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# The First Commercial Plant for Carbon Steel Strip Casting at Crawfordsville


By

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# THE FIRST COMMERCIAL PLANT FOR CARBON STEEL STRIP CASTING AT CRAWFORDSVILLE

# MANFRED WOLF SYMPOSIUM ZURICH, 10 MAY, 2002

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## INTRODUCTION

The technology of direct twin-roll casting of carbon steel strip less than 2.0 mm, without further hot or cold rolling, is now being introduced commercially by Nucor at its Crawfordsville, Indiana plant in the United States. The use of the term "commercial" very specifically means a plant that makes excellent profits considering the full cost of the products, including capital.

The CASTRIP® process used by Nucor produces steel strip between 0.7 and 2.0 mm in thickness, directly from liquid steel. For many applications the product will be directly usable by customers, without further hot rolling, pickling or cold rolling. It can be coated with zinc or aluminum/zinc, painted and formed without further processing, and will be available in strength levels from about 250 Mpa to more than 600 Mpa – all using a single, simple chemistry.

This paper will discuss the technical achievements that have been necessary to realize a commercially successful strip caster, as well as some of the challenges that lie ahead. Also discussed will be the factors that have contributed to the success to date, including the direct involvement of Manfred Wolf.

## BACKGROUND

BHP (Broken Hill Proprietary Company) of Australia and IHI (Ishikawajima-Harima Heavy Industries) of Japan began a collaborative development project in 1988 to commercialize twin-roll strip casting of steel. Code-named Project 'M', BHP and IHI built a pilot plant in Port Kembla, Australia with the capability of casting five-tonne coils 800 mm in width. Initial results with austenitic stainless steels were promising. By 1991, commercially acceptable 304 stainless coils were cast at 800 mm widths and subsequently rolled at BHP Steel's stainless steel facilities. Initial attempts at casting carbon steels indicated that this would be much more difficult. The pilot plant successfully cast a series of 1300 mm wide, low-carbon heats in 1992.

In 1993, the Board of Directors of BHP approved construction of a full size "Development Plant" aimed at proving the technical viability of strip casting of carbon steels. Construction began in 1993 and first casts were conducted in early 1995. This plant was "full size" in that it was capable of casting 60-tonne ladles of carbon steels into coils with a width of 1,345 mm (although the equipment was capable of widths to 2,000 mm wide). Initially, the target thickness was 2.5 mm. Heat sizes for the plant were limited by the old, low-power EAF (electric arc furnace) utilized for the project, which limited continuous operation.

The Project 'M' Development Plant was operated until the end of 1999, perfecting the technology of casting low-carbon steels into a variety of commercial products. In total, more than 35,000 tonnes were produced at the plant, culminating with a process capability trial of 29 heats at 50 tonnes each at a cast thickness between 1.9 and 2.0 mm. Material was subsequently cold rolled, metallic coated, painted and rollformed into commercial roofing products for the Australian market. Additional material from the run was shipped to a BHP subsidiary in the United States where it was processed into structural decking for the construction market. Approximately 30 tonnes were processed into pipe and tube by another BHP subsidiaryCASTRIP material has also been processed into pipe and tube of various diameters. Customers have used the CASTRIP material as-cast, single stand hot rolled with the built in mill, pickled, unpickled, cold rolled and coated. For most of these trials, the yield rate of the material exceeded 90%. The results clearly proved the technical feasibility of the CASTRIP process. However, without a supply of molten steel to conduct multi-heat sequences, full commercial feasibility could not be determined.

During 1999, a Commercialization Team was formed within BHP to carefully examine the most appropriate path forward for commercializing the BHP/IHI technology. The status and future of the industry was examined, and testing of various alternatives was done using scenario planning. Alternatives considered ranged from simply ending the technology development, through construction of a BHP owned, full size commercial plant. The final recommendation was to invite the participation of a third partner to bring the CASTRIP technology to full-scale commercial production.

