MINIMIZATION OF HYBRID PRODUCTION DURING STEEL GRADE INTER-MIXING IN THE TUNDISH[1]

Lawrence (Larry) Heaslip[2]
James (Jim) Dorricott[2]
Johan Richaud[2]
John Rogler[2]
Wender Andrade Alves[3]

Abstract

The continuous casting of steel semis, such as slabs or blooms, with hybrid chemistry as a result of steel grade intermixing in the tundish, can be a significant cost factor in continuous caster operations, particularly if tundish grade mixing occurs regularly. Grade mixing is often practiced to avoid lost production time and reduce tundish consumption by eliminating tail-outs or tundish flys when the production schedule includes a high proportion of short runs of the same grade. The cost of grade mixing in the tundish can be significantly reduced if the quantity of hybrid chemistry product (i.e. product that fits neither the outgoing nor the incoming chemical grade specifications) can be reduced. In this paper it is shown that tundish design, caster operations, and the use of chemical intermix prediction and control software can be highly beneficial in reducing the amount of hybrid steel produced during tundish grade mixing. Tundish design factors, including tundish flow control furniture, and caster operations, such as tundish level practice, are shown to have a significant influence in promoting a shorter transition. Hybrid steel reduction and tracking software (HYTRAK) is also shown to be of great assistance in improving steel yields during tundish grade mixing. HYTRAK has been developed for use in real-time at ladle metallurgy to adjust heat chemistries to reduce hybrid steel production and for use on the caster to predict and track the changing steel chemistry of the casting strand.

Key words: Hybrid steel tracking; Grade transition; Flow analysis; Continuous casting.

REDUÇÃO DE PERDAS EM MISTURAS DE GRAUS DE AÇO EM DISTRIBUIDORES DE MÁQUINAS DE LINGOTAMENTO CONTÍNUO

Resumo

O Lingotamento contínuo de misturas de grau de aço é o resultado de transição química de graus dentro de um mesmo seqüencial, podendo representar uma parcela significativa do custo operacional. Apesar disso, esta é uma prática comum que tem por finalidade a redução de tempo ocioso de máquinas de lingotamento contínuo e de consumo de distribuidores. O custo das transições pode ser severamente reduzido se a quantidade de aço de transição for reduzida. Neste artigo é apresentada a influência de projeto de distribuidor, práticas operacionais e utilização de software de predição e controle químico na diminuição de massa de aço de transição. Hybrid Steel Reduction and Tracking Software (HYTRK) foi desenvolvido para uso em tempo real na metalurgia secundária para ajuste químico e redução de perdas, além do uso no próprio lingotamento para apontamento e predição das transições químicas.

Palavras-chave: Lingotamento contínuo; Análise de fluxo; Mistura de aços; Rendimento metálico.

---

[1] *Tecnhical contribution to XXXVIII Steelmaking Seminar – International, May 20th to 23rd, 2007, Belo Horizonte, MG, Brazil.*

[2] *Advent Process Engineering, Inc., 5035 North Service Rd., C-13, Burlington, ON, Canada, L7L-5V2.*

[3] *Vesuvius Brazil, Av Brasil, 49550. Rio de Janeiro, RJ, Brasil.*

1 INTRODUCTION

Hybrid product is No-Grade or Unapplied-to-Order cast product that can result when two sufficiently different steel grades are mixed in the tundish during a casting sequence. If the new (i.e. the incoming heat) grade is sufficiently different than the old (outgoing heat) grade, such that the grade specifications of one or all of the chemical elements do not overlap, then the mixing of the two liquid steels in the tundish and in the mold can develop a mixed steel chemistry that does not qualify as either the new or the old grade, in which case some transition length (or tonnage) of hybrid cast product is produced. The minimization of transition length and the prediction and tracking of the start and finish positions of hybrid chemistry product on the casting strand, when making a grade transition in the tundish without interruption of casting, requires two things. Firstly, a comprehensive understanding of the influence of both tundish design and tundish operations on the mixing behavior in the tundish bath is required. This understanding can be developed using modeling. In this study, water modeling methods have been adopted. Computational modeling methods could have been used, but water modeling was deemed to be sufficiently reliable and more time efficient. Secondly, an online system for transition optimization/prediction is required. This system is herein referred to as HYTRAK. The purpose of HYTRAK is to provide operators with the real-time guidance required to: (1) minimize transition length, and (2) locate the start and finish of transition on the casting strand or strands.

