NEW DESIGN OF HOT STRIP MILL RUNOUT TABLE
NEW DESIGN OF HOT STRIP MILL RUNOUT TABLE

By

MIROSLAV KRATKY, Dipl. Ing.

A thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Engineering

McMaster University
March 1972
SCOPE AND CONTENTS

Reduction of high capital and operating costs of the existing hot strip mill runout tables is the main objective of this thesis. This is accomplished through the introduction of a new principle for conveying and cooling hot strip.
SUMMARY

The work presented herein describes the production of hot strip with special attention to the runout table. Because of its high capital and operating costs, a new principle in conveying the strip using an air cushion and a new cooling system for strip cooling have been proposed.

Information given here is nearly all from available literature and the author's own experience with Hot Strip Mill production problems.

To support the idea of using an air cushion for strip conveying, experimental equipment was designed and built which confirmed the feasibility of the method.

A new cooling system was also proposed to meet the ever increasing requirements for better mechanical properties of hot strip.

Runout table design application may serve as a guideline in designing new Hot Strip Mill runout table.
ACKNOWLEDGEMENTS

It is difficult to account for all of the influences which have helped me in this work.

Particular thanks is due to Professor J.N. Siddall of the Mechanical Engineering Department of McMaster University, who provided many suggestions and criticisms and read the manuscript. Without his help in building the model and his patience in the last phases of my work, the completion of the task would have been much more difficult.

Thanks are also due to my supervisor, S.W. Wood and Mr. J. Lawler, Superintendent of Industrial Engineering Department, Steel Company of Canada, for the encouragement and effort to use the ideas in the industry.

Finally, Mr. B.G. Stewart's experience and knowledge of Hot Strip Mill operation have helped me avoid many mistakes in assumptions for industrial applications. He challenged me on expression and grammar at every turn of the page.
TABLE OF CONTENTS

Summary
List of Figures
Nomenclature

1.0 Introduction

2.0 The Manufacture of Hot Strip Mill Products
   2.1 Classification
   2.2 Historical Development
   2.3 Types of Steel for Strip
   2.4 Continuous Hot Strip Mills
      a) General Arrangements for Modern Mills
      b) Metallurgy of Hot Strip

3.0 Hot Strip Mill Control
   3.1 Control of Strip Temperature

4.0 Conventional Hot Strip Mill Runout Tables
   4.1 Conveying
   4.2 Cooling

5.0 Air Cushion Principles
   5.1 Plenum Chamber Principle
   5.2 Peripheral Jet Principle
   5.3 Recirculation System
   5.4 The Hydrostatic Thrust Bearing

6.0 Practical Applications of Air Cushion Principles
   6.1 Hovercrafts
   6.2 Hover Pulley
   6.3 Aero-Go System
   6.4 Air-Jet Conveying Method

7.0 Air Cushioned Runout Table
   7.1 Derivation of Basic Equation

-v-
8.0 Experimental Work
8.1 Purpose of the Experiment
8.2 Description of the Experimental Equipment
8.3 Performance of the Experiment
8.4 Results
8.5 Conclusion

9.0 The Cooling of Hot Strip
9.1 Theory of "Continuous Water Jet" Cooling

10.0 Calculation of Air Cushion for Typical Hot Strip Mill Product

11.0 Calculation of Strip Cooling for Typical Hot Strip Mill Product

12.0 Runout Table Design Application

13.0 Economical Comparison of Conventional and Air Cushioned Runout Table

14.0 Conclusions

15.0 References

16.0 Appendix
| Fig. 1. | Hot Strip Mill arrangement |
| Fig. 2. | Hot Strip Mill arrangement |
| Fig. 3. | Hot Strip Mill arrangement |
| Fig. 4. | Hot Strip Mill arrangement |
| Fig. 5. | Hot Strip Mill control |
| Fig. 6. | General view of finishing train, showing crop shear and descaling unit preceding the train |
| Fig. 7. | General view of finishing train, showing exit and part of runout table with cooling sprays |
| Fig. 8. | View showing arrangement of headers and pipes for low pressure stream cooling on runout table |
| Fig. 9. | Low pressure stream cooling on the runout table is favored by the most recent mills |
| Fig. 10. | Cooling on this runout table is accomplished through water sprays of pressure up to 200-250 psi |
| Fig. 11. | End of the runout table - three downcoilers on 24 ft. centers |
| Fig. 12. | General arrangement of Hot Strip Mill |
| Fig. 13. | The Plenum Chamber |
| Fig. 14. | Peripheral Jet Principle |
| Fig. 15. | Recirculation System |
| Fig. 16. | The Hydrostatic Thrust Bearing |
| Fig. 17. | Hovercraft |
| Fig. 18. | Hover Pulley |
| Fig. 19. | Aero-60 System |
| Fig. 20. | Air Jet Conveying System |
Fig. 21. Two Dimensional Jet System
Fig. 22. Simplified Conditions at Formation of Air Cushion
Fig. 23. Testing Equipment - Plenum Chamber
Fig. 24. Testing Equipment - Peripheral Jets
Fig. 25.) Experimental Set-Up
Fig. 26.)
Fig. 27. Air Supported Area
Fig. 28. Fan Characteristic
Fig. 29. Different Way of Cooling
Fig. 30. The Cooling of Strip on Runout Table
Fig. 31. Laminar Water Jets
Fig. 32. Continuous Water Jets
Fig. 33. Sketch Illustrating Runout Table Subsection
Fig. 34. Top Continuous Water Jet Unit
Fig. 35. Bottom Continuous Water Jet Unit
Fig. 36. Cooling Subsection
Fig. 37. Strip Cooling on Runout Table at $V_{S1}$
Fig. 38. Strip Cooling on Runout Table at $V_{S2}$
Fig. 39. Strip Cooling in TTT Diagram
Fig. 40. Air Horsepower vs. Strip Gauge
Fig. 41. Deceleration Force Along the Strip Length
Fig. 42. Strip Speed vs. Strip Gauge
Fig. 43. Finishing Temperature vs. Strip Gauge
Fig. 44. Theoretical Number of Continuous Jets vs. Strip Gauge at $V_{S1}$ and $V_{S2}$
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Po</td>
<td>Atmospheric Pressure</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>Pc</td>
<td>Cushion Pressure</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>H</td>
<td>Gap between Strip and Table Surface</td>
<td>in</td>
</tr>
<tr>
<td>S</td>
<td>Density of Air</td>
<td>lb/sec²/ft⁴</td>
</tr>
<tr>
<td>V</td>
<td>Velocity of Air at Nozzle</td>
<td>ft/sec</td>
</tr>
<tr>
<td>Vm</td>
<td>Mean Velocity of Air in Curtain</td>
<td>ft/sec</td>
</tr>
<tr>
<td>Vx</td>
<td>Velocity of Air Escaping from Cushion</td>
<td>ft/sec</td>
</tr>
<tr>
<td>δo</td>
<td>Nozzle Angle</td>
<td>Radians</td>
</tr>
<tr>
<td>δ</td>
<td>Jet Angle</td>
<td>Radians</td>
</tr>
<tr>
<td>t</td>
<td>Nozzle Width</td>
<td>in</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
<td>in², ft²</td>
</tr>
<tr>
<td>At</td>
<td>Flow Area at Nozzle</td>
<td>in²</td>
</tr>
<tr>
<td>Dh</td>
<td>Hydraulic Diameter</td>
<td>ft</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>lbf</td>
</tr>
<tr>
<td>Q</td>
<td>Volumetric Flow Rate</td>
<td>GPM</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration Due to Gravity</td>
<td>ft/sec²</td>
</tr>
<tr>
<td>gc</td>
<td>Conversion Factor Relating Absolute Mass Units (Slugs) to the More Commonly Used Weight Units (lbfm)</td>
<td>ft-lbm/sec²</td>
</tr>
<tr>
<td>hf</td>
<td>Fluid Static Pressure Head</td>
<td>in</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>ft</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>lbf·sec²/ft</td>
</tr>
<tr>
<td>mf</td>
<td>Mass Flow Rate, mf = w gc</td>
<td>lbf·sec²/ft</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Rh</td>
<td>Hydraulic Radius</td>
<td>ft</td>
</tr>
<tr>
<td>SCFM</td>
<td>Flow Rate in Standard Cubic Feet Per Minute</td>
<td>ft³/min</td>
</tr>
<tr>
<td>T</td>
<td>Time (Temperature)</td>
<td>sec (°F)</td>
</tr>
<tr>
<td>μ</td>
<td>Coefficient of Absolute Viscosity</td>
<td>lbf·sec/ft²</td>
</tr>
<tr>
<td>Vr</td>
<td>Roller Table Speed</td>
<td>ft/min</td>
</tr>
<tr>
<td>a</td>
<td>Acceleration Due to Force</td>
<td>ft/sec²</td>
</tr>
<tr>
<td>f_n</td>
<td>Neck Coefficient of Friction</td>
<td>-</td>
</tr>
<tr>
<td>f</td>
<td>Sliding Friction Coefficient</td>
<td>-</td>
</tr>
<tr>
<td>dr</td>
<td>Roller Neck Diameter</td>
<td>in</td>
</tr>
<tr>
<td>n</td>
<td>Roller Revolutions</td>
<td>rpm</td>
</tr>
<tr>
<td>w</td>
<td>Strip Width</td>
<td>in</td>
</tr>
<tr>
<td>S</td>
<td>Roller Spacing</td>
<td>in</td>
</tr>
<tr>
<td>G</td>
<td>Strip Gauge</td>
<td>in</td>
</tr>
<tr>
<td>ρ_s</td>
<td>Specific Weight of Hot Rolled Steel = 0.283</td>
<td>lb/in³</td>
</tr>
<tr>
<td>f_e</td>
<td>Coefficient of Friction (No Sliding Between Roller and Strip)</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>Inertia Moment of the Roller $I = \frac{Mr Dr^2}{2}$</td>
<td>lbf·sec²·ft</td>
</tr>
<tr>
<td>E_k</td>
<td>Kinetic Energy</td>
<td>lbf·ft</td>
</tr>
<tr>
<td>L_r</td>
<td>Length of the Roller Table (L_r = 450' - 0'')</td>
<td>ft</td>
</tr>
<tr>
<td>N</td>
<td>Motor Output</td>
<td>HP</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>Emissivity Coefficient of Steel Strip = 0.8</td>
<td>-</td>
</tr>
<tr>
<td>G_b</td>
<td>Stefan-Boltzmann Constant</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>C</td>
<td>Specific Heat of Steel = .209</td>
<td>BTU/lb °F</td>
</tr>
<tr>
<td>P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Air Pressure in the Chamber</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>t</td>
<td>Jet Thickness</td>
<td>in</td>
</tr>
<tr>
<td>P&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Total Pressure Rise Across Fan</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>HP</td>
<td>Horsepower</td>
<td>Hp</td>
</tr>
<tr>
<td>T&lt;sub&gt;F&lt;/sub&gt;</td>
<td>Finishing Strip Temperature</td>
<td>°F</td>
</tr>
<tr>
<td>T&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Strip Cooling Temperature</td>
<td>°F</td>
</tr>
<tr>
<td>K</td>
<td>Thermal Diffusivity of Steel</td>
<td>ft²/sec</td>
</tr>
<tr>
<td>k</td>
<td>Thermal Conductivity of Steel</td>
<td>BTU/sec-ft-°F</td>
</tr>
<tr>
<td>w</td>
<td>Water Quantity</td>
<td>gal/min</td>
</tr>
</tbody>
</table>
INTRODUCTION

