*************** NEXT HALF TIME STEP

100 DMID(L) = A - B + D + E
DTOP(L) = -D
DBOT(L) = -E
R(L) = (T * (A - C)) + (C * TLATE) - (B * TAM)

200 RETURN

1

END

SUBROUTINE TBONE(T, TLATER, TBEFORE, ROW, CP,  
1, AK, AKRIG, AKLEF, AKBOT, DZ1, KSTEP, *, N, M)

IMPLICIT REAL*8 (A-H, O-Z)

COMMON /C5/ DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9/ MTIMES, NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
COMMON /C13/ FSLANT, FHORIZ, TAMB

L = L + 1

VOL = DX * DZ1 / 2.0D0
   A = ROW * CP * VOL / (DT / 2.0D0)
   CALL ESTMAT(T, KSTEP, VOL, A, N, M)

AREA = DX
HC = (2 / (10.0D0 ** 4)) * ((T - TAMB) ** (0.25D0))
HR = (1.335D0 / (10.0D0 ** 12)) * FHORIZ * (((T + 273) ** 4) - ((TAMB + 273) ** 4)) / (T - TAMB)
H = HC + HR
B = -H * AREA
C = (2 * DX * (AK + AKBOT)) / (3 * DZ1)
D = DZ1 * (AK + AKRIG) / (4 * DX)
E = (6 * DZ1 * (AK + AKLEF)) / (23 * DX)

IF(KSTEP.EQ.1) GO TO 100
C*********************************************************************** FIRST HALF TIME STEP
DMID(L) = A - B + C
DTOP(L) = - C
DBOT(L) = 0.0D0
R(L) = (T * (A - D - E)) + (C * TLATER) + (E * TBEFOR) - (B * TAMB)
C
GO TO 200
C*********************************************************************** NEXT HALF TIME STEP
100 DMID(L) = A + B + D + E
DTOP(L) = - D
DBOT(L) = - E
R(L) = (T * (A - C)) + (C * TLATER) - (B * TAMB)
200 RETURN 1
END
C
SUBROUTINE RB(T, TBEFOR, TLATER, ROW, CP, 1, AK, AKTOP, AKBOT, AKLEF, DZ0, DZ1, KSTEP, *, N, M)
C******************************************************************************************
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9 / MTIMES, NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
C
L = L + 1
VOL = DX * (DZ0 + DZ1) / 4.0D0
A = ROW * CP * VOL / (DT / 2.0D0)
CALL ESTMAT(T, KSTEP, VOL, A, N, M)
B = DX * (AK + AKTOP) / (4 * DZ0)
C = DX * (AK + AKBOT) / (4 * DZ1)
D = (DZ0 + DZ1) * (AK + AKLEF) / (4 * DX)
C
IF(KSTEP.EQ.1) GO TO 100
C*********************************************************************** FIRST HALF TIME STEP
DMID(L) = A + B + C
DTOP(L) = - C
DBOT(L) = - B
R(L) = (T * (A - D)) + (D * TBEFOR)
C
GO TO 200
C*********************************************************************** NEXT HALF TIME STEP
100 DMID(L) = A + D
DTOP(L) = 0.0D0
DBOT(L) = - D
R(L) = (T * (A - B - C)) + (B * TBEFOR) + (C * TLATER)
SUBROUTINE RBONE(T,TBEFOR,TLATER,ROW,CP
1,AK,AKTOP,AKBOT,AKLEF,DZ0,DZ1,KSTEP,*,N,M)

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD

L=L+1
VOL=DX*(DZ0+DZ1)/4.0D0
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=DX*(AK+AKTOP)/(3*DZ0)
C=DX*(AK+AKBOT)/(4*DZ1)
D=(DZ0+DZ1)*(AK+AKLEF)/(4*DX)

IF(KSTEP.EQ.1)GO TO 100

C******************* FIRST HALF TIME STEP
DMID(L)=A+B+C
DTOP(L)=-C
DBOT(L)=-B
R(L)=(T*(A-D))+(D*TBEFOR)

GO TO 200

C****************** NEXT HALF TIME STEP
100 DMID(L)=A+D
DTOP(L)=0.0D0
DBOT(L)=-D
R(L)=(T*(A-B-C))+(B*TBEFOR)+(C*TLATER)