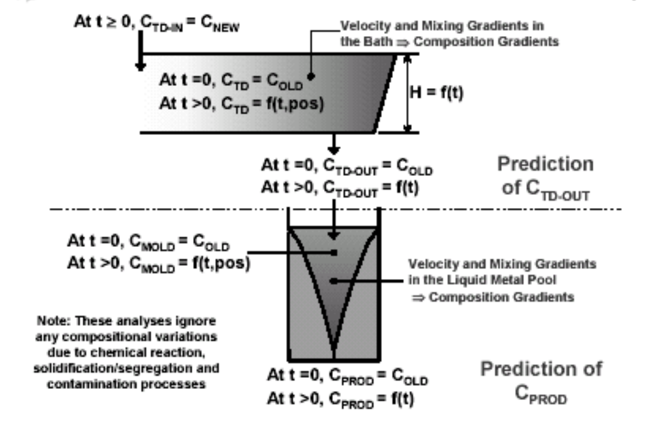
2 METHOD & PROCEDURES

Transition Prediction

As shown in Figure 1, prediction of the time-varying as-cast-product composition during a grade transition is a highly complex problem that can be divided into two parts:

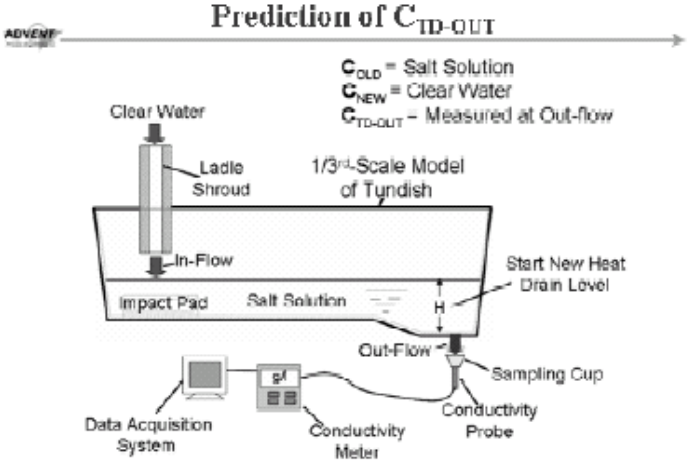
- The first part is the prediction of the time-varying composition of liquid steel exiting the tundish after transition start – Prediction of CTD-OUT;
- Knowing **CTD-OUT,** the second part is the prediction of the time-varying composition of the as-cast product after transition start – Prediction of CPROD.

Fig. 1 : Transition Prediction Schematic



Knowledge of **CTD-OUT** is in general not sufficient to predict **CPROD**. To predict **CPROD** the composition of the liquid metal in the mold (**CMOLD**) must first be determined. The relationship between **CTD-OUT** and **CMOLD** depends on the mixing behavior in the liquid pool of the solidifying casting strand. In many instances, a reasonable simplification is to determine **CMOLD** by means of a simple mixing model that considers the upper portion of the liquid pool in the strand to be intensively mixed by the entrance of the liquid metal into the mold and the lower portion of the strand to be free of mixing. The length of the upper portion is generally considered to be a function of the casting conditions (i.e. section size and casting speed).

Fig. 2: Water Model Schematic - Prediction of C_{TD-OUT}



To predict **CTD-OUT**, the time-varying and position-varying composition of the liquid in the tundish (**CTD**) must be determined. However, determination of **CTD** requires a detailed understanding of mixing behavior in the tundish, which is influenced by any factors including (but not limited to):