In the past 30 years the consumption of flat rolled steel has increased by more than 300 percent, while total hot rolled products over only about 225 percent. Since 1960, ten new Hot Strip Mills have gone into operation in the United States only and more are under construction.

The present going cost of a complete new Hot Strip Mill with sophisticated control has reached $150,000,000. It is therefore very important to look for new methods of strip production and handling which may bring the capital investment considerably down and make the hot strip prices more competitive on international markets.

It depends on engineering ability to introduce and adopt new principles for the existing industrial utilization.
2.0 The Manufacture of Hot Strip Mill Products

2.1 Classification

2.2 Historical Development

2.3 Types of Steel for Strips

2.4 Continuous Hot Strip Mills

2.1 Classification

The products of the hot strip mill are classed flat rolled steel products. Flat rolled steel products may be distinguished from other forms of rolled steel in two general ways. First, flat rolled steel is produced on rolls with smooth faces in contrast with the cut or grooved roll faces employed in the manufacture of shapes and, second, in flat rolled products the ratio of width to thickness is generally high as distinguished from other rolled products. The ranges of dimensions are wide, varying in thickness from 0.005 inch in light strip to 15 inches in heavy plates, and in width from 3/16 inch in narrow strip to 200 inches in wide plates.

By common custom, finished flat hot rolled carbon steel strip is produced in the following dimensional ranges.

<table>
<thead>
<tr>
<th>Width (In.)</th>
<th>Thickness (In.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.05</td>
</tr>
<tr>
<td>96</td>
<td>1.25</td>
</tr>
</tbody>
</table>
2.2 Historical Development

The mills used for rolling flat rolled steel products include the following, named in the order of their development:

a) the two-high mill,
b) the Universal mill,
c) the three-high mill or Lauth mill,
d) the continuous or tandem hot strip mill,
e) the cold reduction mill.

The method for rolling sheets on two-high, single stand mills originated between 1720 and 1728. Up to about 1890 the finished flat-rolled steel products could be classed as sheets, plates, and bars. The bar mills also rolled thinner sections and about this time there developed such a demand for very thin flats that special mills were built to supply the material. The differentiation first took place in the narrower widths, ranging from 5/8 inch to 3 inches and from 0.065 to 0.028 inch in thickness.

In 1926, at Butler, Pennsylvania, the first mill was built to combine successfully the use of the following principles:

a) four-high finishing stands
b) control of the direction of travel of steel through the pass line of the tandem finishing mills by progressively decreasing the product crown in successive mill passes.
c) hot coiling equipment at the discharge end of the unit.
This installation was the first of the modern wide continuous mills as known today.
2.3 Types of Steel for Strips

Chemical Composition

Steel compositions used for the manufacture of thin, flat steel products range from so called "pure iron" in which the sum of all elements other than iron in the product is less than one-third of one percent of the total weight, to the high alloy stainless and heat resisting steels composed of as much as 50 percent alloying additions. About four fifths of the strip rolled, however, is made from steel compositions within the following ranges.

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.03 to 0.12</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.20 to 0.60</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.04 maximum</td>
</tr>
<tr>
<td>Other Elements</td>
<td>Low as possible</td>
</tr>
</tbody>
</table>

This general range of compositions provides the best combination of rollability during manufacture and formability in most of the applications for which these products are used. Such compositions, too, are well suited for the production of rimmed steel, which is preferred for flat products because of the superiority of its ingot surface. Deviations from this basic composition range are deliberately employed to obtain specific desired properties in the steel.
Sulphur, silicon, copper, nickel and chromium generally are considered as the "other elements" of the basic composition given above. Except in the steels where they are added deliberately to produce alloy steels with definite properties, these elements offer no advantages and, when present in greater than certain amounts, may even be detrimental to the rolling or fabricating properties of steel. An effort is made to keep sulphur and chromium contents each below 0.05 percent, and copper and nickel contents below 0.15 percent.

Silicon content naturally falls under 0.002 percent in the rimmed and capped steels popularly used for sheets, strip and tin plate.

Slabs are the raw material for the modern continuous hot strip mill. A slab is defined as a rectangular steel section having a minimum thickness of 2 inches and minimum width not less than twice the thickness. Slabs are generally provided in thickness of 6 inches to 10 inches, widths of 18 to 76 inches and lengths 168 to 389 inches, depending on strip mill requirements. They must be accurate enough in dimensions and sound enough in structure to permit conversion in subsequent rolling operations with a minimum of difficulty, and their edges and surfaces must be free of injurious
defects which would carry through to the finished product.
2.4 Continuous Hot Strip Mills

a) General Arrangement of Modern Mills

The modern wide hot strip mill has become quite standardized in its general layout. Slabs are heated in two or more continuous reheating furnaces. A typical rolling train will consist of a roughing scalebreaker, four four-high roughing stands, a finishing scalebreaker, and six four-high finishing stands.

Driven table rolls convey the slab from furnace to mill and also from stand to stand. The first component is usually a vertical scalebreaker followed by a horizontal scalebreaker. The next is reversing rougher and two continuous roughers. The holding table separates the roughing train from the finishing train composed of the finishing scalebreaker and six finishing stands. Following the last finishing stand there is usually a flying shear for cutting the rolled products into length. It is carried over a long table called the run-out table consisting of individually driven rollers. Two or more coilers are located in this table. They operate to coil the material when continuous long lengths are required.

Figures 1, 2, 3 and 4 shows general arrangements of recently built Hot Strip Mills.
FIG. 1 HOT STRIP MILL ARRANGEMENTS
FIG. 2  HOT STRIP MILL ARRANGEMENT
FIG. 3  HOT STRIP MILL ARRANGEMENT
FIG. 4  HOT STRIP MILL ARRANGEMENT
b) Metallurgy of Hot Strip

Wide hot rolled strip from a modern continuous mill may be used with or without the application of such auxiliary treatments as pickling, shearing and flattening. When produced as hot rolled break-downs for cold reduction, it is pickled in coil form, cold reduced as much as 90 percent of its original thickness.

The metallurgical requirements of the great bulk of the product are relatively simple and lend themselves to best operating conditions on the hot strip mill and subsequent processing units.

The last hot rolling operation (in the last finishing stand) should be conducted above the upper critical temperature on virtually all continuous hot mill flat rolled products. Such a practice permits the rolled steel to pass through a phase transformation after all hot work is finished and produces a uniformly fine ferritic grain throughout all portions of the strip. For the low carbon steels generally used, proper finishing temperatures will have been attained when the product temperature at the last rolling stand is over 1,550°F. This finishing temperature is practical over most thicknesses rolled on modern mills at normal maximum rolling speeds.
If part of the hot rolling is conducted on steel which already has transformed partially to ferrite, the deformed ferrite grains usually will re-crystallize and form patches or layers of abnormally coarse grains during the self anneal induced by coiling or piling at the usual temperatures of 1,200 to 1,350°F. Such a structure is more likely to occur at the surface of the product, which is colder than the interior during rolling. Very thin hot rolled material, inadvertently finished far below the upper critical and coiled too cold to self anneal may retain microstructural evidence of hot working.

Neither condition is suitable for some types of severe drawing applications, both must be corrected by normalizing the strip.

A special case occurs in the steels of the so-called "pure iron" compositions in which the sum of the carbon and manganese contents may be well under 0.10 percent. Such compositions often exhibit a hot short temperature range between 1,650 to 1,900°F, and normal hot rolling in that range may produce deep cracks on the edge of the product.
Accordingly, it is the practise on many mills to complete the roughing operations above the hot short range, to allow the steel to cool through the range by holding it on the conveyor table between the last roughing strand and the finishing train, and to resume rolling by passing the product into the finishing train below the hot short range. By this practice it is impossible to finish above the upper critical temperature of these steels.

The run-out table following the last rolling stand of most hot strip mills is long enough and equipped with enough quenching sprays to cool the single thickness of rolled product 200°F below the finishing temperatures. In addition, some mills have auxiliary tables or holding beds which allow single-thickness cooling to a take-off temperature of 500°F or lower. The cooling practice is determined by the metallurgical properties of the steel, its suitability for further processing and its final applicability to the intended use.

