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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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LATEST DEVELOPMENTS IN CONTINUOUS CASTING OF SLABS: TECHNICAL AND ECONOMIC CONSIDERATIONS[1]

by

H. Fastert
Concast Incorporated
United States of America
and
R. Gautschi
Concast Aktiengesellschaft
Switzerland

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Introduction

The change of continuous slab casting from an experimental or pilot-plant stage to a full-scale production process took place about 10 to 15 years ago. The main problems with these first-generation production units were for many years the proper and reliable functioning of their mechanical equipment. The design of the main components of a slab machine, namely mould, mould oscillation, roller apron, and withdrawal-straightening unit, have undergone considerable modifications since that time, resulting not only in more reliable operation but also in improved product quality. Ten years ago, the start-up of a new slab machine was often a lengthy procedure, but today it is not uncommon that, already in the very first cast, an entire ladle can be emptied and cast into good slabs.

Nevertheless, continuous-casting technology is far from being stationary. The last few years have again brought considerable refinements and modifications, most of them made in order to satisfy the ever-increasing demands on today's installations. The main trends in recent years have been toward

I) - increased casting speeds
II) - higher machine utilization
III) - improved product quality
IV) - automation and computer control

In the following, we shall discuss these items, which required careful control in order to achieve the above goals.

I) Increased Casting Speeds

Until recently the normal casting speed for a slab section of 220 mm thickness was 0.8 - 1.0 m/min, or for a slab thickness of 235 mm 0.6 - 0.8 m/min. Today, these two thicknesses are being cast at speeds from 1.3 to 1.5 m/min and, on test basis, speeds up to 2.0 m/min have been achieved. In order to cast safely at such speeds and still maintain slab quality, the following items require careful control and have necessitated modifications in the casting technique as well as in the mechanical equipment:

a) liquid steel temperature in ladle
b) mould geometry and design
c) support of partially solidified slabs, particularly in upper zone, where solidified shell is thin, and in withdrawal unit, where ferrostatic pressure is highest.

a) Liquid Steel Temperature in Ladle

When leaving the mould, the solidified shell of the slabs must have a certain thickness in order to withstand tension as well as ferrostatic pressure. The thickness of the shell at this point depends on several factors such as casting speed, heat transfer in mould, etc. and also on liquid steel temperature. It is therefore important that liquid steel temperature is kept within certain limits and that it is uniform.

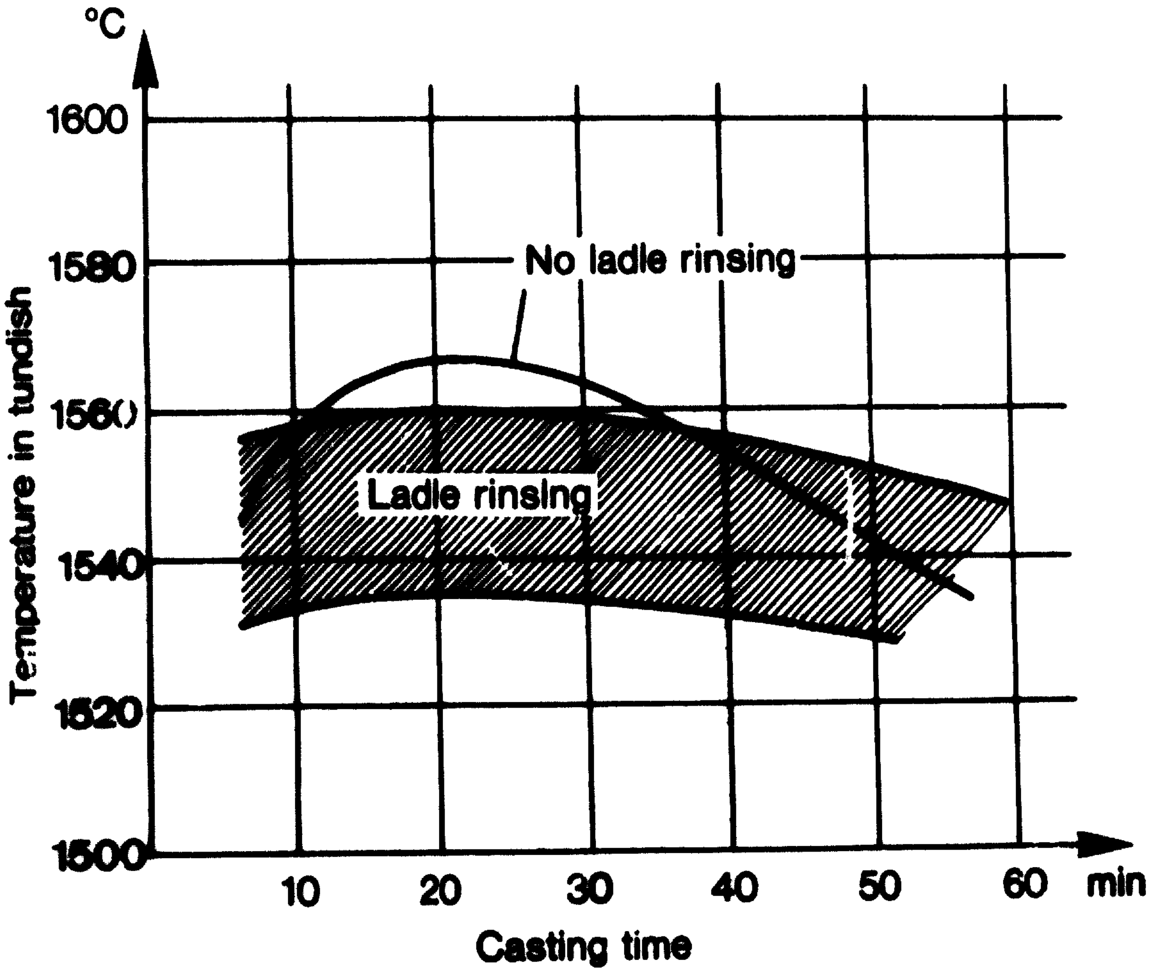
If a ladle is taken directly from the furnace to the cc-machine this is not the case. It is well known that in such a ladle there are various zones of different temperatures. The first steel tapped into the ladle is losing some of its heat to the refractory lining until an equilibrium is reached, and the steel near ladle walls and at the top is also colder than the steel in the center. When casting a ladle with such temperature stratifications, steel temperature at the beginning of the cast is relatively cold, then rises, and toward the end of cast drops again.

In order to eliminate these temperature variations, the practice of rinsing the ladles with an inert gas, argon or nitrogen, has been widely adopted in recent years. The gas is inserted either through a porous brick in the ladle bottom or through a hollow stopper rod inserted from the top. The latter method is more popular today, mainly because the porous bottom brick has occasionally caused a ladle breakout. This gas rinsing leads within a few minutes to a thorough mixing of colder and warmer steel, and, as a result, the course of temperature during the cast is more uniform, as can be seen in Figure 1.

When the steel temperature in the ladle is too high, this gas rinsing is combined with the addition of a calculated amount of scrap. This makes it possible to start the cast with a temperature very near the specification. We shall see later on that this has also a beneficial effect on the extent of segregation.

Figure 1.