200 RETURN 1
END

SUBROUTINE LB(T,TLATER,TBEFOR,ROW,CP
1,AK,AKTOP,AKBOT,AKRIG,DZ0,DZ1,KSTEP,*,N,M)

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
L=L+1
VOL=DX*(DZ0+DZ1)/4.0D0
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=DX*(AK+AKTOP)/(4*DZ0)
C=DX*(AK+AKBOT)/(4*DZ1)
D=(DZ0+DZ1)*(AK+AKRIG)/(3*DX)
E=-(QMOLD*(DZ0+DZ1))/2

IF(KSTEP.EQ.1)GO TO 100

C******************* FIRST HALF TIME STEP
DMID(L) = A + B + C
DTOP(L) = -C
DBOT(L) = -B
R(L) = (T * (A - D)) + (D * TLATER) + E

GO TO 200

C*............................. NEXT HALF TIME STEP

100 DMID(L) = A + D
    DTOP(L) = -D
    DBOT(L) = 0.0D0
    R(L) = (T * (A - B - C)) + (B * TBEFOR) + (C * TLATER) + E

200 RETURN 1

C

C************************* NEXT HALF TIME STEP

C************************* FIRST HALF TIME STEP

C************************* NEXT HALF TIME STEP
C
L=L+1
VOL=DX*DZ0/2.0D0
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=DX*(AK+AKTOP)/(2*DZ0)
C=DZ0*(AK+AKRIG)/(4*DX)
D=DZ0*(AK+AKLEF)/(4*DX)
C
IF(KSTEP.EQ.1)GO TO 100
C****************************** FIRST HALF TIME STEP
DMID(L)=A+B
DTOP(L)=0.0D0
DBOT(L)=-B
R(L)=(T*(A-C-D))+(D*TBEFOR)+(C*TLATER)
C
GO TO 200
C****************************** NEXT HALF TIME STEP
100 DMID(L)=A+C+D
DTOP(L)=-C
DBOT(L)=-D
R(L)=(T*(A-B))+(B*TBEFORE)
200 RETURN
1
END
C
SUBROUTINE BBONE(T,TLATER,TBEFOR,ROW,CP
1,AK,AKTOP,AKRIG,AKLEF,DZ0,KSTEP,*,N,M)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQID,TSOLID,SUHEAT,TPOUR,HEAT,OMOLD
C
L=L+1
VOL=DX*DZ0/2.0D0
A=ROW*CP*VOL/(DT/2.0D0)
CALL ESTMAT(T,KSTEP,VOL,A,N,M)
B=DX*(AK+AKTOP)/(2*DZ0)
C=DZ0*(AK+AKRIG)/(4*DX)
D=DZ0*(AK+AKLEF)/(4*DX)
C
IF(KSTEP.EQ.1)GO TO 100
C****************************** FIRST HALF TIME STEP
DMID(L)=A+B
DTOP(L)=0.0D0
DBOT(L)=-B
R(L)=(T*(A-C-D))+(D*TBEFOR)+(C*TLATER)
C
GO TO 200
C****************************** NEXT HALF TIME STEP
100 DMID(L)=A+C+D
DTOP(L)=-C
DBOT(L)=-D
R(L)=(T*(A-B))+(B*TBEFORE)
SUBROUTINE TLCORN(T, TOTHER, ROW, CP, AK, AKBOT, AKLEF, DZ1, KSTEP,

IMPLICIT REAL*8 (A-H, O-Z)
COMMON /C5/ DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9/ NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
COMMON /C13/ FSLANT, FHORIZ, TAMB
L=L+1

VOL=DX*DZ1/4.0D0
  A=ROW*CP*VOL/(DT/2.0D0)
  CALL ESTMAT(T, KSTEP, VOL, A, N, M)
AREA=DX/2
HC=(2/(10.0D0**4))*(T-TAMB)**(0.25D0)
HR=(1.335D0/(10.0D0**12))*FHORIZ*(((T+273)**4)-(T Tamb)**4)*FSLANT
H=HC+HR
B=-H*AREA
C=DX*(AK+AKBOT)/(3*DZ1)
D=DZ1*(AK+AKLEF)/(4*DX)

IF(KSTEP.EQ.1)GO TO 100

C******************************************** FIRST HALF TIME STEP
DMID(L)=A-B+C
DTOP(L)=-C
DBOT(L)=0.0D0
R(L)=(T*(A-D))+(D*TOTHER)-(B*TAMB)