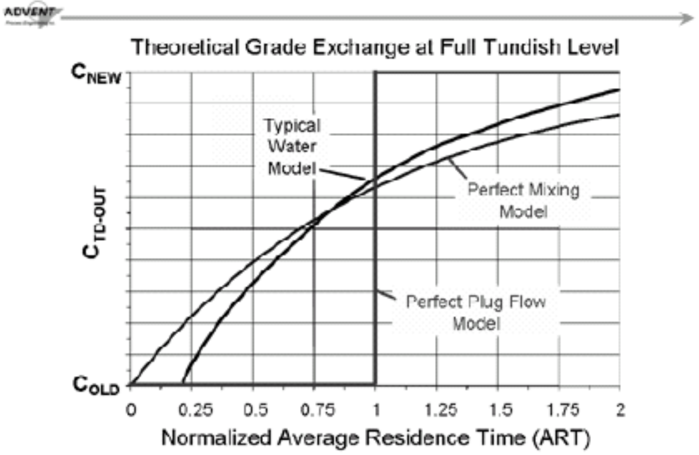
- initial tundish bath depth and subsequent changes to bath depth, and
- tundish size and geometry (including relative inlet and outlet locations), and the design and arrangement of any flow-modifying tundish furniture, such as an impact pad, weirs or dams, etc.

Tundish mixing is not accurately predicted by any simple means such as a perfect-mixing model or a plug-flow model. One method that may be used to help provide reasonable predictions is tundish water modeling as illustrated in Figure 2.

As shown in Fig. 3, perfect plug flow in a tundish (i.e. no mixing) would achieve an ideal steel grade transition, with a step function change from COLD to CNEW. Thus, although it is not possible to eliminate tundish mixing, promoting a more plug-like flow in a tundish is clearly desirable to reduce transition length. In a perfectly mixed tundish, transition would begin immediately but then show very slow asymptotic approach to absolute completion. Water modeling predicts that actual mixing behaviour is less intense and less extensive than this. A delay is seen between start of pouring of the new grade and the start of transition at the tundish outlet as the strongly mixed region in the tundish inlet region typically does not extend all the way to the outlet.

Water modeling allows many of the significant factors that affect the mixing to be easily taken into account, such as the overall tundish design and furniture arrangement, etc. as well as the grade change operating procedures. However, a matrix of modeling experiments is required in order to properly consider the significant process variations (initial bath depth, tundish refilling practice, etc.) that can occur during actual practice. It should also be recognized that the modeling results are in their details specific to the particular tundish configuration that is being studied.

Fig. 3: Comparative Predictions of C_{TD-OUT}



Transition Finish Criterion

To predict transition length, both the start and the finish of transition must be located and tracked on the casting strand, but in order to do this location the mixes that define transition start and transition finish must be calculated. These mixes are dependant, not only on the steel grade specifications, but are also dependant on the actual chemistries of both the new (incoming) and old (outgoing – already in the tundish) heats. For example, consider the determination of a tundish transition finish criterion for a particular transition. To determine this criterion, the following parameters can be defined:

TOUT – Mixture (in %) of new heat in old heat at the tundish outlet
AE-OLD – Analysis of element (E) in the old heat
AE-NEW – Analysis of element (E) in the new heat
SE-NEW-MIN – Minimum specification of element (E) in new grade
SE-NEW-MAX – Maximum specification of element (E) in new grade
TE-FINISH – Mixture of old and new heats that must be achieved at the tundish outlet to meet the chemical specification of element (E) in the new grade

For elements that are increasing in concentration during transition, the mix required for transition finish for element E is given by:

AE = AE-NEW - AE-OLD
TE-FINISH = [(SE-NEW-MIN - AE-OLD)/ .AE] ·100

And, similarly for elements that are decreasing in composition, the mix required for transition finish for element E is given by:

TE-FINISH = [(SE-NEW-MAX - AE-OLD)/ .AE] ·100)

Considering all elements, tundish transition finish is achieved when the following criterion is satisfied:

TOUT > TMAX-FINISH
Where, TMAX-FINISH = Maximum of all TE-FINISH

The element that controls transition completion in the tundish is identified as the element with the maximum value of TE-FINISH. It is the magnitude of TMAX-FINISH that determines whether the heat chemistries are similar or radically different. Similar calculations are used to identify the start of tundish transition criterion and the element controlling transition start.

3 RESULTS

Influence of Tundish Configuration

Tundish configuration can play an important role in the minimization of transition length. For example, consider the three similar two-strand tundishes shown in Figure 4. The general dimensions of the three tundishes are identical, but the type-1 configuration is a simple one with a flat bottom and a flat impact pad, whereas the type-2 and type-3 configurations utilize more advanced impact pad shapes and bottoms that are raised in the central portions of the tundishes. The type-2 configuration includes a lipped impact pad and raised bottom, while type-3 includes a special impact pad with lateral outlet holes and higher raised bottom. As illustrated in Figure 4, the special impact pad with lateral holes provides a wider dispersion of the steel flow exiting the pad, and can therefore induce a more plug-like flow pattern in the tundish with little disturbance of the bath surface even with a high central raise of the tundish bottom.