On hot rolled products properly finished above the upper critical temperature, a uniform ferrite grain has been established and the runout cooling practice determines the carbide characteristics and, to some extent, the grain size. The self annealing effect of a large mass
of steel coiled or piled at around 1,350°F produces considerable carbide agglomeration, a coarse ferrite grain and a soft, ductile sheet. Coiling around 1,200°F yields a fine, dispersed spheroidal carbide in a finer ferrite matrix, resulting in a somewhat harder strip, which still retains excellent ductibility. Even more drastic quenching produces various transformation states of carbide, down to and including martensite.

For most low carbon steel made either for use as hot rolled strips or as breakdowns for subsequent cold reduction, coiling temperatures of 1,200 to 1,300°F are employed. This range provides optimum uniformity of mechanical properties without excessive scale formation or over-annealing.

Steels of 0.15 to 0.30 percent carbon content and alloy steels often are quenched drastically to attain higher strength levels from finer carbide dispersions or are coiled very hot to facilitate cold reduction.
3.0 Hot Strip Mill Control

For continuous hot strip mill the most important elements for computer control are: stand speeds, sideguard position, product gauge, and initial section.

Each element must be considered an essential part of any integrated system of computer control of the entire operation of a hot strip mill. In addition to the sensing devices (tachometers, load cells, x-ray gauges) and actuating mechanisms required for successful operation of each individual control system, an overall system controlled by a computer requires further instrumentation. The additional instrumentation is required to enable the computer to accept, analyze and correlate data describing conditions at various stages in the process, perform any necessary calculations, and develop a new set of operating conditions to correct any deviation at any stage of the actual process from the program shoved in the computer's memory by operating regulators and actuating mechanisms that will bring the process within the desired controlled limits.

Since uniformity of grain size and mechanical properties of hot rolled steel are influenced by the temperatures at which finish rolling and coiling occur, the computer exercises further control over the mill operation through both the mill pacing and mill set-up functions to maintain the temperatures of these points within
specified limits over the entire length of each coil. With the assistance of temperature measuring sensors at several points in the mill, the finish mill delivery speed together with all roll openings in both the roughing and finishing mills are modified as required. Run-out table sprays are also subject to computer control, with spray patterns varied according to rolling conditions.
3.1 Control of Strip Temperature

Achieving and maintaining the correct temperature of the strip at the exit of the finishing mill and at the entry to the coiler is one of the most important factors governing the quality of the final product since it vitally affects the grain structure and hence the ductility of the steel. Accurate control of temperature by computer is made difficult by a number of factors which include:

a) Inconsistent heating along the length of and between consecutive slabs.

b) Difficulties of accurate temperature measurement especially at mill entry caused by atmospheric pollution and scale formation.

c) Varying temperature requirements dictated by steel grade and customer requirements.

d) Difficulty of developing accurate mathematical models defining the heat transfer and cooling characteristics of the finishing mill and runout table sprays respectively.

The philosophy largely adopted to date on computer projects on hot strip mills has been that of utilizing one computer to perform all the separate control and logging functions on the mill. Author's thoughts of splitting the duties between a number of computers might be extremely controversial. Such a configuration
could consist of a control computer which would perform the combined duties of A.G.C. and all mill auxiliaries position control, utilizing direct digital control techniques, a process computer to perform all mill set-up duties, a process computer to perform all temperature control duties including slab furnace control and a logging computer to perform all quality, engineering and production logging duties.

Figure 5 illustrates in schematic form the temperature control.
FIG. 5  HOT STRIP MILL CONTROL
4.0 Conventional Hot Strip Mill
Runout Table

Runout table is located between the last stand of finishing mill and the coiler. It is the last place where some action may be done to achieve the changes in strip structure by means of water cooling.

For runout table arrangements see figures 1, 2, 3 and 4.
4.1 Conveying

The runout table, which is usually 450 to 500 ft. long, uses hollow cast iron rollers on forged steel hubs. Rollers are 12 in. diameter, on 18 in. centers, and are skewed and canted to keep the strip centered as it travels over the table.

The rollers run in roller bearings, spherical type on the drive side and cylindrical type on the free end, or perhaps spherical on both sides. The entire roller assembly, including bearing cages and motor, is mounted on a common independent frame which is bolted to the table beams. The rollers are driven by individual d-c motors of 4 or 5 hp under adjustable voltage control, at speeds slightly in excess of the finishing speed. After the coiler mandrel picks up the load the table speed drops to match speed with the finishing stand.

The table is divided into five or six control sections, and designed to accelerate at rates of 200 to as much as 400 fpm per sec. The rates normally used are lower 5 to 40 fpm per sec.

Following sketches show typical modern design of runout table and its lengths in recently built hot strip mills.

For runout table roll see drawing. Table 1 shows table lengths, numbers of rollers, roller diameter, roller
spacing and maximum roller table speed in recently built mills.

Table 2 shows type of drives used for driving runout table rollers.
### Table 1: Runout Tables

<table>
<thead>
<tr>
<th>Plant No.</th>
<th>Table Length</th>
<th>No. of Rollers</th>
<th>Roller Diameter</th>
<th>Roller Spacing</th>
<th>Max. Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>in</td>
<td>in</td>
<td>in</td>
<td>rpm</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
<td>267</td>
<td>-</td>
<td>18</td>
<td>2500</td>
</tr>
<tr>
<td>2</td>
<td>472</td>
<td>316</td>
<td>-</td>
<td>18</td>
<td>3455</td>
</tr>
<tr>
<td>3</td>
<td>474</td>
<td>305</td>
<td>-</td>
<td>18</td>
<td>3750</td>
</tr>
<tr>
<td>4</td>
<td>459</td>
<td>306</td>
<td>12</td>
<td>18</td>
<td>3770</td>
</tr>
<tr>
<td>5</td>
<td>530</td>
<td>342</td>
<td>12</td>
<td>18</td>
<td>4000</td>
</tr>
<tr>
<td>6</td>
<td>478</td>
<td>318</td>
<td>-</td>
<td>18</td>
<td>3730</td>
</tr>
<tr>
<td>7</td>
<td>444</td>
<td>297</td>
<td>12</td>
<td>18</td>
<td>3770</td>
</tr>
<tr>
<td>8</td>
<td>483</td>
<td>321</td>
<td>12</td>
<td>18</td>
<td>4400</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>336</td>
<td>12</td>
<td>18</td>
<td>4000</td>
</tr>
<tr>
<td>10</td>
<td>495</td>
<td>319</td>
<td>12-1/4</td>
<td>18</td>
<td>4320</td>
</tr>
<tr>
<td>11</td>
<td>493</td>
<td>322</td>
<td>12</td>
<td>18</td>
<td>4200</td>
</tr>
</tbody>
</table>
### Table 2: Runout Table Drives

<table>
<thead>
<tr>
<th>Plant No.</th>
<th>Drives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>individual 3 - horsepower d-c motors</td>
</tr>
<tr>
<td>2</td>
<td>individual 4/5.88 horsepower d-c motors</td>
</tr>
<tr>
<td>3</td>
<td>individual 5.6/11.2 - horsepower d-c motors</td>
</tr>
<tr>
<td>4</td>
<td>individual 4 - horsepower 750/1200 tpm d-c motors</td>
</tr>
<tr>
<td>5</td>
<td>individual 4/6.7 - horsepower d-c motors</td>
</tr>
<tr>
<td>6</td>
<td>individual 4/6.4 - horsepower d-c motors</td>
</tr>
<tr>
<td>7</td>
<td>individual 4 - horsepower 750/1200 rpm d-c motors</td>
</tr>
<tr>
<td>8</td>
<td>individual 4/7.5 - horsepower d-c motors</td>
</tr>
<tr>
<td>9</td>
<td>individual 5 - horsepower d-c motors</td>
</tr>
<tr>
<td>10</td>
<td>individual 5/9 - horsepower d-c motors</td>
</tr>
<tr>
<td>11</td>
<td>individual 4/7.2 - horsepower d-c motors</td>
</tr>
</tbody>
</table>
4.2 Cooling

Between 250 and 350 ft. of the runout table is equipped with cooling water systems. Top cooling may consist of banks of headers carrying nozzles operating at pressures of 200 to 250 psi or it may consist of a low pressure stream flow system, wherein water flows at almost no pressure from overhead siphon tubes of about 3/4 in. diameter.

Tests have shown the low pressure system to be 30 to 40 percent more efficient than turbulent jets. Table 3 shows typical modern installations which provide 20,000 to 45,000 gpm for top cooling and 6,000 to 15,000 gpm for bottom cooling.