C
GO TO 200

C******************************************** NEXT HALF TIME STEP
100 DMID(L)=A-B+D
DTOP(L)=0.0D0
DBOT(L)=-D
R(L)=(T*(A-C))+(C*TOTHER)-(B*TAMB)

200 RETURN 1
END

SUBROUTINE BRCORN(T, TBEFOR, ROW, CP, AK, AKTOP, AKLEF, DZ0, KSTEP,

IMPLICIT REAL*8 (A-H, O-Z)
COMMON /C5/ DMID(7600), DTOP(7600), DBOT(7600), R(7600), DX, L
COMMON /C9/ NTIMES, END, THEEND, TIME, DT
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
L=L+1
VOL=DX*DZ0/4.0D0
  A=ROW*CP*VOL/(DT/2.0D0)
  CALL ESTMAT(T, KSTEP, VOL, A, N, M)
B=DX*(AK+AKTOP)/(4*DZ0)
C=DZ0*(AK+AKLEF)/(4*DX)
IF (KSTEP.EQ.1) GO TO 100
C************************** FIRST HALF TIME STEP
   DMID(L) = A + B
   DTOP(L) = 0.0D0
   DBOT(L) = -B
   R(L) = (T*(A-C)) + (C*TBEFOR)
GO TO 200
C*************************** NEXT HALF TIME STEP
100 DMID(L) = A + C
   DTOP(L) = 0.0D0
   DBOT(L) = -C
   R(L) = (T*(A-B)) + (B*TBEFOR)
200 RETURN 1
END
C
SUBROUTINE BLCORN(T,TOTHER,ROW,CP,AK,AKTOP,AKRIG
1,DZ0,KSTEP,*,N,M)
C
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C5 / DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C9 / MTIMES,NTIMES,END,THEEND,TIME,DT
COMMON /C10/ CARBON,TLIQUID,TSOLID,SUHEAT,TPOUR,HEAT,QMOLD
   L=L+1
C
   VOL=DX*DZ0/4.0D0
   A=ROW*CP*VOL/(DT/2.0D0)
   CALL ESTMAT(T,KSTEP,VOL,A,N,M)
   B=DX*(AK+AKTOP)/(4*DZ0)
   C=DZ0*(AK+AKRIG)/(3*DX)
   D=-(QMOLD*DZ0)/2
C
IF (KSTEP.EQ.1) GO TO 100
C************************** FIRST HALF TIME STEP
   DMID(L) = A + B
   DTOP(L) = 0.0D0
   DBOT(L) = -B
   R(L) = (T*(A-C)) + (C*TOTHER)+D
GO TO 200
C*************************** NEXT HALF TIME STEP
100 DMID(L) = A + C
   DTOP(L) = -C
   DBOT(L) = 0.0D0
   R(L) = (T*(A-B)) + (B*TOTHER)+D
200 RETURN 1
END
C
REAL FUNCTION CLIQ*8(T)
C
-- ---------------------------
C
IMPLICIT REAL*8 (A-H,O-Z)
C
IF(T.LE.1493.0D0) GO TO 100
   CLIQ=(-0.012439D0*T)+19.081463D0
RETURN
232

100 CLIQ=167.7523373565D0-T*0.36470799D0
A+((T**2.0D0)*0.00027556876D0-(T**3.0D0))
A*0.00000007120875D0
RETURN
END

C
REAL FUNCTION CSOL*8(T)
-----------------------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
C
IF(T.LE.1493.0D0) GO TO 100
CSOL=(-0.002439D0*T)+3.7414634D0
RETURN
100 IF(T.LE.1492.98D0)GO TO 200
CSOL=(-3.0D0*T)+4479.1D0
RETURN
200 CSOL=(-0.0054913D0*T)+8.3585549D0
RETURN
END

C
REAL FUNCTION TLIQ*8(C)
-----------------------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
C
IF(C.GT.0.51D0)  GO TO 100
TLIQ=(-80.392157D0*C)+1534.0D0
RETURN
100 TLIQ=1506.36955637144D0-17.40733404564D0*C
A-27.01800384717D0*(C**2.0D0)+(C**3.0D0)
A*2.83618411819D0
RETURN
END