A worldwide search for the ideal partner was conducted and Nucor Corporation, the largest steel producer in the United States, was identified as the optimum choice. Nucor possesses an excellent track record in technology implementation combined with significant experience in flat rolled steel production. Discussions among BHP, IHI and Nucor led to the formation of Castrip LLC, which is now established in Charlotte, North Carolina (Nucor's headquarters). Castrip LLC is a Limited Liability Company owned 47.5% by Nucor, 47.5% by BHP and 5% by IHI. The purpose of Castrip LLC is to make the technology and patents related to the CASTRIP process available to third parties. Nucor is the first licensee of the CASTRIP technology through Castrip LLC and has now built the first truly commercial strip casting plant in the world at Crawfordsville, Indiana. When the Nucor CASTRIP plant is operating, cumulatively more than US$ 400 million will have been spent on the development from laboratory through commercialization.

## PROCESS OVERVIEW

The CASTRIP process is based upon the same concepts that Sir Henry Bessemer patented in the mid-19th century. Figure 1 shows a simple schematic of the basics of the process – two counter-rotating rolls that provide a surface or mold against which molten steel solidifies. As the figure indicates, the steel begins to solidify against the rolls just below the meniscus and shell growth continues as they move as it moves downwards through the melt pool. At the roll nip or pinch-point, the two shells fuse together forming a continuous strip, which then exits the caster in a downward direction.

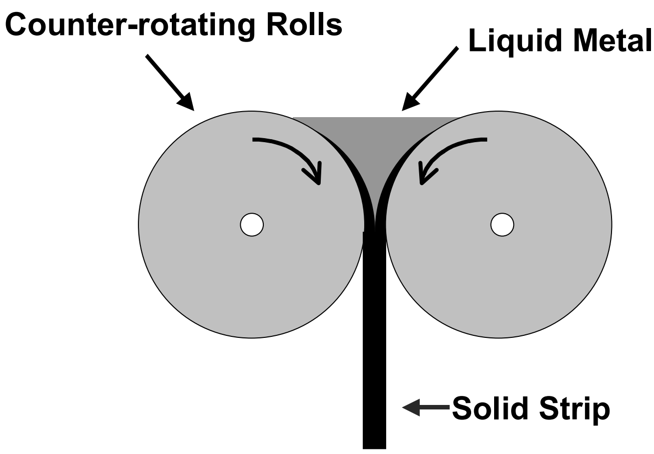


Fig. 1 – Simple schematic of the twin-roll strip casting process.

Although the concept is relatively simple, its application at a commercially viable production level has proven to be extremely difficult. Several technical advancements have occurred in recent years that have made twin roll casting possible at a commercial level. These include:

- High speed computing and process control

- Advanced ceramics and materials (including copper alloys)
- Sensing technology
- Mathematical modeling of physical phenomena

In addition to these advancements, the Project 'M' team had to significantly increase the body of knowledge related to several key areas of process metallurgy directly connected to the twin-roll process. Previous papers have discussed the development of the CASTRIP process (1-4); these advancements or breakthroughs are what sets CASTRIP technology apart from other twin roll processes and can be divided into 5 key areas:

1. Metal delivery
2. Early solidification
3. Edge containment
4. Roll distortion
5. Refractories

**Metal delivery -** Metal delivery to the melt pool is critical for a number of reasons. Unlike conventional casting, the melt pool is very small in the CASTRIP process. As a result, the ratio of mass flow rate into the pool to the pool volume is nearly an order of magnitude higher in the CASTRIP process compared to slab casting. Thus, the metal delivery nozzle or core nozzle utilized in the CASTRIP process is completely different from that used for conventional casting, with major emphasis on reducing the turbulence in the steel as it enters the melt pool plus theand the need for effective distribution of metal along the roll length. A further requirement of the metal delivery system is to provide metal to the meniscus in a stable and repeatable manner. Any disturbance at the meniscus invariably manifests itself as a strip defect. Thus the process must be stable and in control at all times to ensure excellent surface quality.