Table shows strip finishing temperature, coiling temperature and water quantity used for strip cooling.
## Table 3: Runout Cooling

<table>
<thead>
<tr>
<th>Plant No.</th>
<th>Strip Temperature</th>
<th>Coiling Temperature</th>
<th>Cooling</th>
<th>Water Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Finishing (T_F) (°F)</td>
<td>Coiling (T_C) (°F)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Up to 2000</td>
<td>1000/1600</td>
<td>Top - 12 000 GPM @ 150 psi</td>
<td>Bottom - 4000 GPM @ 50 psi</td>
</tr>
<tr>
<td>2</td>
<td>1530/1700</td>
<td>950/1350</td>
<td>Top - 12 000 GPM @ 30-300 psi</td>
<td>Bottom - 4 400 GPM @ 60</td>
</tr>
<tr>
<td>3</td>
<td>1400/1800</td>
<td>1000/1700</td>
<td>Top - laminar 10 000 GPM</td>
<td>Bottom - + sprays at top and bottom</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>900/1400</td>
<td>Top - 1800 GPM @ 200 psi</td>
<td>Bottom - 6000 GPM @ 10 psi</td>
</tr>
<tr>
<td>5</td>
<td>1400/1750</td>
<td>900/1300</td>
<td>Top - 21 000 GPM @ 250 psi</td>
<td>Bottom - 4875 GPM @ 60 psi</td>
</tr>
<tr>
<td>6</td>
<td>1450/1600</td>
<td>950/1300</td>
<td>Top - laminar 45 000 GPM</td>
<td>Bottom - 15 000 GPM</td>
</tr>
<tr>
<td>7</td>
<td>1500/1650</td>
<td>-</td>
<td>Top - laminar</td>
<td>Bottom - at 35 psi</td>
</tr>
<tr>
<td>8</td>
<td>1440/1605</td>
<td>900/1600</td>
<td>Top - laminar 21 000 GPM</td>
<td>Bottom - 25 000 @ 10 psi</td>
</tr>
<tr>
<td>9</td>
<td>1500 +</td>
<td>950/1450</td>
<td>Top - 28 000 GPM @ 250 psi</td>
<td>Bottom - 32 000 GPM @ 45 psi</td>
</tr>
<tr>
<td>10</td>
<td>1500/1750</td>
<td>900/1300</td>
<td>Top - laminar 45 000 GPM</td>
<td>Bottom - 15 000 GPM @ 5-20 psi</td>
</tr>
<tr>
<td>11</td>
<td>1450/1850</td>
<td>1060/1700</td>
<td>Top - laminar 33 000 GPM</td>
<td>Bottom - 7 000 GPM @ 29 psi</td>
</tr>
</tbody>
</table>
FIG. 6. GENERAL VIEW OF FINISHING TRAIN, SHOWING CROP SHEAR AND DESCALING UNIT PRECEDEING THE TRAIN

FIG. 7. GENERAL VIEW OF FINISHING TRAIN, SHOWING EXIT AND PART OF RUNOUT TABLE WITH COOLING SPRAYS
FIG. 8. VIEW SHOWING ARRANGEMENT OF HEADERS AND PIPES FOR LOW PRESSURE STREAM COOLING ON RUNOUT TABLE

FIG. 9. LOW PRESSURE STREAM COOLING ON THE RUNOUT TABLE IS FAVORED BY MOST RECENT MILLS
FIG. 10. COOLING ON THIS RUNOUT TABLE IS ACCOMPLISHED THROUGH WATER SPRAYS OF PRESSURE UP TO 200-250 psi

FIG. 11. END OF THE RUNOUT TABLE – THREE DOWNCOILERS ON 24 ft. CENTERS
FIG. 12. GENERAL ARRANGEMENT OF HOT STRIP MILL
5.0 Air Cushion Principles

It is well known that two surfaces may be kept apart by introducing a supply of liquid between them. This arrangement constitutes a bearing with a very low friction between the surfaces. The potential advantages inherent in the application of this principle to a strip runout table are great, in that it is possible to avoid differential speeds of the strip and the roller without the necessity for adjusting and maintaining the speed of the rolling mill and the roller table. The strip surface will not be marked by contact with the rolls. Due to the simple design without moving parts the capital and operating costs are only a fraction of the conventional runout table costs.

Type of Liquid

From operating cost point of view there are only two types of liquids which could be economically used as a lubricant between the moving strip and the supporting surface:

1) water
2) air.

However, runout table is used primarily as a place for lowering the strip temperature to desired level. High rolling speeds does not allow sufficient time necessary for natural cooling the strip (unless the table is extraordinarily long), water is used as a cooling
medium. The amount of water used for cooling differs according to the strip thickness $G$, and metallurgical requirements. Therefore water cannot be used in this particular application.

An air cushion device requires air to be supplied between the support and body surface at a pressure which will provide resultant forces to maintain the body above the support. The leakage of this air from beneath the device must be kept to a minimum to reduce power losses. The clearance between the air cushioned body and the surface of the support may be only a fraction of an inch.

This clearance, or "air gap" must be adequate to prevent surface contacts in order to take advantage of the low friction forces of the supporting layer of air. Air is a nearly ideal supporting medium because it is a low density mixture of gases with an extremely low viscosity.

A strip supported on a cushion of air, therefore, has a relatively friction-free surface to travel upon and is thus capable of high speeds for a given amount of thrust. Movement of air supported strip at low speeds is easily accomplished with almost insignificant thrust forces.
There are several types of air-cushion arrangements in general use today. The plenum type is the simplest from a mechanical standpoint, but it is not as stable as is desired, see figure 13.

The peripheral-air curtain type of air cushion proved to be the most successful in Hovercraft vehicles. It is more efficient than the plenum type, although somewhat more complicated. The peripheral system would appear to be always preferable. Figure 14.

For wider supported bodies is convenient to use recirculation principle where under surface intakes recover the air curtain and re-issue it to give secondary and even tertiary air curtains, see figure 15.

THE HYDROSTATIC THRUST BEARING
This system requires air to be supplied under pressure through a number of small orifices recessed in pockets in the bearing surface. The air escapes through the bearing clearance to atmosphere. The load which this form of bearing can support is proportional to the number and area of the pockets, and to the air supply pressures. Also, for a given pressure, the volumetric air flow rate determines the bearing lift. The principle is very simple, however, the power required for air supply is prohibitive. Clearance gap H obtained is very small (0.005 in.), see figure 16.
FIG. 14. PERIPHERAL JET PRINCIPLE
FIG. 15. REcirculation system
FIG. 16. THE HYDROSTATIC THRUST BEARING
6.0 Practical Application of Air-Cushion Principles

6.1 Hovercrafts

6.2 Hover Pulley

6.3 Aero-Go System

6.4 Air-Jet Conveying Method

6.1 Hovercraft

The air-cushion principle is proving to be practical concept, economically feasible for military, commercial and pleasure vehicles. The experimental applications of these principles to other devices such as trains on special rails, tracks or tubes is indicative of the trend toward utilizing this principle in practical way. (Figure 17).
FIG. 17. HOVERCRAFT
6.2 Hover Pulley

BISRA have developed a new device, the Hover Pulley, which enables thin steel strip to be guided through mill processing lines on cushions of gas or liquid, so avoiding the use of guide rolls.

The cushion is formed by blowing a quantity of low pressure gas or liquid between the strip and the guide service. In principle the method is similar to that used in the hovercraft in that a pressure rise occurs within the area bounded by jets, if the jets are in close proximity to a boundary surface.

The laboratory rig built by BISRA supplies air for the cushion at between 20 and 30 in Hg. Strip 12 in. wide by 0.008 in. thick has been used on the tests and the gap between the strip and the bearing surface is in the order of 1/10 in. The jets are 10 in. apart and about 1/10 in. wide. It appears that as long as the edge of the strip overlaps the peripheral slits of the jet, sufficient lift is obtained.

(Figure 18)
FIG. 18. HOVER PULLEY - THE LABYRINTH LOOPING TOWER AT BISRA'S BATTERSEA LABORATORIES SUPPORTS STRIP 12 in WIDE, 0.008 in THICK ON A CUSHION OF AIR
6.3 Aero-Go System

With Aero-Go's air bearing transporters, loads are lifted from the ground and held suspended — in effect "floated" on a friction-eliminating cushion of air.

First, low pressure air is introduced into the flexible torus bag. As the "doughnut" inflates, air is also forced into the plenum chamber. When the total downward force of the air in the flexible chamber exceeds the payload, the load floats off the floor. Since there is a direct and unique path of air between torus bag and plenum chamber, the aero caster is self-stabilizing. No external tanks are needed to assure stability. Within the limit of the caster design capacity, the load lifted is in direct proportion to the air pressure applied. Air source may be plant air fed by the hose, self-contained electrical or gas engine driven blower. (Figure 19).
STEP ONE: AERO-CASTER AT "REST". THE LOAD IS SOLIDLY SUPPORTED ON THE LANDING PADS. BLACK ARROWS REPRESENT AIR FLOW.

STEP TWO: AIR ENTERS FLEXIBLE TORUS BAG (TB) AND PLENUM CHAMBER (PC). TORUS BAG INFLATES.

STEP THREE: WHEN AIR FORCE IN PLENUM CHAMBER EXCEEDS TOTAL LOAD, CASTERS THEN FLOATS LOAD OFF THE FLOOR.

FIG. 19. AERO-60 SYSTEM
6.4 Air-Jet Conveying Method

The conveyor consists of a multiorificed plate or "deck" which forms the top of a pressurized plenum chamber. The air is introduced through relatively large openings at a high velocity (on the order of 100 FPS). The orifices are formed such that there are significant air-velocity components parallel to the conveyor deck.

Since the openings are arranged to give a directional flow, the family of co-operative jets produces a resultant sheet of air just above the deck which is capable of entraining solid and liquid matter and transporting it in a layer which need only be contained by sidewalls.

When air is introduced throughout the length of the plenum, the jets always provide a vertical component of air velocity which lifts the material to negate frictional drag by "floating" the material in the airstream where the horizontal component can take over to accomplish lateral motion of the entrained material.

Advantages which are unique to the air-jet system are:

1) Power requirements are lower since the material need not to be accelerated to excessive velocities.
2) The conveyor can be fed at any point since it is open to the atmosphere.

3) A wide variety of sizes and shapes of materials can be handled since they need not fed or discharged from the conveyor through air locks.

4) In most cases there is little or no contact between the conveyed materials and the conveyor. (Figure 20).
FIG. 20. AIR JET CONVEYING SYSTEM
7.0 Air Cushioned Runout Table

The conventional Hot Strip Mill Runout Table as used today has several weak points.

a) High Capital Cost - (expensive bearings, electro motors, heavy, forged rollers, complicated speed control).

b) High Operating Cost - frequent maintenance which results in mill delays (production losses) and numerous maintenance crew (expensive labor). - Energy consumption is unproportionally high (D.C. current is used for driving the rollers).

c) Damaged Product - due to the difference between strip speed and roller speed the strip surface is damaged by the rough roller surface.

The purpose of Runout Table is conveying hot strip from rolling mill to coiler. The strip dimensions which varies insignificantly help to find a solution for a new type of runout table.
7.1 Air Cushioned Run-Out Table - Derivation of Basic Equation

Considering the two-dimensional flow, it is assumed that the velocity \( v \) of the jet is uniform across the nozzle. Escaping air fills the gap between the strip and table surface.