Steel Temperature in Tundish with and without Rinsing



b) Mould Geometry and Design

It was indicated above that a certain shell thickness at the mould exit is necessary, and it is obvious that this shell thickness should be uniform around the circumference of the slab. An even growth rate of the shell within the mould will only take place if the heat transfer from slab surface to mould wall is also uniform, and this in turn will only be the case when the contact between the slab and the mould can be maintained. Between the point of the first shell formation in the area of the liquid steel meniscus and the mould exit, the slab shell is subject to a certain shrinkage, and if the mould walls were parallel, there would soon be an airgap between slab surface and mould wall, causing a drastic drop of heat transfer (radiation only). As a result, the temperature of the shell would rise again and the ferrostatic pressure would force it toward the mould wall until contact would be established again. However, such an interruption of heat transfer and shell growth would lead to an even thinner shell at the mould exit, with increased danger of a breakout. While the first-generation slab moulds had parallel walls, it has now become standard practice to provide their narrow sides with a taper. However, it is not easy to calculate how much this taper should amount to, since there is first the shrinkage from liquid steel to solid steel, then the shrinkage due to lowering of the temperature of the solid steel, which is not exactly known. Also, at high-speed casting the surface temperature of the slab at mould exit is higher than at lower casting speeds, resulting in less shrinkage, and finally the shrinkage of carbon steels is not the same as, e.g. for stainless steels. Although supported by sophisticated computer calculations, the suitable tapers for individual conditions were mainly determined on an empirical basis. It would lead too far to go into details here, but we should mention that the narrow-side taper we use today is approx. 0.9 % per meter of mould length for normal casting speeds, and somewhat less for higher speeds. Between wide sides of the slab, there is no taper or just a nominal taper, in that the dimensional tolerances at mould top are x + a fraction of a millimeter, - 0 mm, while at mould exit it is x + 0 mm, minus a fraction of a millimeter.

Besides of the taper, a most important feature of the moulds is their dimensional stability. On first-generation moulds, the copper plates were warping to some extent during the cast, but the fact that they went back to near-normal after the cast made it quite difficult to detect this undesirable effect. Today's moulds have a heavy, sturdy steel frame onto which the copper plates are bolted in a way that the mould cross-section is hardly changed during the cast. This feature also contributes to maintaining good contact between slab surface and mould, ensuring good heat transfer and even shell thickness.

c) Support of Partially Solidified Slab

In the first attempts to cast at considerably higher speeds than normal, it was found that in the first zone of the roller apron (i.e. shortly below mould exit) the thin shell was unable to withstand the ferrostatic pressure, and therefore the slab would bulge in between the supporting rolls, and the break-out frequency would increase. The efforts that were made to overcome this situation can be divided into three steps:

- First, it was attempted to shorten the distance over which the slab was not supported, by reducing the diameter of the roller apron rolls. With larger slab widths, this would lead to bending of the rolls, and back-up rolls were necessary to prevent this. The method had two disadvantages. Back-up rolls are making the device more expensive and, in case of a break-out are easily damaged. The second disadvantage is that it becomes difficult to arrange the secondary spray pipes in between these small-diameter rolls with back-up rolls.

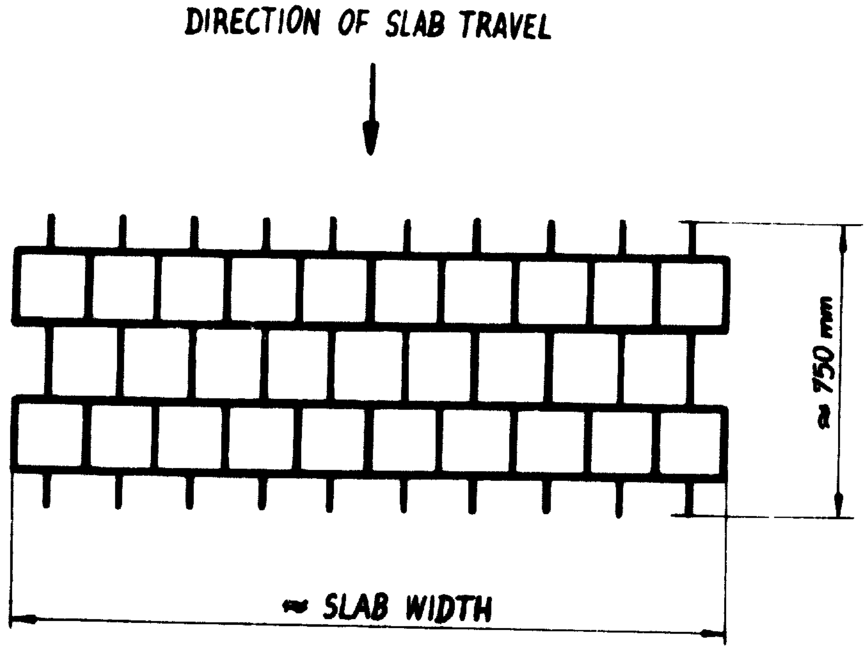
- The second step was the introduction of so-called "cooling plates". These consist of a copper plate (other materials such as cast iron and steel have also been tried) which supports the slab, and on the opposite side it is water-cooled. Through small holes across the copper plate, a direct water cooling of the slab surface is also accomplished. By replacing the entire first zone of the roller apron, or at least part of it, by such cooling plates, it was possible to achieve higher casting speeds without bulging of the slab. Such plates are still in operation on many slab machines, but in the meantime an even better solution has been developed by CONCAST, namely "cooling grids".

- Cooling grids consist of a web- type cast-iron frame (see Figure 2), which supports the slab after it leaves the mould. These grids are roughly 750 mm long and made of nodular cast iron, whereby on latest-design grids the contact surface toward the slab is made of a specially wear-resistant material, thus ensuring long life of the grids themselves. The advantage of the cooling grids is their very simple design and the fact that a full-cone spray nozzle can easily be arranged to cover the area of one square for secondary cooling. The cooling grid thus gives a very good support to the slab and at the same time allows secondary cooling of desirable intensity. Cooling grids are already in operation on several slab machines and the results are fully satisfactory.

The higher casting speeds also necessitated a modification of the withdrawal-straightening unit. In the first generation of slab machines, the function of this unit was clearly separated from that of the roller apron. It served exclusively for withdrawing and straightening the completely solidified strand. For this purpose, it could be built with large-diameter rolls. The advantage of this design was that it allowed the application of considerable straightening forces, so that in case of trouble, even a completely cold slab could still be straightened and thus removed from the machine (Figure 3).