**Early solidification -** Most of the effort related to the understanding of solidification in steels has been confined to continuous casting over the past 20 years. There are some major differences between CASTRIP technology and slab casting that have significant effects on the formation and growth of the shell. Figure 2 shows a close-up of the meniscus area in both processes. Among the main differences between the two processes are that the CASTRIP technology does not use any type of mold powder or lubrication and that the mold (roll) and steel shell remain in direct contactmaintain the same velocity, i.e. no mold oscillation. As a resultBecause there is no mold powder, there is significantly better contact between the roll surface and solidifying shell, starting at the meniscus and extending down to exit at the roll nip. Significant work has been done in trying to understand the mechanisms for shell formation and growth as well as heat transfer between the steel and roll surface. This work has been described previously (1) and it is critical that the variables affecting the early solidification of the shell and its subsequent growth be understood for the production of quality strip.

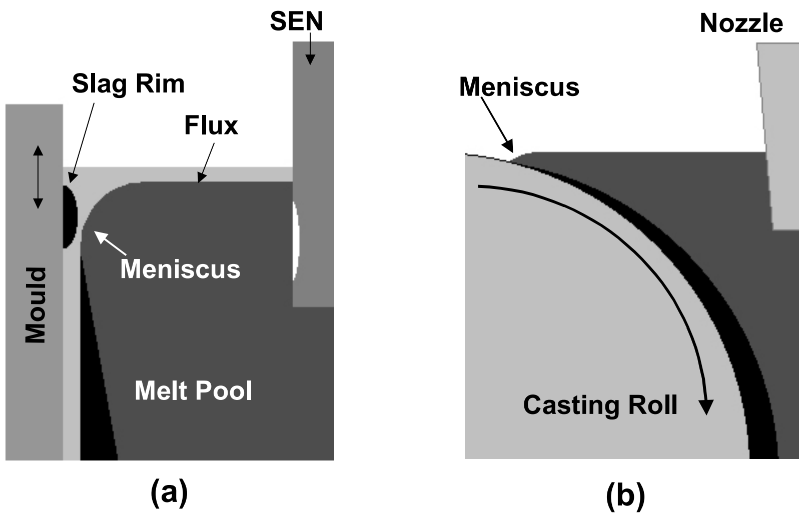

Fig. 2 – Comparison of the meniscus region in (a) conventional slab casting and (b) the CASTRIP process.

**Edge containment –** Although most of the surface area of the solidifying strip is confined to contact against the face of the rolls, the edge containment of the melt pool proved to be a technical challenge that required significant focus during the development of the CASTRIP process. Freezing is most likely to occur in this area because of heat loss through the side dam material as well as through the rolls. Premature freezing can lead to poor edge quality as well as triggering a series of events that eventually lead to the cessation of casting. Many materials were tested for use as side dams before a suitable refractory was found.

**Roll distortion –** Roll distortion is caused by the generation of thermal stresses as the casting rolls become heated by the solidifying steel. The proper design of casting rolls must take into account this unavoidable distortion in order to produce strip with a desired thickness profile. Previous publications have demonstrated the variation in heat flux and temperature across a casting roll (2). This work also showed that rolls with a machined-in crown, where the center is smaller in diameter than the edges, will provide the optimum strip profile.

**Refractories –** The interaction between the liquid steel in the melt pool and the refractories utilized for the metal delivery nozzle hasve been shown to cause defects in the strip cast material (2). Active oxygen contained in the pool was shown to combine with carbon in the alumina graphite nozzle, resulting in the formation of CO bubbles. These bubble caused disturbances at the steel surface and at the meniscus where they resulted in surface defects on the strip. Defects caused by this mechanism have been eliminated through the selection of appropriate refractory materials.