**FIG. 21. TWO-DIMENSIONAL JET SYSTEM - HOVERCRAFT PRINCIPLE**

Detail "A" - Formation of Air Curtain, see page 52
Without considering boundary layer effects and frictional losses through the nozzle orifice, the total thrust on unit length of the curtain due to the air pressure in the cushion must equal the rate of change of momentum of the air jet in the direction parallel to the surface.

Mathematical expression of the mechanism:

\[ -P \times H = \int_{y=0}^{H} \rho \cdot V_x \cdot dy = \int_{\delta=\delta_0}^{\Pi} \frac{d(V_m \cdot \cos \delta)}{d\delta} \]

\[ P \times H = \int_{y=0}^{H} \rho \cdot V_x \cdot (V_x + V \cdot \cos \delta_0) d\delta \]

\[ P \times H = \rho \cdot V_x \cdot H \cdot (V_x + V \cdot \cos \delta) \]

The volume flow past all points is assumed constant

\[ V_x \times H = V \times t \]

Therefore

\[ P \times H = \rho \cdot V^2 \cdot \frac{t}{H} (\frac{t}{H} + \cos \delta) \]
FIG. 22. SIMPLIFIED CONDITIONS AT FORMATION OF AIR CURTAIN

This diagrammatic representation of air curtain formation serves for basic derivation of air cushion formulae.

No consideration is given at this time to the flow split, friction losses and water presence.
8.0 Experimental Work

8.1 Purpose of the Experiment

8.2 Description of the Experimental Equipment

8.3 Performance of an Experiment

8.4 Results

8.5 Conclusion

8.1 Purpose of the Experiment

Although there is a considerable volume of literature on the technicalities of hovercraft principles, only a small portion of it is available. The working devices using air cushion principles are still in a state of experimentation and design is an art combined with technical knowledge.

Experiments can be used to verify relationships which have been derived theoretically. A theoretical approach to a problem always involves the making of assumptions, some of which may not be valid in practice, and some may be applicable only in certain ranges. Experiments are therefore required to determine any modifications to a theoretical law needed to make it usable in actuality - and this is author's main concern.
8.2 Description of the Experimental Equipment

The predominant aim in designing the apparatus should be simplicity. Author's first intention was using plenum chamber principle. The equipment was built using that principle.

As shown in figure 23 a motor-driven centrifugal blower is attached to the plenum chamber with an interconnecting transition section. The plenum chamber is designed with a relatively large cross-sectional area in order to insure a uniform pressure. The plenum chamber is 120 in. long.

Two slots at the upper part of the chambers enable the air to get under the strip and form air cushion. Because of a very small lift (about 0.01 in.), the plenum chamber principle was

* Static pressure taps are located along the chamber length.
abandoned and the author decided to re-design and rebuild the equipment.

The peripheral jet principle seems to be superior to the plenum chamber principle. It was necessary to make a new top part of the equipment where two pairs of air nozzles are located. The inner nozzles were used for narrower strips in order to obtain more data. The testing equipment is shown in Figure 24 and Drawing ME-1.
8.3 Performance of an Experiment

Experiments were made with thin galvanized cold rolled sheets of three different gauges and two widths.

Exhibit A shows experimental and calculated data for Test No. 5. The results of all tests are shown in Tables 4 and 5.

Exhibit A

Test No. 5

1) Strip Dimensions

Gauge: 0.0209 in.
Width: 9 in.
Length: 60 in.

2) Air Cushion

Nomenclature

- Pc - air cushion pressure lb/ft²
- H - gap between the table base and the strip In.
- Po - atmospheric pressure lb/ft²
- P1 - air pressure in the chamber lb/ft²
- t - jet thickness In.
- v - air velocity at the jet exit FPM
- W - strip width In.
- G - strip gauge In.
- WN - jet separation In.
- δ - jet angle Degrees
- HPair - air horsepower HP
- Q - air flow rate lb³/min
- ρ - air density lb/ft³
- ψ - coefficient of nozzle losses --
Data

\( t = 0.1 \text{ in.} \)
\( W = 9 \text{ in.} \)
\( G = 0.0209 \text{ in.} \)
\( W_N = 6 \text{ in.} \)
\( \delta_N = 30^\circ \)
\( \rho = 0.075 \text{ lb/ft}^3 \)
\( \psi = 0.7 \)
\( L = 60 \text{ in.} \)

Experimental Data:

Air pressure observed at the plenum chamber

\( P_1 = 0.5 \text{ inches water gauge} \)

Air cushion pressure

\( P_c = 0.25 \text{ inches water pressure} \)

Gap between the table base and strip

\( H = 0.15 \text{ inches} \)

Calculated Data:

Air supported area \( A_s \).

FIG. 27. AIR SUPPORTED AREA
\[ \Delta W = \frac{0.15}{0.5774} = 0.26 \text{ in.} \]

\[ W_s = W_N - 2 \Delta W \]

\[ = 6 - 0.52 \]

\[ W_s = 5.48 \text{ in.} \]

\[ A_s = W_s \times x_2 \times L \]

\[ A_s = 330 \text{ in}^2 = 2.30 \text{ ft}^2 \]

Strip Weight:

\[ \text{WGHT} = 3.20 \text{ lbs.} \]

Required Air Cushion Pressure:

\[ \text{Pc} = \frac{\text{WGHT}}{A_s} \]

\[ = \frac{3.20}{2.30} \]

\[ \text{Pc} = 1.39 \text{ lbs/ft}^2 \]

Corresponding air volume from fan characteristics

\[ Q = 129 \text{ CFM @ 0.5 inch water gauge. See Fig. 28.} \]
Air velocity at the jet exit.

\[ V = \frac{Q}{t \times L} \]  
\[ V = \frac{129}{2 \times 0.1 \times 60} \times 144 = 1,550 \text{ ft/min} \]

\[ V = 26 \text{ ft/sec} \]

\( \frac{t}{H} \) Ratio:

\[ \frac{t}{H} = \frac{0.1}{0.15} = 0.67 \]  
\[ \left( \frac{t}{H} \right) \text{ expression} \]  

\[ \frac{t}{H} + \cos \delta = 1.536 \]  

Theoretical air cushion pressure \( P_{CT} \) (calculated from observed figures)

\[ P_{CT} = \rho \frac{V^2}{H} \left[ \frac{t}{H} + \cos \delta \right] \]  
\[ P_{CT} = \frac{0.075}{32.2} \times 675 \times 0.67 \times 1.536 \]

\[ P_{CT} = 1.620 \text{ lbs/ft}^2 \]
The higher calculated pressure is attributed to the losses between strip and table where the area is not enclosed by the air jets.

Total pressure rise across the fan:

\[ P_T = P_c + \left[ (1 + \psi) \frac{\rho V^2}{2} \right] \]

\[ = 1.39 + \left[ (1.7) \frac{0.075}{32.2} \times 26.0 \right] \]

\[ P_T = 2.7 \text{ lb/ft}^2 \]

Air horsepower:

\[ \text{HP air} = \frac{P_T \times Q}{33,000} \]

\[ \text{HP air} = \frac{2.7 \times 129}{33,000} = 0.0106 \text{ HP} \]
### TABLE 4. EXPERIMENTAL DATA I

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Cushion Pressure $P_c$ (lb/ft$^2$)</th>
<th>Calculated Values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air Velocity $V$ (FPS)</td>
<td>Air Volume $Q$ (CFM)</td>
</tr>
<tr>
<td>1</td>
<td>2.33</td>
<td>23</td>
<td>116</td>
</tr>
<tr>
<td>2</td>
<td>1.89</td>
<td>24.8</td>
<td>121</td>
</tr>
<tr>
<td>3</td>
<td>1.86</td>
<td>24.5</td>
<td>122</td>
</tr>
<tr>
<td>4</td>
<td>1.58</td>
<td>25.1</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>1.36</td>
<td>26.0</td>
<td>129</td>
</tr>
<tr>
<td>6</td>
<td>1.11</td>
<td>26.6</td>
<td>131</td>
</tr>
</tbody>
</table>
TABLE 5. EXPERIMENTAL DATA II

<table>
<thead>
<tr>
<th>Test</th>
<th>Gauge No.</th>
<th>Thickness (In.)</th>
<th>Weight (Lbs.)</th>
<th>Measured Values</th>
<th>Pressure $P_1$</th>
<th>Pressure $P_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gap H (In.)</td>
<td>(In. W.G.)</td>
<td>(Lb/ft$^2$)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>0.0359</td>
<td>5.503</td>
<td>0.1</td>
<td>0.9</td>
<td>4.66</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0.0359</td>
<td>9.176</td>
<td>0.12</td>
<td>0.73</td>
<td>3.79</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>0.0299</td>
<td>4.585</td>
<td>0.12</td>
<td>0.72</td>
<td>3.74</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>0.0299</td>
<td>7.642</td>
<td>0.13</td>
<td>0.61</td>
<td>3.16</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0.0209</td>
<td>3.205</td>
<td>0.15</td>
<td>0.50</td>
<td>2.59</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0.0209</td>
<td>5.34</td>
<td>0.15</td>
<td>0.43</td>
<td>2.23</td>
</tr>
</tbody>
</table>
8.4 Results

Results obtained are shown in tabular form in Tables 4 and 5.

Measured values correspond rather well with the calculated ones and the air cushion theory used may serve also for the calculation of an air cushion for industrial applications.

8.5. Conclusion

Obtained results give good guide lines for calculation and design of strip runout tables. Though not accurately manufactured, testing equipment was a good help in final conclusions for the type of air cushion for this particular application.
FIGS. 25 & 26
EXPERIMENTAL SET-UP
FIG. 28. 4-1/4 in DIA. CENTRIFUGAL FAN CHARACTERISTIC
9.0 The Cooling of Hot Strip

The desired coiling temperature $T_c$ is a function of finishing temperature $T_f$, rolling speed $V_s$ and strip gauge.