C
REAL FUNCTION TSOL*8(C)
-----------------------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
C
IF(C.GE.0.10D0)GO TO 100
TSOL=-(C*410.0D0)+1534.0D0
RETURN
100 IF(C.GE.0.16D0)GO TO 200
TSOL=-(0.3333D0*C)+1493.3333D0
RETURN
200 TSOL=-(182.10526D0*C)+1522.1368D0
RETURN
END

C
SUBROUTINE ESTMAT(T,KSTEP,VOL,A,N,M)
-----------------------------------------------
IMPLICIT REAL*8(A-H,O-Z)
COMMON /C3 / AK(75,100),CP(75,100),ROW(75,100)
COMMON /C1 / TT(75,100),TS(75,100)
COMMON /C4 / SOLID(75,100)
COMMON /C10/ CARBON, TLIQID, TSOLID, SUHEAT, TPOUR, HEAT, QMOLD
COMMON /C20/ SHELLF(75), XMINSC(75), DIST(75)
COMMON /C21/ FS(75, 100), FRACTN, NREPET
COMMON /C9/ MTIMES, NTIMES, END, THEEND, TIME, DT

C
WEIGHT = VOL * ROW(N, M)
TOHEAT = WEIGHT * HEAT
FSOLID = 0.0D0
CARLQ = 0.0D0
CARSL = 0.0D0
ELHEAT = 0.0D0
ELRATE = 0.0D0

C
IF (KSTEP.EQ.0) GO TO 1000
C
IF (T.GE.TLIQID) GO TO 800
C
IF (T.LT.TSOLID) GO TO 500
C
C-----------------------------------------------
FS(N, M) = (TLIQID - T) / (TLIQID - TSOLID)
FSOLID = FS(N, M) * WEIGHT
ELHEAT = DABS ((FSOLID - SOLID(N, M))) * HEAT
ELRATE = ELHEAT / (DT * DABS (TS(N, M) - TT(N, M)))
SOLID(N, M) = FSOLID
GO TO 900
C-----------------------------------------------
500 IF (FS(N, M).GE.1.0D0) GO TO 1000
FS(N, M) = 1.0D0
FSOLID = WEIGHT
ELHEAT = DABS ((FSOLID - SOLID(N, M))) * HEAT
ELRATE = ELHEAT / (DT * DABS (TS(N, M) - TT(N, M)))
SOLID(N, M) = FSOLID
GO TO 900
C-----------------------------------------------
800 IF (FS(N, M).GT.0.0D0) GO TO 801
GO TO 1000
801 ELHEAT = HEAT * WEIGHT * FS(N, M)
ELRATE = ELHEAT / (DT * DABS (TS(N, M) - TT(N, M)))
A = A - ELRATE
FS(N, M) = 0.0D0
SOLID(N, M) = 0.0D0
GO TO 1000
C-----------------------------------------------
C
900 A = A + ELRATE