## NUCOR'S CRAWFORDSVILLE CASTRIP FACILITY

Construction of the Nucor CASTRIP facility began in February 2001, with the start-up of the plant expected in May 2002. Fed from an existing EAF shop located less than 1 Km away, the CASTRIP plant includes a ladle metallurgy furnace (LMF) to make the necessary temperature and chemistry adjustments prior to casting. Figure 3 shows a sketch of the general layout of the Nucor CASTRIP caster building. In overall dimensions, the building is approximately 135 meters wide and 155 meters long. The total length of the casting operation, from ladle turret to coilers is only 60 meters. This is in contrast to a slab caster with reheat furnace and hot strip mill that typically requires 500 to 800 meters of length to make the same hot rolled products.

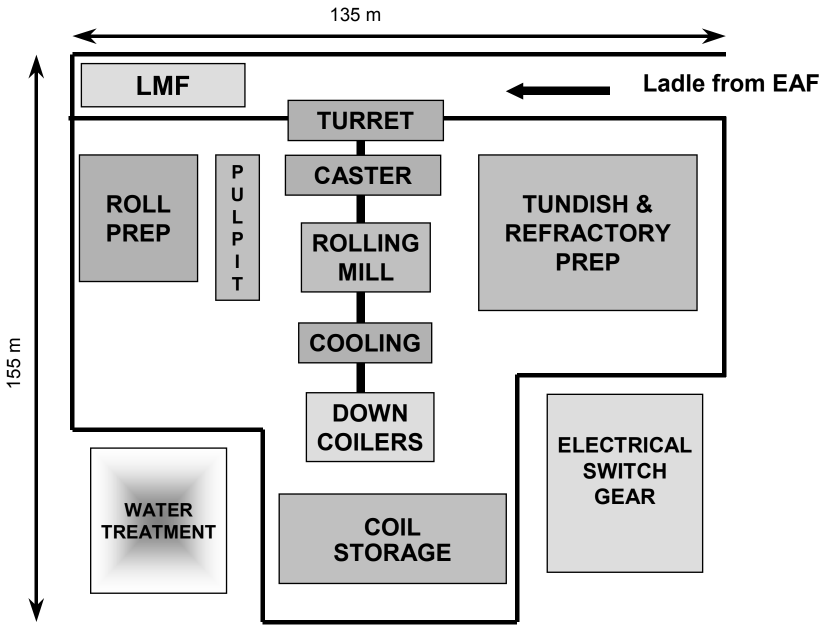

Fig. 3 – Nucor CASTRIP plant layout.

The CASTRIP facility is shown in profile in Fig. 4, indicating the main features of the process. The ladle and tundish are based on standard steel industry designs, as is the ladle turret (not shown). The tundish feeds a transition piece, which is situated just above the delivery (core) nozzle. The caster does not use a dummy bar for start-up. Upon exit from the casting rolls, the solidified strip is directed to a pinch roll then through a hot rolling stand. In this transition, the atmosphere is controlled to limit oxidation of the strip and the formation of scale. Equipment from the hot rolling mill through the coilers is also of standard steel industry design.