Figure 2

Schematic Sketch of Cooling Grid



Photograph Showing Part of a Cooling Grid

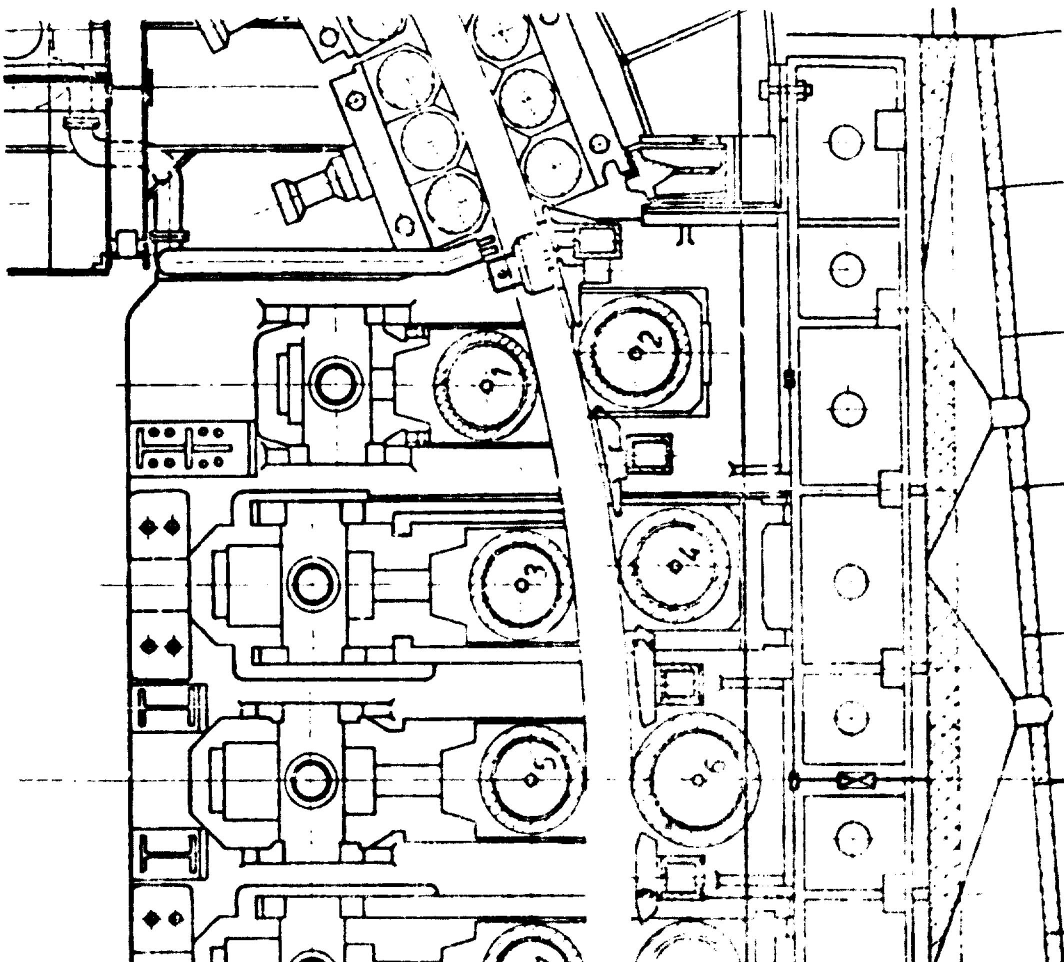


Figure 3. Conventional Concept of Withdrawal-Straightening Unit.

With higher casting speeds, the liquid core of the slab could no longer be prevented to exceed the roller apron, unless the casting radii would be increased to uneconomical proportions. However, with liquid cores in the withdrawal units of the above design, the high ferrostatic pressure at this point again caused bulging of the slabs. In order to give the strand sufficient support in this area, the large rolls had to be replaced by a number of smaller rolls with smaller roller spacing. The withdrawal-straightening unit thus takes on the additional function of a strand guidance (see Figure 4).

Limitations

For the sake of completeness it must be mentioned that the higher casting speeds, which were mentioned in the beginning and which are possible with the above modifications, are presenting problems when applied to plate grades. With a liquid core reaching down into the horizontal area of the machine, segregation can occur, and the subsequent hot reduction on plate grades may not be sufficient to reduce this to acceptable levels. For strip grades, this limitation does not apply. In fact, the application of high casting speeds is today mostly in connection with steel grades intended for cold-rolled sheet.

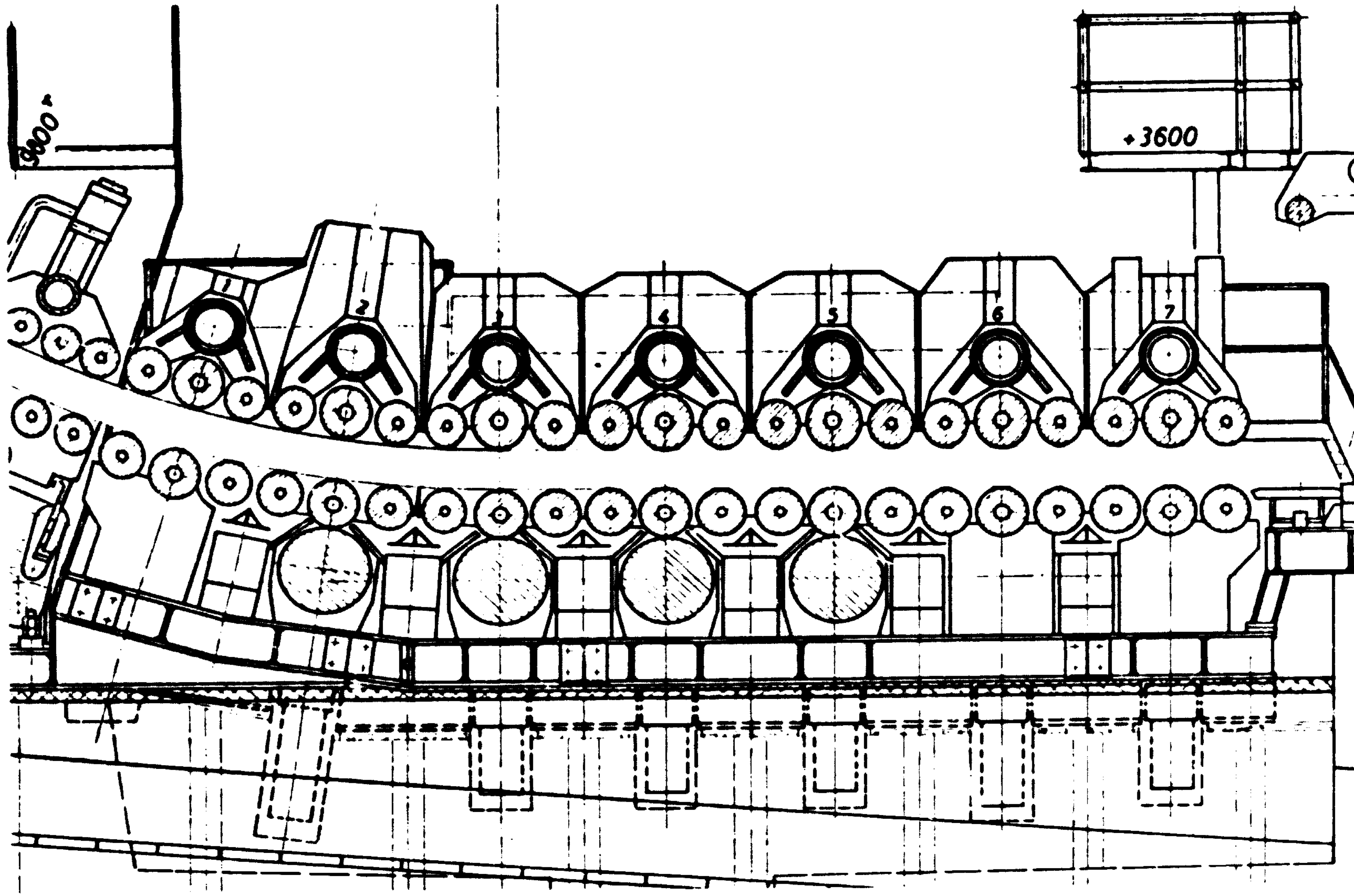


Figure 4. Modern Multiroll Withdrawal-Straightening Unit for High Casting Speeds.