C
1000 IF (N.EQ.25) GO TO 1001
GO TO 1005
1001 IF (M.EQ.1) GO TO 1002
GO TO 1005
1002 IF (TIME.LT.DT) GO TO 1003
GO TO 1005
1003 IF (KSTEP.EQ.0) GO TO 1005
WRITE(7,1004)N,VOL,HEAT,M,ROW(N,M),TLIQID,TOHEAT,WEIGHT,TSO
1004 FORMAT(9X,'N=',12,6X,'VOL ..=',F6.5,2X,'HEAT..=',F4.1,/, 19X,'M=',I2,6X,'ROW ..=',F6.2,2X,'TLIQID=',F6.1,/, 1'TOTAL HEAT=',F6.4,2X,'WEIGHT=',F6.5,2X,'TSOLID=',F6.1,/, 1'---------------------------------',/)
WRITE(7,1007)
1007 FORMAT('K',2X,'TIME',2X, 1'C-LIQ',2X,'C-SOL',2X,'FS ',2X,'SOLID',2X, 1'LATENT HT',2X,' TEMP ',2X,'R',7X,'PERCENT',2X,'RATE',/)
C 1005 PERCEN=(ELHEAT/TOHEAT)*100.0D0
IF(KSTEP.EQ.0)GO TO 1009
WRITE(7,1006)KSTEP,TIME,CARLQ,CARSL,FS(N,M), 1SOLID(N,M),ELHEAT,T,A,PERCEN,ELRATE
GO TO 1100
1009 WRITE(7,1006)KSTEP,TIME,CARLQ,CARSL,FS(N,M), 1SOLID(N,M),ELHEAT,T,A,PERCEN,ELRATE
1006 FORMAT(I1,2X,F4.2,2X,F5.4,2X,F5.4,2X,F5.3,2X,F5.4,2X,F8.6, 12X,F6.1,2X,F6.1,2X,F6.1,2X,F10.4)
C 1100 RETURN
END
C SUBROUTINE CURFIT(N,X,Y,P,KURVE,ORDER)
C IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION X(15),Y(15),Z(15),ZZ(15),P(15),ZE(15)
DIMENSION S(75),SIGMA(75),AA(75),BB(75),YF(200)
1,YD(200),WT(200)
LOGICAL LK
LK=.FALSE.
NWT=0
C NUMBER=N-2
IF(NUMBER.GE.40)NUMBER=40
C CALL DOLSF (NUMBER,N,X,Y,IF,YD,WT,NWT,S 1,SIGMA,AA,BB,SS,LK,P)
C KURVE=NUMBER+1
C DO 2 I=1,N
   Z(I)=P(1)
   DO 1 J=2,KURVE
      ZZ(I)=P(J)*(X(I)**(J-1))
      Z(I)=ZZ(I)+Z(I)
1 CONTINUE
   ZE(I)=(Z(I)-Y(I))/Y(I)*100.0D0
2 CONTINUE
C WRITE(6,3)NUMBER
3 FORMAT(60X,'---',1X,I2,1X,'---',/)
WRITE(6,4)(X(I),Y(I),Z(I),ZE(I),I,P(I),I=1,KURVE)
KU=KURVE+1
WRITE(6,5)(X(I),Y(I),Z(I),ZE(I),I=KU,N)
C
4 FORMAT(F5.0,3X,F7.5,3X,F7.5,4X,F5.2,4X,'P(',I2,')=',F20.15)
5 FORMAT(F5.0,3X,F7.5,3X,F7.5,4X,F5.2)
C
RETURN
END
C
REAL FUNCTION AKSOL*8(T)
-------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
C
COMMON /C18/ YK(15),YCP(15),PK(75),PCP(15),ORDERK,ORDERC,KK
AKSOL=0.0D0
DO 100 I=1,KK
AKSSS=PK(I)*(T**(I-1))
AKSOL=AKSOL+AKSSS
100 CONTINUE
C
RETURN
END
C
REAL FUNCTION CPSOL*8(T)
-------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
C
COMMON /C18/ YK(15),YCP(15),PK(75),PCP(15),ORDERK,ORDERC,KK
CPSOL=0.0D0
DO 100 I=1,KCP
CPSSS=PCP(I)*(T**(I-1))
CPSOL=CPSOL+CPSSS
100 CONTINUE
C
RETURN
END
C
C SUBROUTINE PROFILE PRINTS THE MINISCUS PROFILE IN FILE-8 8
C AND THE SHELL PROFILE IN THE FILE-9
C
SUBROUTINE PROFILE(TIME)
-------------------------------
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /C1/ TT(75,100),TS(75,100)
COMMON /C5/ DMID(7600),DTOP(7600),DBOT(7600),R(7600),DX,L
COMMON /C14/ NTOTAL,MTOTAL,NX
COMMON /C20/ SHELLF(75),XMINSC(75),DIST(75)
COMMON /C21/ FS(75,100),FRACTN,NREPET
C
DO 1000 N=1,NTOTAL
C************************  ********
DO 400 M=1,MTOTAL
IF(TT(N,M).GT.0.0D0) GO TO 100