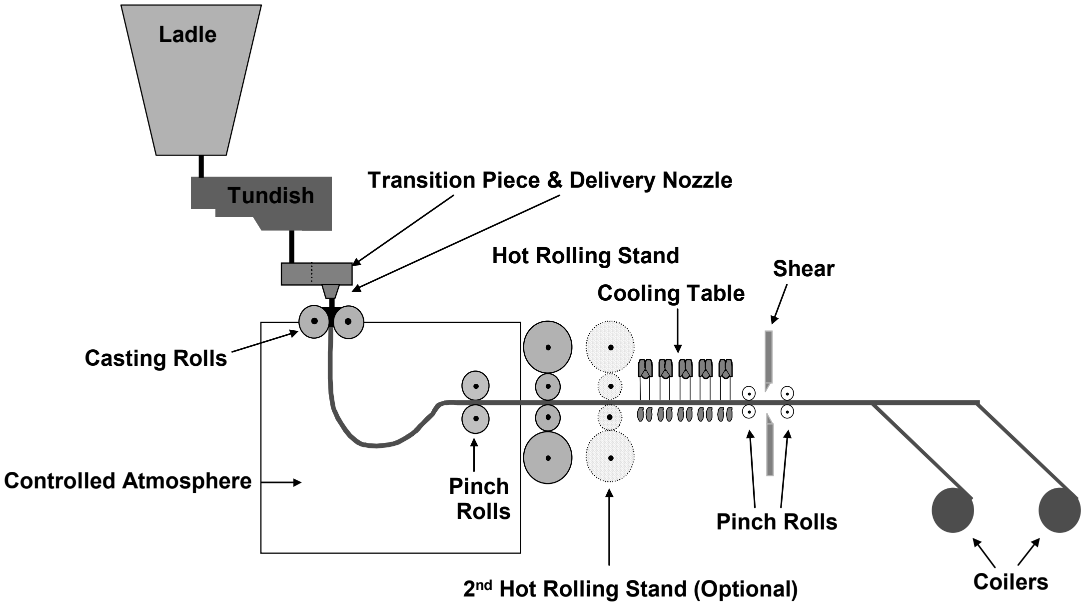


Fig. 4 – CASTRIP plant schematic.

A recent photograph of the Nucor CASTRIP plant interior is shown in figure 5.

Fig. 5 – Interior photo of Nucor's CASTRIP plant taken in February 2002.

General specifications for the Nucor CASTRIP caster are shown in Table I. Of particular note is the diameter of the casting rolls – 500 mm. This diameter is significantly smaller than other twin-roll casting projects and was chosen based on the development work done previously. The Nucor CASTRIP plant will have the capability of casting steel strip at 1.0 to 2.0 mm in thickness, plus a single hot rolling stand to reduce the material another 30%. At casting speeds of ~80 m/min, average cast thickness of 1.6 mm, and average strip width of 1211 mm, the output of the plant is expected to be ~500,000 tons per year.

Although the initial casting of Ultra-thin Cast Strip (UCS) steel at the Nucor CASTRIP plant will be low-carbon steels – and this is by far of the greatest commercial interest worldwide – Nucor also plans to begin casting ferritic stainless steel within the first year of operation. Development work recently undertaken indicates that 409 grade stainless should be well within the casting parameters of the Nucor CASTRIP plant. Combined with BHP's earlier development work, it is expected that a single CASTRIP plant will be able to easily cast carbon, austenitic and ferritic stainless steels. In general, the development path has indicated that a twin-roll casting machine designed and built for the rigors of carbon steel will be able to cast stainless steels, but the reverse is not true.

Table I – Nucor CASTRIP Plant Specifications

| **Unit** | **Specification (in metric units)** |
|---|---|
| Building Dimensions | 155 m x 135 m |
| Heat/Ladle Size | 110 tons |
| Caster Type | 500-mm Diameter Twin Roll |
| Casting speed | 80 m/min (typical)<br>150 m/min (maximum) |
| Product Thickness | 0.7 to 2.0 mm |
| Product Width | 2000 mm maximum |
| Coil Size | 25 tons typical, 40 tons max. |
| In-Line Mill | Single stand – 4 High with Hydraulic AGC |
| Work Roll Dimensions | 475 x 2050 mm |
| Back-up Roll Dimensions | 1550 x 2050 mm |
| Rolling Force | 30 MN maximum |
| Main Drive | 3500 kW |
| Cooling Table | 10 top and bottom headers |
| Coiler Size | 2 x 40 ton coilers |
| Coiler Mandrel | 760 mm diameter |
| Annual Capacity | ~500,000 tons/year |