II) Higher Machine Utilization

We shall now look at those changes in casting technique and equipment which were made in order to satisfy the requirement of higher machine utilization.

a) Sequence Casting

Ten years ago, it was standard practice to make one cast, i.e. to empty one ladle of steel, then the cast was terminated and preparation for the next cast was begun (insertion of the dummy bar, replacing tundish, etc.). Casting times were in the order of 45 to 60 minutes, and preparation time amounted to 30 to 45 minutes, sometimes longer. One can readily see that, with this procedure, actual casting time was only 50 to 66 % of the available time, and 12 to 16 casts only were possible each day.

A significant increase in machine utilization was only possible by casting two or more ladles consecutively, i.e. without interrupting the actual casting process. This technique is referred to as "sequence casting" and has been widely adopted in recent years. There are quite a number of machines in operation, whose production is accomplished mainly by sequence casts.

In order to cast two or more ladles in sequence the following requirements have to be met:

1) The second ladle must always be ready with steel of proper temperature and analysis when the first ladle is nearly empty.
2) Equipment must be available to exchange empty and full ladle in a minimum time.
3) Since casting from tundish to mould is maintained during ladle exchange, the tundish capacity must be sufficiently large to allow several minutes' casting.

The most critical of these requirements is the first one, as it necessitates scheduling of the melting furnaces and good coordination between steel plant and casting plant. This has occasionally presented not only technical but also psychological problems, because in conventional ingot casting the casting pit took full ladles whenever the steel plant had them ready, while, for sequence casting, the steel plant has to take orders from the continuous casting operators as to when a heat must be ready and tapped.

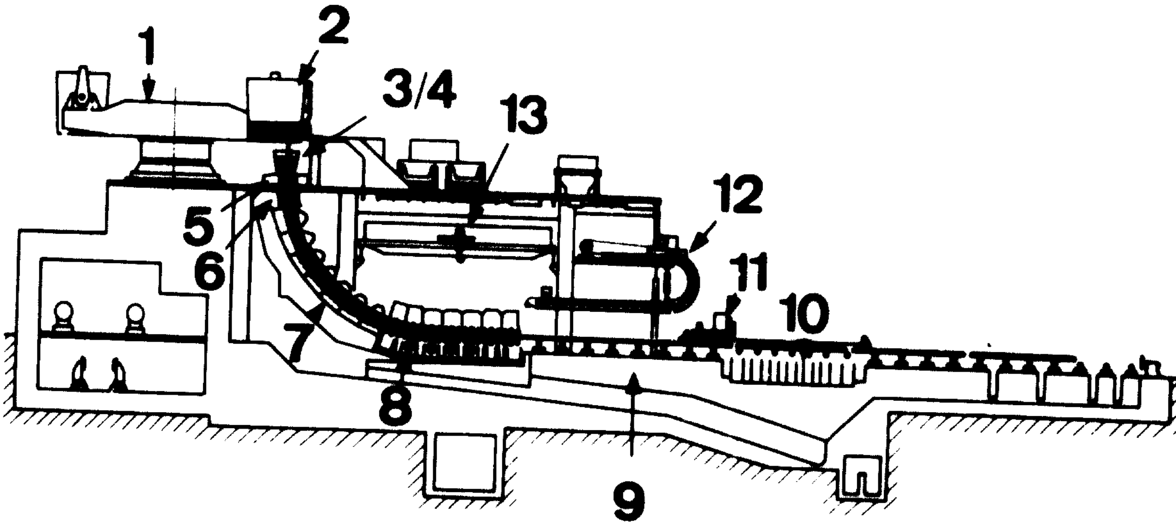
With respect to the second requirement — equipment for quick ladle exchange — this is accomplished by one of the following methods:

- two ladle cranes
- ladle cars
- ladle rotating tower

Figure 5 shows the ladle rotating tower of a recently commissioned slab machine. A 180° turn takes only 30 seconds and an exchange with ladle cars takes about the same time. Including the time for getting the stopper gear ready, the total time from closing the

Figure 5

Cross-Section of a Slab Machine with Ladle Turn Tower



1 Ladle turn tower
2 Ladle
3 Tundish
4 Tundish car
5 Mould
6 First zone of strand guide
7 Roller segments, secondary cooling zone
8 Roller-segment
withdrawal and straightening zone
9 Intermediate roller table
10 Cutting roller table
11 Cutting machine
12 Dummy bar storage
13 Auxiliary hoist for roller segment maintenance

stopper of the empty ladle to opening the stopper of the full ladle takes 1 to 2 minutes for ladle tower or with ladle cars. With two ladle cranes, some 3 to 4 minutes are required, because this involves careful positioning of the full ladle, and lifting as well as travelling speeds of ladle cranes are relatively slow.

At casting rates of 2-3 tons per minute (the casting speed is reduced during ladle exchange) a considerable tundish capacity is necessary to maintain casting during this period. However, a large tundish capacity is also desirable from the metallurgical point of view, because the longer residence time of the steel gives the non-metallic inclusions a chance to rise.

If several ladles are to be cast in sequence, the tundish refractories, in particular the nozzle or submerged tube, can become a problem. In this case it is possible to exchange the tundishes either on tundish cars or with a rotating tower. The short interruption of the casting causes no problems if it does not last longer than a minute. After that, the shrinkage causes the shell to retract from the mould wall, and on continuation of the cast the liquid steel would flow in between shell and mould wall.

As routine operation many steel plants make sequence casts of 2 to 6 ladles, but records of 80 to 100 ladles cast in sequence have already been accomplished.

b) <u>Shorter Down-Time for Machine Preparation, Size Change, Maintenance and Repairs</u>

b 1) Machine Preparation

The second possibility to increase machine utilization is to shorten the down-time for

- machine preparation,
- size change,
- maintenance and repairs.

The time required for machine preparation between two casts is mainly a function of the following steps:

I Stop or slow-down withdrawal of slab at end of cast to await solidification of steel meniscus (danger of explosion if secondary cooling water hits liquid steel),

II Withdrawal of slab end from machine,

III Reinsertion of dummy bar.

The steps I and II can hardly be shortened, but it is possible to reinsert the dummy bar from the top, i.e. through the mould, which can be done while the slab end is slowly discharged from the machine. Special care has to be taken to avoid damage to the mould, and the use of inflatable-type dummy bars has been suggested in this connection. The insertion of a conventional-type flexible dummy bar from above on slab machines is presently being tested with good results and it is likely to become operational in the near future.