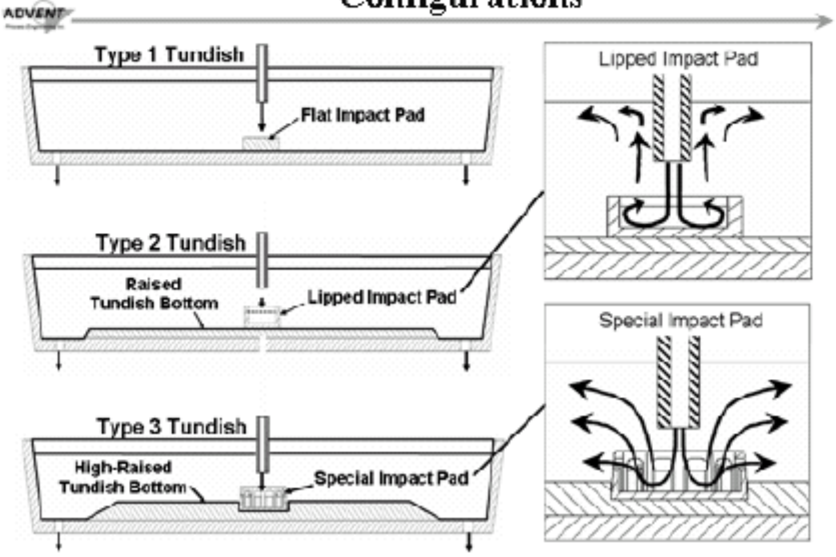


Fig. 4: Example Tundish Configurations

The general tundish flow behavior in each tundish type under steady-state casting conditions was observed during water modeling and the minimum residence times (MRT) were measured by and compared with theoretical average residence times (ART). Fig. 5 summarizes the observations.

Configuration type-3 was observed to provide the highest proportion of plug flow and therefore it is expected that this configuration would show improved transition performance. A comparison of water model transition performance is presented in Figure 6. In this comparison, the tundishes were drained to ½ of normal operating level (NL), then the new ladle was opened and the level was directly returned to NL while at all times a constant casting rate was maintained and the mixture at the tundish outlet (TOUT) was continuously monitored. Once NL was attained, each experiment was continued until a simulated 35 tons was cast. Figure 6 shows that after about 5 tons cast, the type-3 tundish configuration shows a clear benefit with regards to promoting a higher TOUT which may also be thought of as the % completion of transition. The type-3 tundish shows a clear advantage in reaching completions between 80 and 95% (as typically required for dissimilar and radical (very dissimilar) grade changes much faster than the other tundish types.