## THE CHALLENGES OF A COMMERCIALLY SUCCESSFUL STRIP CASTER

As was noted in the introduction, Nucor has adopted the CASTRIP technology and built the world's first commercial carbon strip caster for only one reason – to make significant profits. From the earliest work done in Australia, the team has had a very clear focus on achieving a design that would be commercially successfully and not merely a laboratory curiosity. Of course, it is still too early in the development of strip casting to be able to undertake a historical analysis of what the real challenges were and how they were overcome, but following is a point-in-time assessment of the major challenges and how the development team addressed them:

### Metal-in-Mold Time

As was demonstrated at BHP's Project M plant, and as is currently being demonstrated at other strip casting projects around the world, it is undeniably technically feasible to cast commercially acceptable product for limited amounts of time. But to make profits, the plant has to be producing prime quality steel as much of the time as possible. This has been a major focus of the design improvements that were made to the Project M design as it was modified for the Nucor CASTRIP plant. Nucor required that the actual time that the CASTRIP machine was to be casting had to be at least as good as they achieve with their thin slab casters. In practice, this means that the Nucor CASTRIP plant is designed to achieve metal-in-mold times about 84% of the total time (which includes every minute of every hour of every day in the year). What does this in turn mean?

1. Minimum three ladle sequence lengths. Longer sequences are desirable (and probable) but the economic benefit diminishes quickly after three ladles. Besides, the realities of running a small scale, agile manufacturing plant include the ability to quickly change widths or other variables according to customer demands. Hence, small lot sizes will be the norm and very long sequences are not expected.

2. Very fast turnaround of the casting machine. There are at least five "consumable" elements in the casting train – The tundish/slide gate, the transition piece, the refractory set of side dams and metal distributor, the casting rolls, and the mill work rolls. A major challenge has been to design both a casting machine and ancillary support shops which allow one or all of these elements to be changed in less than ten minutes, even when all are done simultaneously. Use of relatively small (500 mm diameter) casting rolls has enabled simple roll changing carriages to be designed into the production machine at Nucor.

3. Very fast and reliable start of casting. A production machine cannot afford to be manually set up or have a less than certain start to casting. Therefore tremendous work has had to be devoted to having a totally automated starting sequence with virtual certainty of success in not only producing good strip quickly, but guiding it through the atmosphere control box, picking up the leading edge of the strip and automatically threading it through the pinch roll and mill, etc. To make this all the more complicated, the total operation takes place in a closed chamber containing a special atmosphere to prevent excessive scale formation.

## Yield

As in any steel mill process achieving a high yield is critical to achieving good profits. The goal of the Nucor CASTRIP plant is to process molten steel in the ladle to finished usable coils in one step, and hence Nucor has adopted the straightforward yield measure of weight of finished, side trimmed coils divided by the weight of liquid steel in the ladle. It is the goal of the CASTRIP technology to achieve yields, based on this measure, in the mid 90% range. What does this mean in practical terms?

1. Very quick achievement of thermal stability in the casting rolls. There is practically no opportunity for downstream thickness, profile, surface or shape correction, as there is in both thick and thin slab casters. The strip has to be right the first time, and the time to total solidification is about 150 milliseconds. This is one of the reasons BHP and IHI chose early on to work with small diameter rolls with relatively low thermal mass. Thermal and dimensional stability are usually achieved within twenty seconds of the metal entering the casting rolls.

2. Excellent edges, as cast. Many of the teams working worldwide to develop strip casting have produced strip of acceptable dimensions and surface after taking significant side trim either before or after the mill stand. The CASTRIP technology has previously demonstrated a need for only 15 mm per side trim. This is expected to reduce further with operational experience. No side trimming is done prior to the mill.

3. Minimum head and tail end crops. Head end crops are reduced as noted above by quickly reaching thermal equilibrium and also development of a starting technology that does not use a dummy bar. Tail end losses are virtually non-existent since the ladle, tundish and melt pool can all be sequentially and completely drained.