The cooling on run-out table consists of three sections.

Section I - between last stand and water cooling section - $L_1$

Section II - water cooling section - $L_2$

Section III - between water cooling section and coiler. Section $L_3$

The length of each section varies according to the cooling requirements. A whole spectrum of cooling rates are possible between the finishing and coiling temperature. The physical properties of the steel will be different if there is a different way of cooling the strip.

![Different Ways of Cooling](FIG. 29)
Cooling in the sections I and III is by radiation -- there is no water contact with the strip surface.

Cooling in the section II is by radiation and convection.

Section 1

Neglecting the temperature gradients through the thickness of the strip the basic equation of radiation heat flow is:

\[ 2E_0T^4 \, dt = \rho c \, G \, dT \]  

(10)
Time for cooling in zone I

\[ t_1 = \frac{L_1}{V_s} \quad \text{(11)} \]

\[ t_1 = \int_{T_1}^{T_F} \frac{\rho c G \, dT}{2 E \, T^4} \quad \text{(12)} \]

After integration and re-arrangement the temperature at the end of section I is:

\[ T_1 = \frac{T_F}{\left(1 + \frac{6 \sigma E L_1 T_F}{V_s \rho c G}\right)^{1/3}} \quad \text{(13)} \]

Assuming that the required temperature \( T_c \) would be realized only by radiation, the strip temperature at the beginning of second section should have been \( T_{lr} \).

To achieve the required cooling temperature \( T_c \), a quantity of heat must be removed from the strip surface corresponding to the temperature difference \( T_1 - T_{lr} \).

In the same manner as for cooling zone I.

\[ t_{23} = \int_{T_{lr}}^{T_c} \frac{\rho c G \, dT}{2 E \, T^4} \quad \text{(14)} \]
and also

\[ t_{23} = \frac{L_2 + L_3}{V_s} \]  (15)

\[ T_{Tr} = \frac{T_c}{\sqrt[3]{1 - \sigma E (L_2 + L_3) T_c^3}} \]  (16)

\[ T_1 - T_{Tr} = \frac{T_F}{\sqrt[3]{1 + \sigma E L_1 T_F^3}} - \frac{T_c}{\sqrt[3]{1 - \sigma E (L_2 + L_3) T_c^3}} \]  (17)

Various types of water sprays are used to cool strip prior to coiling. The quantities of water used for removing the amount of heat from strip are disproportionate.

In 1957 BISRA developed the concept of cooling hot steel strip with water jets. This type of cooling is now being used on almost all new installed Hot Strip Mills. However, the water jet system has been applied only for cooling the top surface.

For cooling of the bottom surface pressure sprays are being still used.
In order to get uniform mechanical properties across the strip thickness and width, the author suggests using "continuous water jets" for both top and bottom surface (Figure 32). This pattern provides symmetrical cooling and ensures homogeneous grain structure of the strip. Continuous water jets are in comparison with laminar jets more efficient and simple.

FIG. 31. LAMINAR WATER JETS
9.1 Theory of "Continuous Water Jets" Cooling

This theory is very similar to that developed by BISRA for laminar jet cooling. The heat transfer from a semi-infinite body, initially at a temperature $T^1$ and instantaneously cooled at its surface to $T^{11}$ is equal to

$$q = k(T^1 - T^{11}) (\pi K t)^{-1/2}$$  \hspace{1cm} (18)

If the thickness of the jet is $D$, then the heat $Q$ removed from an area $A$,

$$A = D \times W$$  \hspace{1cm} (19)

during a time interval $t$ is given by

$$Q = D \times W \int_0^t q \, dt$$  \hspace{1cm} (20)

$$Q = D \times W \int_0^t k(T^1 - T^{11}) (\pi K t)^{-1/2} \, dt$$  \hspace{1cm} (21)

$$Q = D \times W \times k \times (T^1 - T^{11}) \left( \frac{t}{\pi K} \right)^{1/2}$$  \hspace{1cm} (22)

The cooling duration $t$ of strip (while the strip element is in contact with water jet) at speed $V_s$ and length $D$ is given by

$$t = \frac{D}{V_s}$$  \hspace{1cm} (23)
Therefore the heat removed from the strip element by one continuous water jet is given by:

\[ Q = D \times W \times k \times (T_1 - T_{11}) \left( \frac{D}{\sqrt{V_s \times \pi \times K}} \right)^{1/2} \]  

(24)

The number of sprays along the strip length required to reduce the temperature from \( T_1 \) to \( T_{lr} \) is expressed by the following equation.

\[ \frac{N_R \times D \times W \times k \times (T_1 - T_{11}) \left( \frac{D}{\sqrt{V_s \times \pi \times K}} \right)^{1/2}}{H} = H \]  

(25)

\[ H = \rho \times c \times G \times W \times D \times (T_1 - T_{lr}) \]  

(26)

Mean temperature during cooling may be expressed as

\[ T_m = \frac{T_1 + T_{lr}}{2} \]  

(27)

and the water temperature \( T_{11} \) can be neglected and

\[ T_1 = T_m = \frac{T_1 + T_{lr}}{2} \]  

(28)

therefore

\[ Q = 2 \times D \times W \times k \times (T_1 + T_{lr}) \]  

(29)

and equation for number of continuous water jets in final form is

\[ N_e = \frac{H}{Q} \]  

(30)
10.0 Calculation of Air Cushion for Typical Hot Strip Mill Product

The runout table is divided into three sections of which the last, section III, is using an air cushion for carrying the strip to the coilers. It covers 150 ft. and is located between the last roller of section II and pinch rolls at the entry to the coiler. From manufacturing point of view section III is divided into 12 subsections.

Strip dimensions:
Gauge: 0.100 in.
Width: 50.00 in.

Exhibit B

a/Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pc</td>
<td>Air cushion pressure</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>H</td>
<td>Gap between the table and the strip</td>
<td>in.</td>
</tr>
<tr>
<td>Po</td>
<td>Atmosphere pressure</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>P₁</td>
<td>Air pressure in chamber</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>t</td>
<td>Jet thickness</td>
<td>in.</td>
</tr>
<tr>
<td>v</td>
<td>Air velocity at the jet exit</td>
<td>ft/min</td>
</tr>
<tr>
<td>W</td>
<td>Strip width</td>
<td>in.</td>
</tr>
<tr>
<td>G</td>
<td>Strip thickness</td>
<td>in.</td>
</tr>
<tr>
<td>Ws</td>
<td>Air cushion width</td>
<td>in.</td>
</tr>
<tr>
<td>As</td>
<td>Air supported area</td>
<td>ft²</td>
</tr>
<tr>
<td>Wn</td>
<td>Jet separation</td>
<td>in.</td>
</tr>
<tr>
<td>δ</td>
<td>Jet angle</td>
<td>radians</td>
</tr>
<tr>
<td>HP</td>
<td>Air horsepower</td>
<td>HP</td>
</tr>
<tr>
<td>ρ</td>
<td>Air density</td>
<td>lb/ft²</td>
</tr>
<tr>
<td>Q</td>
<td>Air flow rate</td>
<td>ft³/min</td>
</tr>
</tbody>
</table>
Steel density
WGHT Strip weight along the subsections
ψ Coefficient of nozzle losses

b/Data

H = 0.50 in.
W = 0.125 in.
W = 50.00 in.
G = 0.100 in.
Wn = 38.00 in.
δ = 30°
ρ = 0.075 lb/ft³
ψ = 0.70
L = 150.00 in.

c/Calculation of Required Air Cushion Pressure

FIG. 33. SKETCH ILLUSTRATING RUNOUT TABLE SUBSECTION
Strip Weight:

\[ \text{WGHT} = L \times W \times C \times \gamma \]
\[ = 150.00 \times 50.00 \times 0.100 \times 0.283 \]
\[ \text{WGHT} = 212.25 \text{ lbs.} \]

Air Supported Area:

For dimensions see Fig. 33.

\[ W_s = W_n - 2 \times H \times \tan \theta \]
\[ = 38 - 2 \times 0.500 \times 0.5774 \]
\[ W_s = 36.268 \text{ in.} \]

\[ A_s = L \times W_s \]
\[ = 150.00 \times 36.268 \]
\[ = 144 \]
\[ A_s = 37.779 \text{ ft}^2 \]

Air Cushion Pressure:

\[ P_c = \frac{\text{WGHT}}{A_s} \]
\[ = \frac{212.25}{37.779} \]
\[ P_c = 5.63 \text{ lb/ft}^2 \]
Air Velocity Through the Nozzles:

\[ v = \sqrt{\frac{P_c \times H}{\rho \times t \times \left( \frac{t}{H} + \cos \delta \right)}} \]  

\[ = \sqrt{\frac{5.63 \times 0.5}{12}} \times \frac{0.075 \times 0.125 \times 0.125 + \cos 30^\circ}{32.2 \times 12 \times 0.500} \]

\[ v = 5585.7 \text{ ft/min.} \]

Air Flow Rate:

\[ \dot{V} = 2 \times (t \times L) \times v \]

\[ = 2 \left( \frac{0.125 \times 150.00}{144} \right) \times 5585.7 \]

\[ \dot{V} = 1454.6 \text{ ft}^3/\text{min.} \]

Total Pressure Rise Across the Fan:

\[ PT = P_c + (1 + \psi) \frac{\rho v^2}{2} \]

\[ = 5.63 (1 + 0.7) \times \frac{0.075}{32.2} \times \left( \frac{5585.7}{60} \right)^2 \times 1/2 \]

\[ PT = 22.78 \text{ lb/ft}^2 \]
Air Horsepower for One Subsection:

\[
HP_{\text{air}} = \frac{PT \times 0}{33,000} = \frac{22.78 \times 1454.6}{33,000}
\]

\[
HP_{\text{air}} = 1.004 \text{ HP}
\]

Air Horsepower for the Section III:

\[
HPT_{\text{air}} = HP_{\text{air}} \times \text{Number of subsections}
\]

\[
HPT_{\text{air}} = 1.004 \times 12
\]

\[
HPT_{\text{air}} = 12.05 \text{ HP}
\]

d/ Deceleration Force

It is a resistance of air to strip movement.

\[
D_f = \frac{0.074}{Re^{1/2}} \times \frac{1}{2} \times \rho \times V_s^2 \times A_s
\]

\[
D_f = 0.1526 \text{ lb}
\]

Reynolds number

\[
Re = \frac{\rho \times V_s \times X}{\mu}
\]

Calculation of deceleration force, boundary layer thickness shown in computer run.
Critical Force

The buckling of the strip occurs when the deceleration force is equal or greater than critical force $P_{cr}$.

$$P_{cr} = \frac{\pi^2 \times E \times I}{X^2_e}$$  \hspace{1cm} (40)

$P_{cr} = 0.3548$ lb.