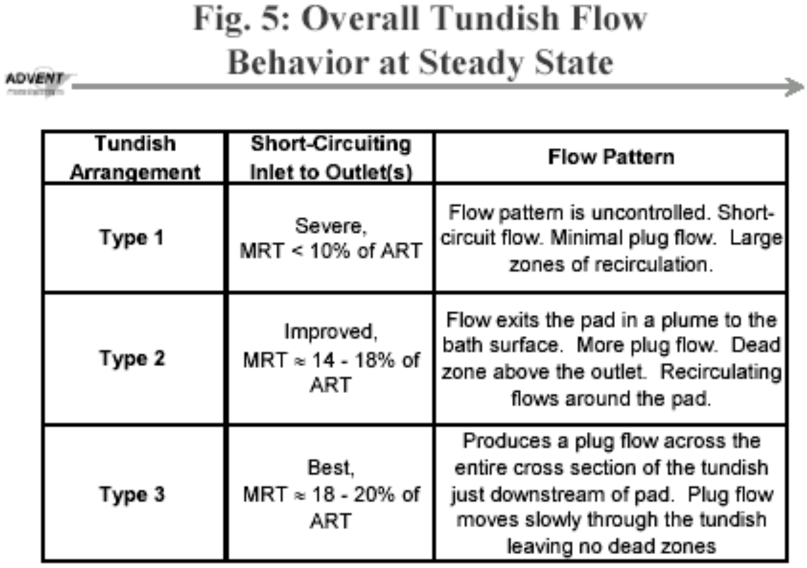
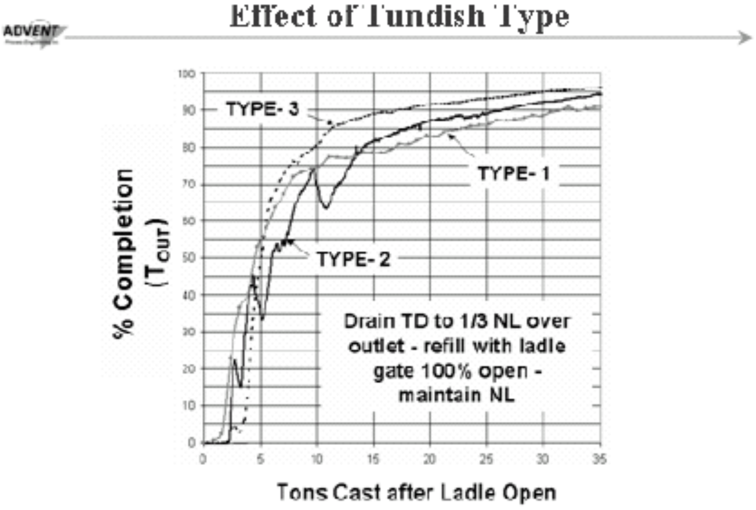


Fig. 5: Overall Tundish Flow Behavior at Steady State

Tundish Arrangement	Short-Circuiting Inlet to Outlet(s)	Flow Pattern
Type 1	Severe, MRT < 10% of ART	Flow pattern is uncontrolled. Short-circuit flow. Minimal plug flow. Large zones of recirculation.
Type 2	Improved, MRT ≈ 14 - 18% of ART	Flow exits the pad in a plume to the bath surface. More plug flow. Dead zone above the outlet. Recirculating flows around the pad.
Type 3	Best, MRT ≈ 18 - 20% of ART	Produces a plug flow across the entire cross section of the tundish just downstream of pad. Plug flow moves slowly through the tundish leaving no dead zones

Fig 6: Water Model Predictions – Effect of Tundish Type

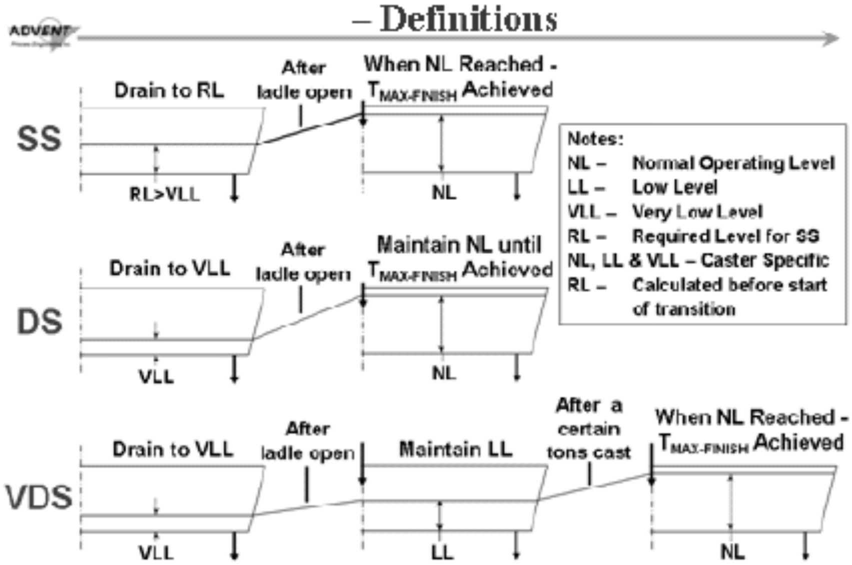


Tundish Level Strategy

Water modeling has shown that reducing the steel level of the old grade heat in the tundish at ladle open and properly controlling the steel level after ladle open of the new grade heat are very important factors in the minimization of transition length. For typical slab casting tundishes, three strategies that can lead to transition length minimization have been identified. These strategies are illustrated in Figure 7. The strategy that is most appropriate for a particular transition is dependant on old and new steel grade specifications and the actual heat chemistries. This optimal strategy is best determined in real-time operations once the ship-to-caster ladle heat chemistry (**ANEW**) is available. The three strategies are herein referred to as:

- **SS** (Similar Steel),
- **DS** (Dissimilar Steel),
- **VDS** (Very Dissimilar Steel)

Fig. 7: Tundish Level Change Strategies – Definitions



The tundish level strategy that minimizes transition length is determined by the magnitude of the transition finish criterion, and by operating factors specific to the particular caster. For example, examine the case where it has been determined that;

- Operations considers that the very lowest tundish level (VLL) that can be typically reached without problems during draining of the old heat is a level equivalent to 25% of the steel volume at normal tundish level (NL),
- And that a maintainable (ladle shroud submerged, etc.) low level (LL) in the tundish after ladle open is a level equivalent to 50% of steel volume at NL.

In this case using strategy **SS**, water modeling indicates that a typical mixture (TOUT) achieved at a tundish outlet when reaching NL is TOUT $\geq$ 75%, if the drain level = VLL. Thus, for TMAXFINISH<75%, the required draining level (RL) of the tundish is > VLL.

Whereas using strategy **VDS**, after draining to VLL, water modeling has shown that LL should be maintained until TOUT $\geq$ 100 – [2· (100 - TMAX-FINISH)] before raising level to NL to complete transition. Accordingly, in this example the following rules would apply to the choice of tundish level strategy:

- If TMAX-FINISH< 75%, then strategy SS minimizes transition length.
- If TMAX-FINISH > 88%, then strategy VDS minimizes transition length.
- If TMAX-FINISH is between 75 and 88%, then strategy DS should be used.

An On-Line Transition Predictor/Optimizer

The goal of an on-line transition predictor/optimizer is the minimization of transition length and to thereby reduce the hybrid product tonnage made during a transition. Transition length is affected not only by process parameters that may be predetermined such as tundish configuration and grade specifications, but also by real-time parameters such as tundish drain depth, actual heat chemistries and casting variables such as section size and casting speed. Thus, an on-line real-time system such as HYTRAK is required. For optimum performance, the system should provide transition information to both ladle metallurgy and to the caster. HYTRAK outputs include:

Ladle Metallurgy:

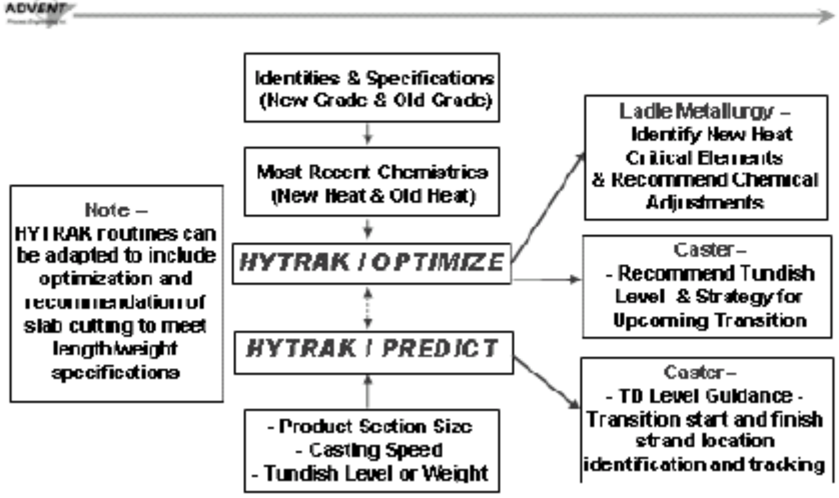
- Identification of the chemical elements in the new heat that will be controlling start and finish of the upcoming transition.
- Recommendation of chemical adjustments that will maintain new heat in specification but reduce transition length.

Caster:

- Recommendation of optimum tundish level strategy.
- Real-time prediction of transition progress.
- Real-time operator guidance notification of optimum tundish level.
- Identification and tracking of location of transition start and transition finish on the casting strand(s).