## Conversion Costs

This is perhaps the most critical area yet to be demonstrated, and can only be proven on a production machine. Even when this is done, it will take great care to make comparisons on an absolute cost basis. The reason for this is that absolute costs are very difficult to compare on a country – to – country basis. Fortunately, however, a more useful comparison standard does exist. Nucor operates what most analysts agree are some of the lowest cost flat rolled production plants in the United States. Since the Nucor CASTRIP plant will be located adjacent to the Crawfordsville thin-slab casters, it will be quite convenient to accurately compare the relative costs of the new CASTRIP plant with those of the thin-slab casters. All calculations done to date indicate that CASTRIP conversion costs will be equal to or slightly lower than those of a best-practice thin slab caster producing conventional hot band. This cost level will be achieved at a much smaller scale (0.5 mtpy) than the thin slab casters (2.2 mtpy). Furthermore, the UCS product of the CASTRIP plant will be on average much higher value than the hot band produced from a conventional hot strip mill. This is due to the fact that it is both thinner than hot band and it has a much superior surface smoothness. The goal of course is to produce a product that customers accept as a cold rolled replacement material. Elements of conversion cost worth noting:

1. Refractory costs. Not surprisingly, costs for refractories including tundish, slide gates, metal distribution and side dams are relatively the single biggest conversion cost element for the CASTRIP plant, on a per-ton basis. The absolute level will have to be established at the Nucor plant.

2. Work roll refurbishment. Surprisingly perhaps, the cost for refinishing the work roll in the single stand mill becomes relatively significant in a twin-roll caster, since the mill operates relatively slowly with high time of contact with the hot strip. For this reason, development of the CASTRIP process has focused on casting very thin and doing as little hot reduction as possible consistent with requirements on surface, strength and formability.

3. Copper casting roll costs. Experience in Australia and subsequent analysis indicates that the per-ton cost of the copper casting rolls is not as significant as expected.

4. Energy. A twin-roll caster uses very little energy, since with the exception of the mill energy is being extracted and not added. Hence energy costs are an insignificant part of the total conversion costs. The largest single energy consumption in the process is for cooling water pumping.

## Capital Costs

Making money with new technology must take into account full costs, including the depreciation of the capital required. Hence initial capital expenditures to construct a plant must be kept to a minimum.

Construction of the Nucor CASTRIP plant is now complete, and construction costs are being totaled. It will be some months before a complete cost analysis including commissioning and start-up costs is possible. However, enough data now exists to project that a typical Greenfield CASTRIP plant, built outside the USA, and including everything required to convert molten steel into finished UCS (including civil works, buildings, etc.), will cost approximately US$ 75 million. Based on a prime production rate of a half million tons per year, this represents an investment cost of approximately US$ 150 / annual metric ton of production. Given that a proper comparison between a strip caster producing 0.7 mm would require a hot strip mill with six or seven stands, the specific investment costs for a CASTRIP plant appear to be equal or lower than a benchmark thin slab caster. Of course, given the small scale of the twin roll strip caster, total investment costs will be much less for a strip caster than for a thin slab caster.

## Product Acceptance

UCS is a new product, and acceptance in the marketplace is essential if the twin roll casting technology is to be successful in establishing itself as viable for the future steel industry. In this area, the experience of both BHP and now Nucor has been better than expected.

After successfully producing commercial quality 304 stainless in Australia in 1991, BHP moved on to further develop the technology for carbon steels. All further development work was done using a silicon-manganese killed steel, as no LMF was available to allow production of an aluminium killed steel. Also, given the propensity of aluminium killed steels to clog small openings, it was decided to complete the development of twin-roll casting of carbon steels using the silicon-manganese killed steel, and take on development of aluminum killed steels when the first commercial plant was built with an LMF.

Hence it would appear natural that a high priority for Nucor would be development of an Al-killed practice. However, this is not the case.