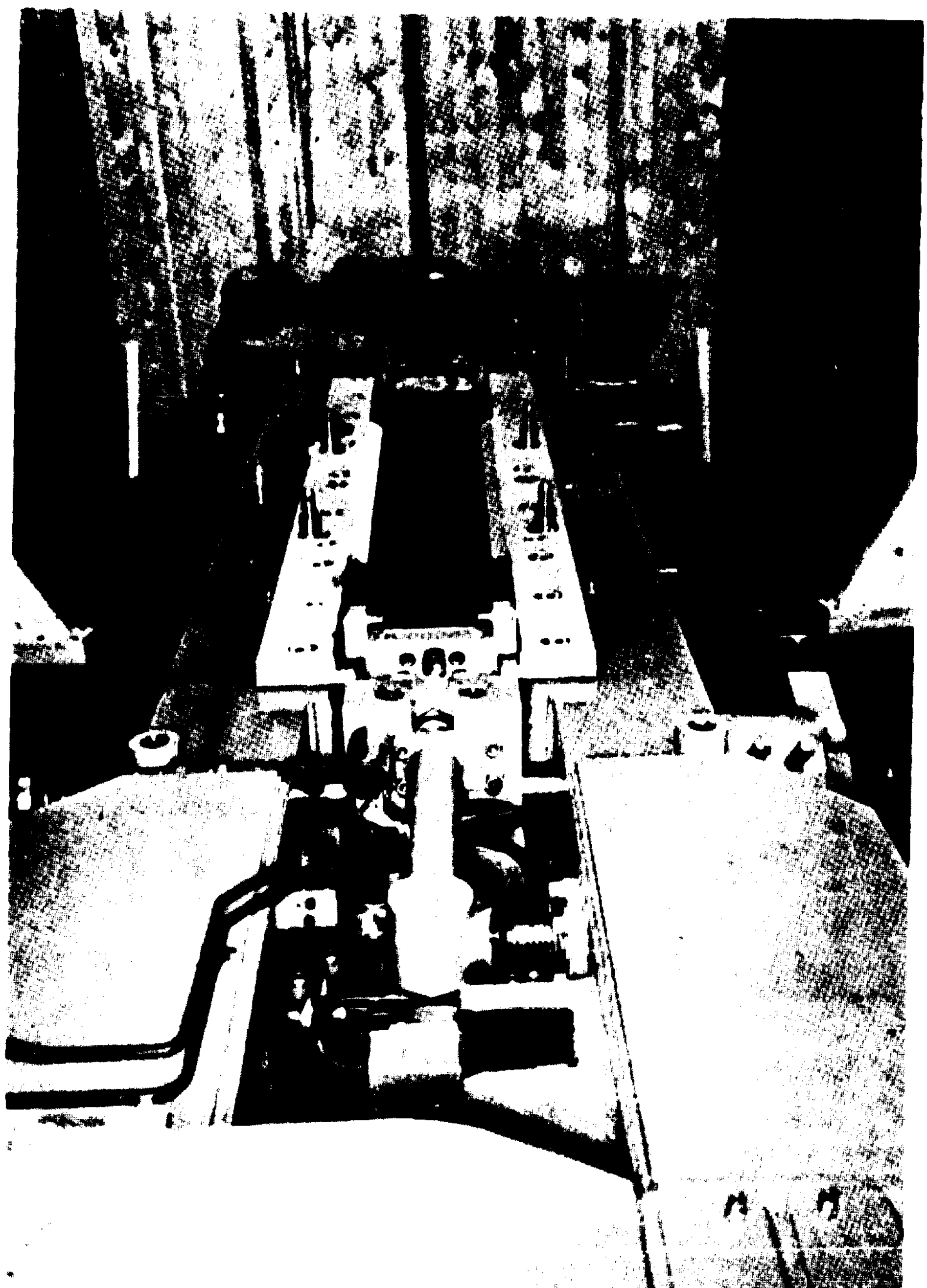
b 2) Size Change

In order to reduce down-time for change of slab sections, considerable modifications have been made, of which the most effective is probably the development of adjustable moulds. First-generation moulds were built for fixed sizes of slab cross-section, and had to be exchanged when a different size was to be cast. The alignment of the new mould relative to the roller apron had to be carried out on the mould table and the coupling of water in- and outlets had to be made manually. On the adjustable moulds (shown on Figure 6), changes of slab width can be carried out in casting position over a width range of approx. 500 mm. This change is no longer limited to starting with a narrow width and increasing it,but narrow sides can be moved inwards and outwards as desired. For this movement the mould is equipped with spreading cylinders between the movable and the stationary sides for releasing the narrow-side plates, and hydraulic cylinders are provided for displacing the narrow sides to the new section width. The new width is dictated by a template hung into the mould.

All aligning devices are incorporated in the mould itself, so that the alignment can be simulated in the machine shop by remachining of adjusting pieces (to suit the remachining of the copper plates) and by resetting of

Figure 6

Adjustable Slab Mould with Adjusting Device.



the guides. The alignment of the mould in the casting position then follows in compulsory fashion by means of suitable rigid guides when the mould is lowered onto the mould saddle.

The cooling water in- and outlets are arranged in the fixed side frame, so that the coupling of them takes place automatically when the mould is lowered.

For a change of slab thickness, the narrow-side copper plates are exchanged in the machine shop.

Similar to the mould, the first zone of the strand guide on older slab machines had to be replaced for every size change. On new machines this zone has a width adjustment matching the adjustment range of the mould.

A simplification of size change was also accomplished with respect to the dummy bar. Only one universal dummy bar per strand is used for all section sizes. Special transition pieces and dummy-bar heads are providing the necessary adaption for individual slab sizes. The dummy-bar heads are adjustable for various slab widths by simple spacers. The dummy-bar heads are claw-shaped in such a manner that disconnection from the strand can be accomplished by simple tilting of the head.

As a result of the above improvements it is now possible to make frequent size changes and still reach high production figures. A slab machine which incorporates these design features and which was commissioned about one year ago reports a monthly production of 50-55,000 tons (2 strands) whereby on the average every ten heats a size change is accomplished. Even without sequence casting, up to 18 heats per day are being made. Another two-strand slab machine reports a monthly production of nearly 70,000 tons, including 1-3 changes of slab section each day. Life time of these adjustable moulds is also quite satisfactory.

It is obvious that such production rates can only be accomplished with a minimum of down-time for maintenace and repairs. This is possible since in the design of these modern machines special emphasis was placed to assure easy accessibility and simple and quick replacement of all parts that are subject to wear and therfore require frequent control and maintenance.

In this connection it should be mentioned that moulds and first zones which were described above can be removed either individually or as one unit. In case of damage resulting from a break-out, this flexibility allows a significant time saving.

b 3) Spray Nozzles

A further effort, also with the aim of equipment simplification and reduction of maintenance, is being made in the field of spray nozzles for the secondary cooling water. The spray nozzles used on slab machines until now were covering a range of 100 to 150 mm slab width, e.g. a slab width of 2200 mm necessitated 17 nozzles on each horizontal spray pipe. The relatively small nozzle bores are subject to clogging, and therefore periodic checking is necessary. For a total of 700 to 1200 nozzles per strand, this is a time-consuming procedure. In addition these nozzles do not allow the wide variation of cooling water intensi y which is required when casting various steel grades at various casting speeds. On a test basis some machines are therefore equipped with specially designed nozzles having extra large spray angles. With only three nozzles a slab width of 2200 mm is covered, and in some cases trials are made with one single nozzle over the entire slab width. At present this appears to be an extreme solution, but there is little doubt that the number of nozzles will be drastically reduced.