HYTRAK consists of two modules – HYTRAK/OPTIMIZE and HYTRAK/PREDICT. The general design of the system is illustrated in Figure 8. The system must obtain the grade specifications and the most recent actual chemistries of the heats involved in the transition. This information is used by HYTRAK/OPTIMIZE to provide operator guidance as regards optimization of the upcoming transition and is used by HYTAK/PREDICT to predict transition on the casting strand at the start of cast of the new heat.

Fig. 8: General Design of HYTRAK



Optimization can have an enormous influence on transition length. For example, consider the transition presented in Figure 9. This example examines a transition from low carbon to medium carbon steel. While the old heat is being cast in the tundish, the new heat is being adjusted at the ladle metallurgy station. At this point the final chemistry of the old heat (i.e. tundish or mold analysis) may be available or the system would use the final ladle chemistry of the old heat in its analysis. New heat chemistries are also shown in Figure 9. As shown in this figure, when the most recent new heat ladle chemistry is 'Ladle Chem-2', HYTRAK/OPTIMIZE would recommend adjustment of the carbon in the new heat. After adjustment, 'Final Ladle Chem' gives the chemistry of the new heat. Considering a properly configured 30T single strand tundish casting at 3T/min., the influence of optimization can be predicted as follows:

- Without HYTRAK, the final ladle chemistry of the new heat can be taken as Ladle Chem-2, in which case:
    - hybrid tonnage cast would have been 48T, using tundish level strategy DS,
    - while, hybrid tonnage cast would have been 32T, using tundish level strategy VDS.
- Using HYTRAK, the ladle chemistry is better adjusted and as a result of this adjustment and following the correct tundish level strategy,
- the hybrid tonnage cast would be only 12T, using tundish level strategy DS.

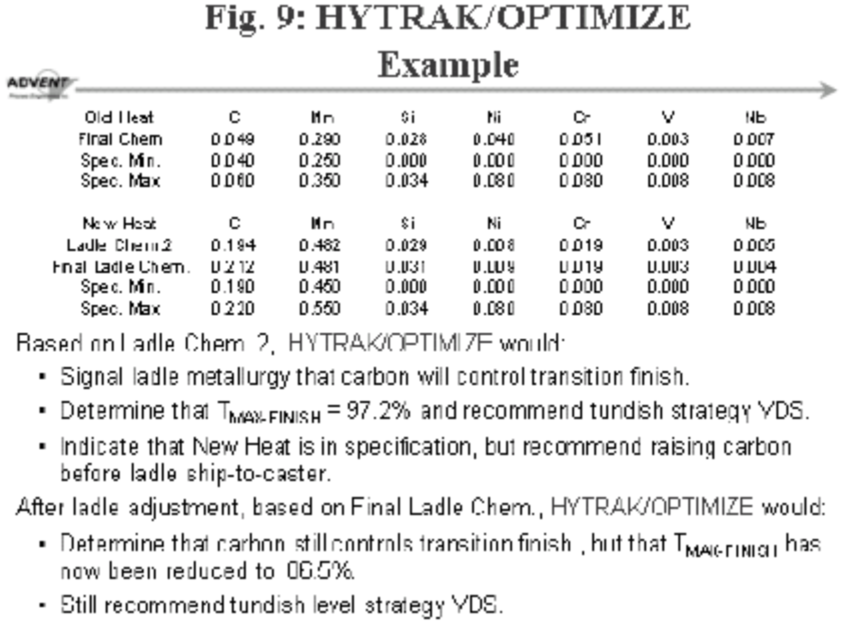


Fig. 9: HYTRAK/OPTIMIZE Example

Old Heat	C	Mn	Si	Ni	Cr	V	Nb
Final Chem	0.049	0.290	0.028	0.040	0.051	0.003	0.007
Spec. Min.	0.040	0.250	0.000	0.000	0.000	0.000	0.000
Spec. Max	0.060	0.350	0.034	0.080	0.080	0.008	0.008

New Heat	C	Mn	Si	Ni	Cr	V	Nb
Ladle Chem 2	0.194	0.482	0.029	0.008	0.019	0.003	0.005
Final Ladle Chem.	0.212	0.481	0.031	0.009	0.019	0.003	0.004
Spec. Min.	0.190	0.450	0.000	0.000	0.000	0.000	0.000
Spec. Max	0.220	0.550	0.034	0.080	0.080	0.008	0.008

Based on Ladle Chem 2, HYTRAK/OPTIMIZE would:

- Signal ladle metallurgy that carbon will control transition finish.
- Determine that $T_{MAX-FINISH}$ = 97.2% and recommend tundish strategy VDS.
- Indicate that New Heat is in specification, but recommend raising carbon before ladle ship-to-caster.