When BHP was running the Project M plant at Port Kembla Australia the focus was on developing technology, not producing commercially saleable coils. However, of the 35,000 tons of coils produced, some thousand tons were deliberately processed through BHP's own pickling, rolling, metal coating and organic coating facilities – both in Australia and the United States. In addition, sufficient coils were held to permit Nucor to trial the material both for their internal purposes and with their customers.

Both internal and external customer acceptance of the SiMn killed coils has been excellent and without reservation. The product is generally similar to that which customers use today, with slightly higher strength. Metal coating poses no issues whatsoever, whether straight zinc or aluminium/zinc. Product tested with tubemakers, roll formers and even automakers has shown no performance issues.

Nucor will begin commercial production with a rather conventional 0.06% carbon steel. Initially the product will be further reduced on the Crawfordsville reversing cold mill. Within the first six months of production 409 stainless will be produced. Within the first nine months UCS < 1 mm, medium carbon and motor lamination steels will all be produced. In all cases discussions with customers are already well advanced.

## THE ROLE OF MANFRED WOLF IN THE DEVELOPMENT OF CASTRIP

It may not be well known that Manfred Wolf played an important role in the development of the CASTRIP technology. Early on in the work being done at Project M in Australia, it was recognized that an expert and ongoing peer review of the work and results would be highly beneficial to the achievement of technical success. Manfred was engaged as that external reviewer. He visited Project M on several occasions during the period 1996 through 1999, in each case performing a "Technical Audit" which reviewed progress made and giving recommendations for future developments.

Manfred's work with Project M culminated with a visit and a report dated 11 October 1999 entitled "Direct Strip Casting of Low Carbon Sheet Steel – a 1999 Assessment of the BHP/IHI 'CASTRIP' Technology in the Context of Global Flat Products Manufacture". This report turned out to be a crucial part of the decision to take the CASTRIP technology "commercial" at the end of 1999. This internal (to BHP and IHI) report was highly complementary of the progress made. Following is a representative excerpt from the October 1999 report:

"…it is obvious that Project M is not only the world leader in low carbon steel strip casting but also has now attained commercial maturity as regards its main product till now, i.e. Mn/Si killed low carbon steel strip in thin gauges. This product shows a surface quality far superior to the equivalent thin slab caster strip."

Manfred's opinions quickly and profoundly changed the direction and pace of BHP/IHI's development of the technology. Sometimes it is difficult when in the middle of intense development work to accept that it is now time to move the technology out of a controlled environment and into the harsh reality of competitive commercial pressure.

In 1999 BHP organized an internal "Strategy Laboratory" – a process designed to reach agreement on what the next steps would be in the development of the CASTRIP technology. Manfred was invited to participate in this Strategy Laboratory. As one can imagine, there were many divergent views held by the attendees at this retreat. The most fundamental issue the group had to deal with was whether to continue the technology development at Project M or to take the leap into commercial production.

The eventual outcome of that retreat is well known – BHP and IHI began a search for a suitable operating partner to take the technology commercial. The formation of Castrip LLC and the construction of the Nucor CASTRIP plant was the result. However, in finally making the decision to move the technology from the development phase to commercial reality, Manfred Wolf played a powerful role in influencing the BHP management team to abandon the safe and cautious continuation of the development work and take the difficult plunge into the harsh and competitive world of commercialization.

With the hot start of the Nucor CASTRIP plant this month, it is a good time to reflect on how far we all have come in developing twin roll strip casting. It is very sad that Manfred will not be present as we pour the first steel between the casting rolls. But for many of us who worked with him on this development, he is still with us and will be as long as we are active in this area.

And for all of us at this conference, we can thank Manfred for having the insight to spur us on and giving us the courage to proceed. Twin-roll strip casting would not be at the stage of development it is were it not for Manfred Wolf.

Thank you, Manfred.

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