III) Improved Product Quality

As in the conventional ingot casting process there are always efforts to improve the product quality of continuously cast material. Leaving apart the adaptations of the melting and deoxidation practice, we would only mention here the modifications in the casting technique. Two points have received most attention in this respect:

a) Prevention of reoxidation by avoiding air-to-liquid steel contact, and

b) Careful control of casting parameters such as steel temperature and cooling intensity.

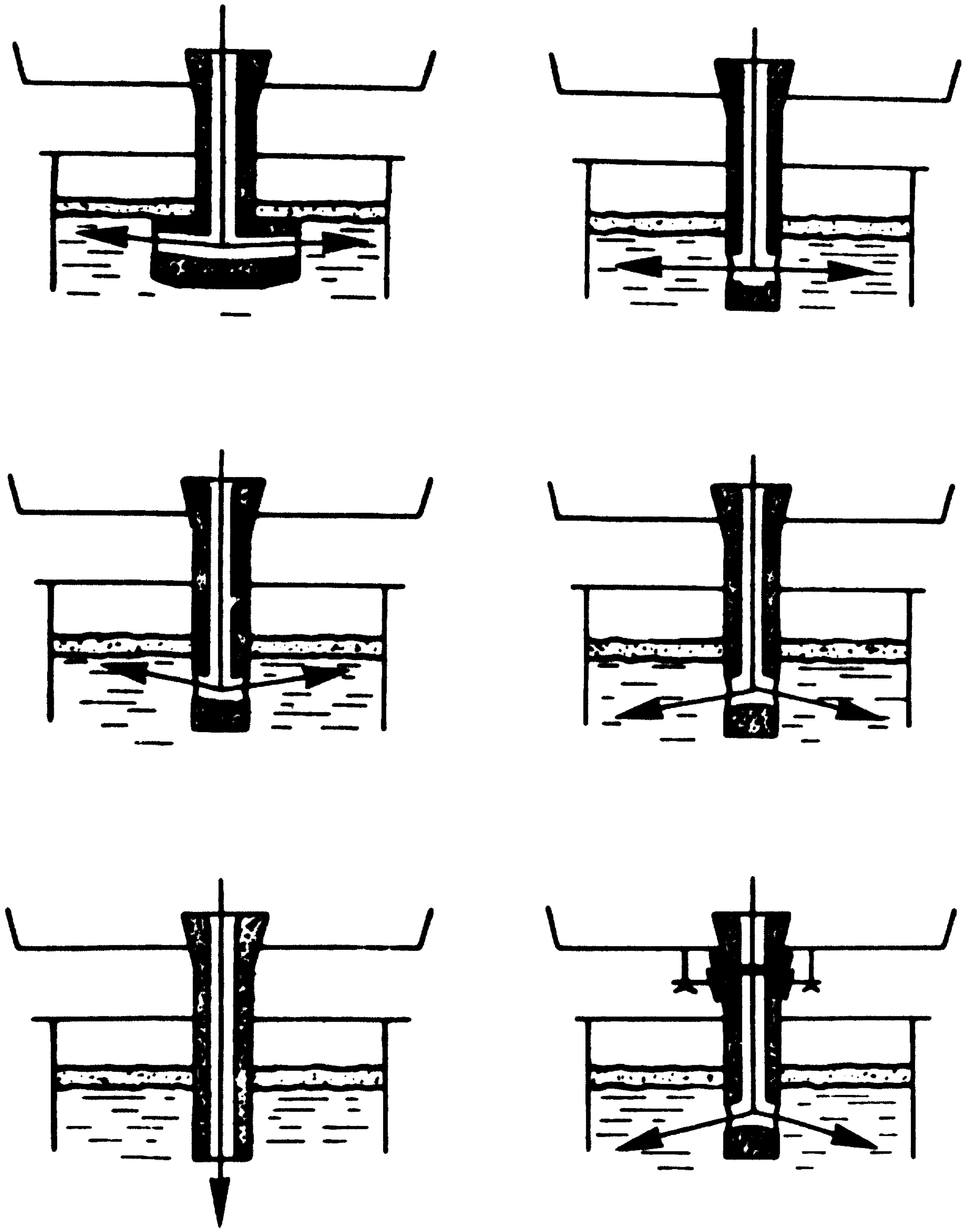
a) The title "latest developments" of this paper does no longer justify the listing of casting powder and submerged tube casting, since this technique is nearly ten years old and has become standard practice in slab casting. It must be mentioned, however, that recent years have still brought new developments and improvements in this field. The scope of this paper only allows listing the areas where progress has made:

- Development of various casting-tube materials to suit individual steel grades (erosion resistance!),

- Study and development of various arrangements of casting tube outlets to optimize flow patterns and inclusion removal (Figure 7),

Figure 7

Various Arrangements of Casting Tube Outlet



- Development of various casting-powder compositions to suit individual steel grades,

- Establishment of important criteria for casting powders and development of methods to control them (powder testing, synthetic powders),

- Protection of steel stream with refractory tube even between ladle and tundish (Figure 8). (This is common practice when casting stainless steels.)

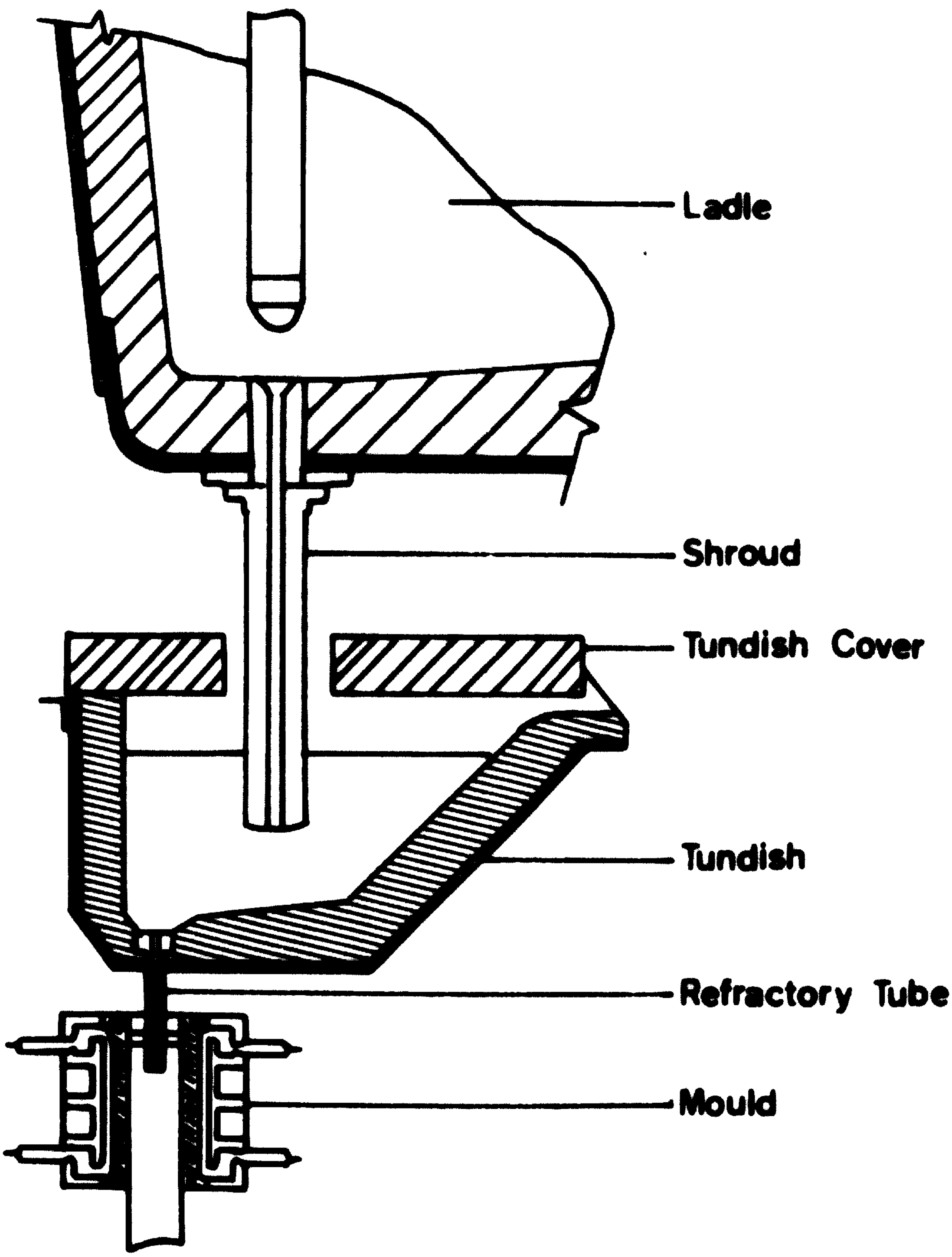
The best evidence for the increased cleanliness resulting from these improvements is that continuously cast deep-drawing material is now used for exposed parts by automobile manufacturers in Europe, USA, and Japan.