After ladle adjustment, based on Final Ladle Chem., HYTRAK/OPTIMIZE would:

- Determine that carbon still controls transition finish , but that $T_{MAX-FINISH}$ has now been reduced to 96.5%.
- Still recommend tundish level strategy VDS.

With HYTRAK/PREDICT, the progress of the actual transition is predicted in real-time, and this allows the influence of the actual events that occur during casting, such as the achieved tundish level (or mass) at ladle open and subsequent variation from the desired tundish level practice, as well as alterations in casting speed, section size (e.g. slab width change during transition) etc. to be considered. For instance, although the theoretical hybrid tonnage cast after optimization is 12T in the previous example, in accordance with how the transition actually occurred, the real time data may indicate that the achieved hybrid tonnage was 16T. The achieved versus theoretical hybrid tonnage cast may be compared and saved in the HYTRAK database. HYTRAK/PREDICT utilizes real-time algorithms for prediction of composition at the tundish outlet (**CTD-OUT)** and the strand (**CPROD)**.

- These algorithms consider both mixing and dilution factors, and in the tundish these factors are dependent on bath depth (or mass), rate of change of bath depth, and casting rate. These dependencies are specific to tundish arrangement and are predetermined by water modeling.
- In the mold, multiple models are possible, but in many instances a simple mixing model can be adopted.
- Real-time data concerning casting rate (i.e. section size and casting speed) and tundish level or weight are required.
- Predictions are updated as real-time data are received. Thus, to obtain a resolution of 25mm on the casting strand, the data rate should exceed (casting speed / 25). For example, data rate should be ¡Ý 40 samples/minute at a casting speed of 1000 mm/min.

4 CONCLUSIONS

1. Prediction of the changing as-cast product composition during grade transition can be divided into two parts:
   - First, the mixture of old and new heats in the tundish outlet flow is estimated.
   - Then, the cast metal composition can be estimated.
2. Mixing in a tundish is not easily predicted by any simple means. However, water modeling is one method that may be used to provide reasonable predictions.
   - Water model results are specific to the tundish configuration studied.
   - Modeling experiments must consider the significant process variations (initial bath depth, tundish refilling practice, etc.) that can occur during actual practice.
3. Reducing the steel level in the tundish at ladle open and properly controlling steel level after ladle open can minimize transition length. Strategies SS, DS & VDS have been identified:
   - Strategy SS should be used if old and new heat steel chemistries are similar.
   - Strategy VDS should be used for very dissimilar steels.
4. Tundish configuration (such as impact pad design and tundish bottom shape) can have a significant influence on transition length.
   - A tundish with special impact pad and high-raised tundish bottom has been shown to improve plug-flow behavior and speed transition.
5. An on-line real-time transition optimizer/predictor has been developed.
   - Identifies critical elements in the new heat that will be controlling start and finish of the upcoming transition and recommends adjustments to the new heat that are inspecification but will reduce transition length.
   - Recommends optimum tundish level strategy upon receipt of ship-to-caster ladle chemistry of new heat.
   - Provides operator guidance as regards current desired tundish level.
   - Predicts transition progress to identify and track the locations of transition start and transition finish on the casting strand or strands.
6. Many factors influence transition length, including tundish design & furniture, similarity or dissimilarity of grades being mixed, actual heat chemistries, and tundish level strategy, etc.
   - Thus, transition length can vary greatly and remarkable improvements are possible with on-line optimization and real-time tracking. An example transition has shown:
   - Without optimization of heat chemistry or level strategy ¡Ö 48T.
   - Without optimization of heat chemistry but with optimized level strategy ¡Ö 32T.
   - With optimization of heat chemistry & level strategy ¡Ö 12T.
7. To facilitate transition optimization, and track transition progress in real-time operations requires implementation of an on-line transition predictor/optimizer such as HYTRAK.