Calculation of critical force shown in computer run together with the deceleration force.
11.0 Calculation of Strip Cooling for Typical Hot Strip Mill Product

For Time-Temperature diagrams see Figures 37 and 39.

Fig. 39 shows the strip cooling in TTT diagram at different rolling speeds and cooling rates. It results in different final grain structure.

Finishing mill reduces the rolling stock thickness continuously in each of its 6 stands. The strip is delivered on the runout table to the coiler, where the strip is coiled.

Slab Dimensions:

| Thickness: | 7.50 in |
| Width:     | 51.00 in |
| Length:    | 216.00 in |
| Weight:    | 22,310 lbs |

Strip Dimensions:

| Gauge:  | 0.100 in |
| Width:  | 50.00 in |

a/Nomenclature:

- TF: Finishing strip temperature °F
- T₁: Strip temperature at the end of section I °F
- T₁r: Hypothetical strip temperature at the end of section II °F
- T₂: Strip temperature at the end of section II °F
- Tc: Strip coiling temperature °F
- G: Strip gauge in
Vs Strain velocity FPM
L1 Length of the section I ft
L2 Length of the section II ft
L3 Length of the section III ft
C Stephan-Boltzman constant BTU/sec, ft²,R⁹
E Emissivity coefficient of steel strip
ρ Specific density of steel lb/ft³
C Specific heat of steel BTU/lb°F
T1 Time needed for strip to pass section I sec
T2 Time needed for strip to pass section II and III sec
D Water jet thickness in
K Thermal diffusivity of steel ft²/sec
k Thermal conductivity of steel BTU/sec, ft,F
NR Number of jets required
R The cooling duration of strip element sec

b/Data:

T_F = 1,600°F
T_C = 1,000°F
G = 0.10 in
Vs₁ = 1,425 FPM
Vs₂ = 2,850 FPM
L1 = 20 ft
L2 = 300 ft
L3 = 150 ft
σ = 4.75 x 10⁻¹³
E = 0.9
ρ = 490 lbs/ft³
C = 0.15
D = 0.75 in
K = 8.079 x 10⁻⁵ ft²/sec
k = 3.333 x 10⁻³ BTU/sec, ft,F
w = 50.00 in

c/Time for Cooling in Section I

\[ t₁ = \frac{L₁}{Vs₁} \]
\[ t_1 = \frac{20.00}{1425.00} \times 60.00 \text{ (Sec.)} \]

\[ t_1 = 0.842 \text{ Sec.} \]

For speed, \( V_{s_2} \) time \( t_1 = 0.421 \text{ Sec.} \)

\[ d/\text{Temperature at the End of Section I} \]

Due to radiation the temperature of the strip drops from \( T_F \) to \( T_1 \).

\[
T_1 = \left( \frac{T_F}{1 + \frac{6\rho ET_F^3 x t_1}{\rho x C x G}} \right)^{1/3}
\]

\[
T_1 = \left( \frac{(1600.00 + 460.00)}{1 + \frac{6 \times 4.75 \times 10^{-13} \times 0.9 \times (2060)^3}{490.00 \times 0.15 \times 0.100 \times 12.0}} \right)^{1/3} \text{ (°R)}
\]

\[ T_1 = 2057.90^\circ R \]
\[ T_1 = 1597.90^\circ F \]

For speed \( V_{s_2} \) temperature \( T_1 = 1598.90^\circ F \)
e/Time for Cooling in Sections II and III

\[ t_{23} = \frac{L_{II} + L_{III}}{V_s_1} \]  

\[ t_{23} = \frac{300.00 + 150.00}{1425.00} \times 60.00 \text{ (Sec.)} \]

\[ t_{23} = 18.947 \text{ Sec.} \]

For speed V_{s_2} \[ t_{23} = 9.473 \text{ Sec.} \]

f/Hypothetical Temperature \[ T_{IR} \]

\[ T_{IR} = T_c \left( 1 - \frac{6gE \cdot T_c^3}{\rho CG \cdot t_{23}} \right)^{1/3} \]  

\[ T_{IR} = \frac{1000.00 + 460.00}{\left( 1 - \frac{6 \times 4.75 \times 10^{-13} \times 0.9}{490.00 \times 0.15 \times 0.100 \times 18.947} \right)^{1/3}} \text{ (°R)} \]

\[ T_{IR} = 1472.20°R \]
\[ T_{IR} = 1012.20°F \]

For speed V_{s_2} the temperature \[ T_{IR} = 1466.10°R \]
\[ T_{IR} = 1006.10°F \]
g/Heat Removed by One Top Continuous Water Jet

\[
O = (T_1 + T_{IR}) W x D \times k \times \left( \frac{D}{V s \times \pi \times K} \right)^{1/2}
\]

\[
O = (2057.90 + 1472.20) \times \frac{50.00}{12.00} \times \frac{0.75}{12.00} \times 3.333 \times 10^{-3}
\]

\[
x \left( \frac{0.75}{12.00} \right) \left( \frac{1925}{60} \pi \times 8.071 \times 10^{-5} \right)
\]

\[
O = 10.255 \text{ BTU}
\]

For \( V_s \), \( O = 7.241 \text{ BTU} \)

h/Total Heat to be Removed From the Strip Element in Order to Reach Temperature \( T_{IR} \)

\[
H = (T_1 - T_{IR}) \sigma \times C \times W \times D \times G
\]

\[
H = (2057.90 - 1472.20) \times 490.00 \times 0.15 \times \frac{50.00}{12.00}
\]

\[
x \frac{0.75}{12.00} \times \frac{0.100}{12.00} \quad \text{(BTU)}
\]

\[
H = 97.08 \text{ BTU}
\]

For \( V_s \), total heat to be removed \( H = 98.27 \text{ BTU} \)
i/ Theoretical Number of Continuous jets

\[ NR = \frac{H}{Q} \quad (30) \]

\[ NR = \frac{97.08}{10.25} = 9.465 \text{ continuous jets for rolling speed } V_{S1} \]

\[ NR = 14 \text{ continuous jets for } V_{S2} \]
Water Quantity for Top Cooling Jet

\[ WOT = Ajt \times Vwt \]

**Water Jet Area**

\[ Ajt = Ww \times Dt \]
\[ = \frac{54 \times 0.75}{144} \]
\[ Ajt = 0.281 \text{ ft}^2 \]

**Water velocity**

\[ Vwt = \sqrt{2gh_t} \quad \text{ht water pressure at the end of the water nozzle} = 6 \text{ In.} \]
\[ = \sqrt{2 \times 32.2 \times 1/2} \]
\[ Vwt = 5.7 \text{ ft/sec} \]

**Water quantity**

\[ WOF = Ajt \times Vwt \]
\[ = 0.281 \times 5.7 \times 60 \]
\[ WOT = 96.01 \text{ ft}^3/\text{min/Jet} \]
\[ WOT = 598.3 \text{ Gal/min/Jet} \]
k/Water Quantity for Bottom Cooling Jet

\[ \text{WOB} = A_{ib} \times W_{wb} \]  

(44)

\[ A_{ib} = Ww \times Db \]

\[ = \frac{54 \times 0.5}{144} \]

\[ A_{ib} = 0.188 \text{ ft}^2 \]  

(45)

Water velocity

\[ V_{wb} = \sqrt{2gh_b} \]

\[ = \sqrt{2 \times 32.2 \times 1} \]

\[ V_{wb} = 8.05 \text{ ft/sec} \]  

Water quantity

\[ \text{WOB} = A_{ib} \times V_{wb} \]

\[ = 0.188 \times 8.05 \times 60 \]

\[ \text{WOB} = 90.5 \text{ ft}^3/\text{min.} \]

\[ \text{WOB} = 564.0 \text{ Gal/min.} \]

h_b - water pressure at the end of the water nozzle = 12 In.

(46)
1/Water Requirements

Top Cooling

\[ WRT = N_T \times WOT \]

\[ = 5 \times 598.3 \]

\[ WRT = 2991.5 \text{ gal/min at pressure of 6 in. of water for strip speed } V_s_1 \]

\[ WRT = 4188.1 \text{ gal/min at pressure of 12 in. of water for strip speed } V_s_2 \]

To provide symmetrical cooling both top and bottom nozzles have the same initial rate of heat extraction. However, the test on existing hot strip mill using laminar cooling (jet diameter 0.75 in.) have shown that the efficiency of cooling water for the bottom unit is roughly 1.5 times less than for the top. The same may apply to continuous water nozzles.

Thus, this results in a cooling effect of 5 top cool units and 8 bottom cooling units.