GO TO 300
DO 100 N=1,NTOTAL
    DO 100 M=1,MTOTAL
        IF(TT(N,M).GT.0.0D0) GO TO 300
        GO TO 100
    300 XMINSC(N)=(DX*M*20.0D0)-(DX*0.5*20.0D0)
    IF(N.GT.N1) XMINSC(N)=0.0D0
    GO TO 200
100 CONTINUE
200 CONTINUE
C
WRITE(12,500)NTOTAL
500 FORMAT(I4)
WRITE(6,600)
600 FORMAT(/,7X,'MENISCUS SHAPE DESCRIPTION',/,'----------',7X)
   DO 900 I=1,NTOTAL
      WRITE(6,700)XMINSC(I),DIST(I)
900 CONTINUE
C
RETURN
END
C
SUBROUTINE XANDY
-----------------------------------------------
C
DIMENSION ABC(6),BCD(6),CDE(6),DEF(6),EFG(6),FGH(6)
C
READ(1,1)(ABC(I),I=1,6)
READ(1,1)(BCD(I),I=1,6)
READ(1,1)(CDE(I),I=1,6)
READ(1,1)(DEF(I),I=1,6)
READ(1,1)(EFG(I),I=1,6)
READ(1,1)(FGH(I),I=1,6)
1 FORMAT(6A4)
C
CALL AXCTRL('XORIGIN',0.0)
CALL AXCTRL('YORIGIN',20.0)
CALL AXCTRL('SIDE',-1)
CALL AXPLOT('DISTANCE BELOW THE MENISCUS(CM);'
1,270.0,15.0,0.0,0.2)
CALL AXCTRL('YORIGIN',5.0)
CALL AXPLOT('DISTANCE FROM THE MOLD WALL(CM);'
1,0.0,20.0,0.0,0.05)
C
CALL PLOT(0.0,20.0,3)
CALL PLOT(0.0,22.0,2)
CALL PLOT(20.0,22.0,2)
CALL PLOT(20.0,5.0,2)
C
CALL PSYM(2.0,23.0,0.6,'SOLIDIFICATION AT THE MENISCUS',0.0
1,100)
CALL PSYM(11.0,11.0,0.4,ABC,0.0,24,100)
CALL PSYM(11.0,10.0,0.4,BCD,0.0,24,100)
CALL PSYM(11.0,9.0,0.4,CDE,0.0,24,100)
CALL PSYM(11.0,8.0,0.4,DEF,0.0,24,100)
CALL PSYM(11.0,7.0,0.4,EFG,0.0,24,100)
CALL PSYM(11.0,6.0,0.4,FGH,0.0,24,100)
CALL PSYM(4.0,22.5,0.3,
1'LATENT HEAT IS RELEASED AS PER FE-C DIAGRAM',0.0,45,100)
CALL PLOT(10.5,12.0,3)
CALL PLOT(10.5,5.5,2)
CALL PLOT(19.5,5.5,2)
CALL PLOT(19.5,12.0,2)
CALL PLOT(10.5,12.0,2)
CALL PLOT(0.0,0.0,3)
C 100 RETURN
END
C
SUBROUTINE MENISC
C
DIMENSION SCUS(75),DIST(75),SHEL(75)
C
*********** THE MENISCUS PROFILE IS PLOTTED ******************
C
READ(2,100)NTOTAL
100 FORMAT(I4)
C
DO 300 N=1,NTOTAL
READ(2,200)SCUS(N),DIST(N)
200 FORMAT(2F5.2)
300 CONTINUE
C
CALL LINE(SCUS,DIST,NTOTAL,1)
CALL PLOT(SCUS(1),DIST(1),3)
CALL PLOT(20.0,DIST(1),2)
CALL PLOT(0.0,0.0,3)
C
RETURN
END
C
SUBROUTINE SHELL(N1)
C
DIMENSION SCUS(75),DIST(75),SHEL(75)
C
*********** THE SHELL PROFILE IS PLOTTED ******************
C
READ(3,400)NTOTAL
400 FORMAT(I4)
C
DO 600 N=1,NTOTAL
READ(3,500)SHEL(N),DIST(N),SCUS(N)
500 FORMAT(3F5.2)
600 CONTINUE
C
CALL PLOT(SHEL(NTOTAL),DIST(NTOTAL),3)
C
DO 800 N=1,NTOTAL
NKPD=NTOTAL-N
IF(NKPD.EQ.0)GO TO 1000
IF(SHEL(NKPD).GT.0.0)GO TO 699
IF(SCUS(NKPD).GT.0.0)GO TO 699
CALL PLOT(0.0,DIST(NKPD),2)
GO TO 1000
699 IF(SHEL(NKPD).GT.SCUS(NKPD))GO TO 700
GO TO 900
700  CALL PLOT(SHEL(NKPD),DIST(NKPD),2)
800  CONTINUE
C
900  NKPD1=NKPD-1
     CALL PLOT(SCUS(NKPD1),DIST(NKPD1),2)
1000 CALL PLOT(0.0,0.0,3)
     CALL PLOT(SHEL(NTOTAL),DIST(NTOTAL),3)
     CALL PLOT(SHEL(NTOTAL),5.0,2)
     CALL PLOT(0.0,0.0,3)
C
1100 RETURN
END