b) With respect to steel temperature and cooling conditions we would only mention that uniformity of steel temperature (as resulting from gas rinsing) together with lowest casting temperature compatible with safe operation have been found to be important factors to minimize segregation.

Maintaining proper and uniform secondary cooling conditions are most efficient for minimizing external and internal cracks.

<u>Figure 8.</u>

Protection of Steel Stream between Ladle and Tundish.



IV) Automation and Computer Control

Another feature of modern slab machines is the application of automatic controls. What has been accomplished by now is far from a complete process control by means of on-line computers but the trend is in this direction. In some cases computers have already been used in connection with continuous casting machines, but mainly for data-logging and evaluation.

Some parts of the machine are already automatically controlled. This has a two-fold advantage. It not only saves manpower but results in more uniform casting conditions and thus in improved product quality.

In order to maintain a constant steel flow from tundish to mould, the steel level in the tundish must be kept constant. This is accomplished by setting the tundish on load cells, and the relative signal is used to automatically open and close the ladle stopper or slide-gate valve.

The steel level in the mould is also stabilized by a control loop. A radio-active source on one side of the mould with a scintillation counter on the other side allow to determine the position of the liquid steel meniscus. The signal is used either to open or close the tundish stopper or to vary the withdrawal speed (see Figure 9/10). This results in more uniform casting conditions and has a beneficial effect on slab surface quality. On multi-strand machines this device allows even a reduction of operators.

Figure 9

Automatic Mould Level Control - Tundish Stopper Control

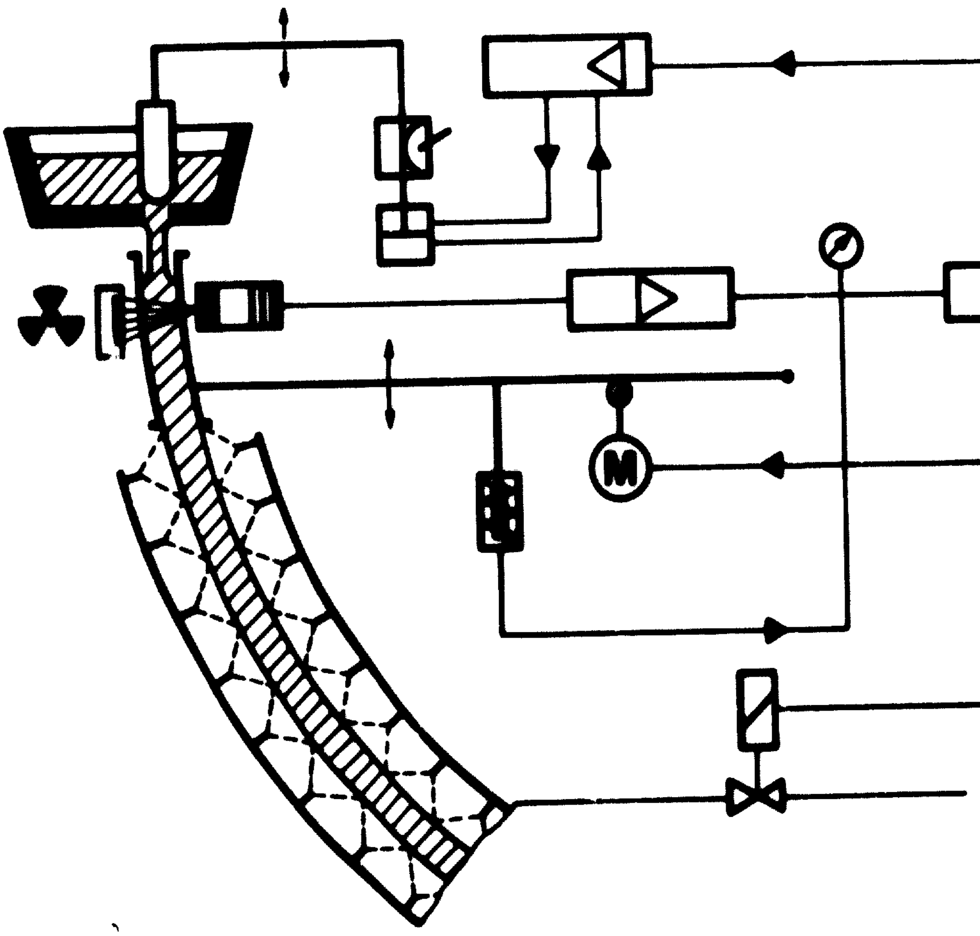
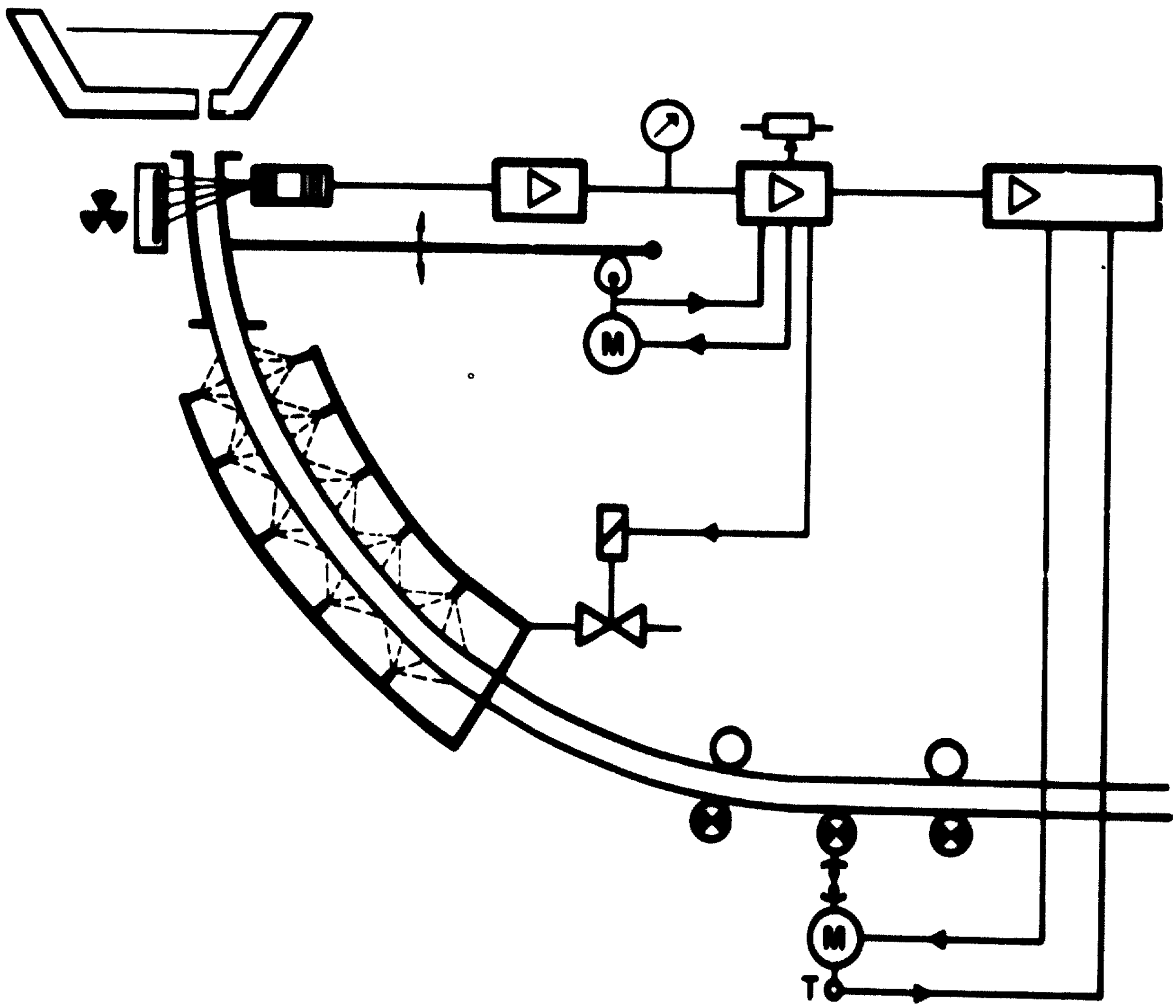


Figure 10

Automatic Mould Level Control - Casting Speed Control



For high-quality slab grades it is important to keep the intensity of secondary cooling within narrow limits. Changes of steel temperature and/or casting speed therefore require an immediate adjustment in cooling water flow. One of the latest developments is the automatic adjustment of the secondary cooling water as a function of slab surface temperature. It can be expected that considerable progress will soon be made in this area.

V) Economic Aspects

The developments that have been described in the foregoing sections of this paper hava undoubtedly a significant effect on the aconomics of continuous slab casting.

a) Investment Costs

The most obvious saving rasulting from these improvements lies in the reduction of investment costs per annual ton of capacity.
A slab machine casting individual heats can be assumed to maka approximately 4000 casts per annum (based on 12 to 14 cast per day and 300 operating days). With sequence casting a figure of 6000 casts can well be reached. This 50 % increasa of production is only causing a minor increase of tha investment (mainly ths additional equipment which is requirsd for a quick exchange of ladles) and thus the investment cost per ton of installed capacity is reduced by about 30 %.

The effect of increased casting speeds is equally significant. The productivity of a machine increases proportionally with increasing casting speed. In practice this means that for a given converter size and slab section a one-strand machine may be sufficient to empty the ladle within the acceptable time, while at lower casting speeds the same conditions made a two-strand machine necessary.

The same is true when a given converter cycle has to be met. If the casting machine is to accept every second heat of a converter, the higher casting speeds of today may allow to reach this casting time with one strand, while two strands would be required at lesser speeds.

Again it must be mentioned that the modifications that were required to allow high-speed casting are causing a higher machine price, but this is in no relation to the overall reduction of investment costs.

Under the heading "Shorter down-time" the development of adjustable moulds has been mentioned. This development has a beneficial effect on the economy in two ways. The productivity of the machine is increased because less time is required for a change of slab cross-section. The other effect is that with fixed size moulds a considerable number of moulds must be on stock, if a large number of slab dimensions is on the casting programme, while with few adjustable moulds the entire size range can be covered. Considering the price of a slab mould, this small stock represents a big saving in equipment cost.

b) Conversion Costs

The conversion costs from liquid steel to continuously cast slabs can be broken up in the following groups:

1) Consumable materials (electric power, preheating fuel, lubricants, refractory material).
2) Wages of operators
3) Maintenance and repair costs (material and wages)
4) General overhead costs
5) Depreciation

1) Besides of the beneficial effects of sequence casting that were already mentioned, it also reduces the consumption of various materials:

- Tundish preheating fuel is saved, because the tundish is preheated only once and then used for casting two or more ladles.

- The cost of the submerged tube is also reduced to 50 % or more, depending on how many heats are being cast through it.

- The consumption of refractory material for lining the tundishes is reduced because of longer life. Most damaging to the lining is the change from nearly room temperature to casting temperature and back. With sequence casting this temperature change takes place only once for several heats.

2) Wages of Operators

These are reduced according to the higher productivity that is achieved by sequence casting and by increased casting speed; therefore more tons are cast per man hour.

To some extent the automation of controls can reduce the number of operators necessary.

3) Maintenance and Repair Costs

Changes, if any, are not significant.

4) General Overhead Costs

These are generally fix according to individual steel plant. They are not affected by improvements as listed.

5) Depreciation

Depreciation costs per ton are significantly lower, namely in proportion to the reduced investment costs.

c) Other Savings

- One more benefit of sequence casting is to be mentioned. The yield from liquid steel to cast slab is higher because, for two or more ladles, there is only one head and foot cropping per slab. The loss caused by tundish skulls is also reduced in relation to the number of heats cast through the same tundish.

- Since not only the tundish but the entire machine is well preheated for the second and further ladles, the required steel temperature for these is approx. 20^{o} C less than the first heat. It has been reported that this has a beneficial effect on lining life of ladle and even of the converter.

- The developments to increase product quality reduce the costs for conditioning the slabs and increase the yield of final product relative to cast slab.

It is not possible to express all these benefits in dollars and cents, but a good evidence for the economic advantage of continuous slab casting over ingot casting is the fact that today this process is being chosen for steel plants with 4 to 8 million annual tons. Until a few years ago, productions of such magnitude were strictly reserved for the conventional ingot casting and rolling method.

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