FIG. 36  COOLING SUBSECTION

Number of top continuous water jets:

\[ N_T = \frac{N_R}{2} \]

\[ = \frac{10}{2} \] (48)
\[ N_T = 5 \text{ top continuous water jets for strip speed } V_s_1 \]
\[ N_T = 7 \text{ top continuous water jets for strip speed } V_s_2 \]

Number of bottom continuous water jets.

\[ N_B = \frac{N_R}{2 \times 0.625} \quad (49) \]

\[ = \frac{10}{1.25} \]

\[ N_B = 8 \text{ bottom continuous water jets for strip speed } V_s_1 \]
\[ N_B = 11 \text{ bottom continuous water jets for strip speed } V_s_2. \]
12.0 Runout Table Design

Application

Generally, runout table consists of three sections:

a) Section I - between stand G and the first cooling subsection. Width and thickness gauges are installed in the area.

b) Section II - cooling section which comprises subsections with top and bottom cooling units.

c) Section III - between the last cooling subsection and pinch rolls before the coiler.

Decisions should concern:

1) Length of the runout table - section I, II, and III.

2) Type and dimension of the cooling units.

3) The cooling water flow.

4) The number of sprays in a subsection.

5) The total number of sprays.

6) Control of the cooling process.

7) Type of the conveying system.

7a) The conventional roller table in section I and II.

Roller diameter
Roller spacing
Maximum speed
Drive
7b) Air cushioned table - section III.
Required air pressure \( P_c \).
Air velocity through the nozzles.
Air flow rates.
Total pressure rise across the fan.
Air horsepower for the subsection.
Total air horsepower for section III.
Deceleration force.
Critical force.

Typical calculating procedures are shown at EXHIBITS for calculation of air cushion and strip cooling at chapter 10.0 and 11.0.

Following charts are summary of results for air cushion and strip cooling for the product mix rolled on 56 In. Hot Strip Mill.
FIG. 38. STRIP COOLING ON RUNOUT TABLE AT $V_{S2}$
FIG. 39. STRIP COOLING IN TTT DIAGRAM
FIG. 40. AIR HORSEPOWER vs. STRIP GAUGE
FIG. 41. DECELERATION FORCE ALONG THE STRIP LENGTH
FIG. 43. FINISHING TEMPERATURE vs. STRIP GAUGE
FIG. 44. THEORETICAL NUMBER OF CONTINUOUS JETS vs. STRIP GAUGE AT $V_{S1}$ AND $V_{S2}$
13.0 Economical Comparison of Conventional and Air Cushioned Runout Table

The benefits realized in capital outlay are listed in tabular form below.

**TABLE 6. CAPITAL COSTS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional Runout Table</th>
<th>Air Cushioned Runout Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical part</td>
<td>$5000/ft</td>
<td>$840/ft</td>
</tr>
<tr>
<td>4-HP DC Motor ($2600 each)</td>
<td>$1730/ft</td>
<td>-</td>
</tr>
<tr>
<td>15HP AC Motor + Fan</td>
<td>-</td>
<td>$70/ft</td>
</tr>
<tr>
<td>Foundations</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Total cost/ft</td>
<td>$6730</td>
<td>$920</td>
</tr>
</tbody>
</table>

Total capital expenditure for 150 ft long conventional runout table is $1,009,500 and $138,000 for the same length of air cushioned runout table.
Due to the complexity of accounting in an operation of this size, individual benefits from maintenance, power and quality can not be precisely calculated.

**TABLE 7. OPERATING COSTS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional Runout Table</th>
<th>Air Cushioned Runout Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td>$121,200/yr</td>
<td>$28,960</td>
</tr>
<tr>
<td>Cobbles (rejects)</td>
<td>$72,000/yr</td>
<td>$12,000</td>
</tr>
<tr>
<td>Power</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Lubrication</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Surface defects</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Metallurgical rejects</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
Many Hot Strip Mills at present are working the maximum possible number of hours. To supplement mill production, hot strip is purchased from steel mills with surplus capacity, for which a premium is paid. As a result, any decrease in delays on the mill is highly profitable to the company, as it offsets these purchases. As an example, delays incurred by cobbles, if reduced by 50%, would result in increased profits of about $400,000/yr. Reduced maintenance time for an air cushioned runout table would allow other preventive maintenance to be carried out, again reducing delays in similar savings.
14.0 Conclusion

Forty-six years of experience have been realized on continuous Hot Strip Mills. In that period, mills have proliferated and technology has expanded at ever-increasing rates. While principles have changed little since continuous mill inception, machinery and tool materials have become highly sophisticated.

To achieve any marked improvement in the profit picture, it is now time that principles of individual components of the system are revised. This thesis is an alternative proposal for improving a particular problem area in such a system.

Subject of this thesis, runout tables conventionally consist of extended series of iron rollers, bearinged at both ends, individually driven by small D/C shunt-wound motors. Speed matching is difficult, as surface speeds exceed 40 mph on 12" O.D. rollers. The conventional runout tables have long been a source of waste and quality reduction. The alternative proposed is a peripheral jet air-cushioned runout table with no moving parts contacting the strip. Construction costs and maintenance are low.

Conventional cooling of the Hot Strip as it exits from the finishing mill train is accomplished by a combination of high-pressure sprays and a recently-devised laminar flow system from individual nozzles.
The alternative proposed is a continuous laminar flow curtain of water delivering uniform cooling across the width of the strip.

Surface quality productivity, control of physical properties of the strip and capital investment are benefited by these proposals. The present financial situation of the Steel Industry prohibits large capital investments to circumvent these problems.

The application of a proven principle, air-cushioned transport, offers a solid procedural change, at low cost, to virtually eliminate the problems currently experienced. Design data, graphically represented in this paper, were calculated and verified experimentally with large-scale models.

It should be kept in mind that while present proposals for air-cushioning applies only to the terminal section of the runout table, further investigations may reveal convenient applications for the cooling section of the table where water must be supplied to both top and bottom of the strip.

An obvious application for air-cushioning is the short span (about 20') immediately at the exit of the final finishing mill. In this section, width and gauge monitoring are carried out. Conventional runout tables cause excessive vertical movement of the strip, hindering these measurements. Discussion of this area in detail is excluded as tangible savings from the short span involved would be small.
Much costly unscheduled processing is caused by inefficient and poorly regulated cooling of the Hot Strip. Structures not initially achieved on cooling on the runout table must be obtained by subsequent annealing.

In many instances, desired structures cannot be attained at all by present industrial reprocessing. Some of the problems causing this poor structure control would be alleviated by a continuous cooling water curtain, exposing the full width of the strip to identical conditions. Due to more efficient cooling, the length of table required could be shortened, again reducing large capital investments.

As the production capacity of present Hot Strip Mills is being pushed by product demand (except for a recent short-term recession in restricted geographical areas), productivity of such mills is at a premium. Importation of Hot Strip from countries utilizing low-cost labour to achieve competitive prices cannot be continued indefinitely for obvious reasons. Any reduction in capital investment that can be realized should be seriously considered, as competitive pricing can be maintained for extended periods by this means alone.

Both these proposals offer such a reduction. Tangible evidence of this is that by substituting only one-third of a conventional runout table with an air-cushioned table, capital investment is reduced by more than 3/4 million dollars. Over a conservative
mill life expectancy of thirty years, maintenance costs are reduced by over 2 million dollars. Current costs for maintaining a conventional runout table are well documented.
16.0 References


12. The Professional Engineer and Engineering Digest, September 1966, Hovercraft Operating Principles and General Design.


## Calculation of decelerating force, critical force, and boundary layer along the air cushioned runout table

<table>
<thead>
<tr>
<th>N</th>
<th>$DF(I)$</th>
<th>$PCR(I)$</th>
<th>$BLT(I)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.2031 &amp; 7426</td>
<td>1996.1 &amp; 47083333333</td>
<td>2.87 &amp; 848774</td>
</tr>
<tr>
<td>3</td>
<td>0.250 &amp; 8453</td>
<td>887.1 &amp; 17648148148</td>
<td>3.52 &amp; 5039591</td>
</tr>
<tr>
<td>4</td>
<td>0.290 &amp; 3788</td>
<td>493.0 &amp; 36778103333</td>
<td>4.17 &amp; 3635114</td>
</tr>
<tr>
<td>5</td>
<td>0.32 &amp; 7578</td>
<td>319.3 &amp; 85333333333</td>
<td>4.55 &amp; 905544</td>
</tr>
<tr>
<td>6</td>
<td>0.3633333</td>
<td>221.7 &amp; 7941203704</td>
<td>4.84 &amp; 158790</td>
</tr>
<tr>
<td>7</td>
<td>0.3942 &amp; 067 &amp; 162.9 &amp; 7507823129</td>
<td>5.53 &amp; 1097913</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.423 &amp; 1693</td>
<td>124.8 &amp; 7927017083</td>
<td>5.76 &amp; 306544</td>
</tr>
<tr>
<td>9</td>
<td>0.443 &amp; 9480</td>
<td>79.8 &amp; 45483333333</td>
<td>6.10 &amp; 5447671</td>
</tr>
<tr>
<td>10</td>
<td>0.4623 &amp; 8956</td>
<td>65.9 &amp; 98833333333</td>
<td>6.43 &amp; 5814333</td>
</tr>
<tr>
<td>11</td>
<td>0.4802 &amp; 9048</td>
<td>55.4 &amp; 4485309920</td>
<td>6.74 &amp; 936921</td>
</tr>
<tr>
<td>12</td>
<td>0.5075 &amp; 1228</td>
<td>47.2 &amp; 4608414126</td>
<td>7.45 &amp; 0071963</td>
</tr>
<tr>
<td>13</td>
<td>0.5341 &amp; 0993</td>
<td>40.7 &amp; 7369557882</td>
<td>7.73 &amp; 7520643</td>
</tr>
<tr>
<td>14</td>
<td>0.5613 &amp; 5191</td>
<td>35.4 &amp; 9705925959</td>
<td>7.91 &amp; 228150</td>
</tr>
<tr>
<td>15</td>
<td>0.5871 &amp; 0486</td>
<td>31.8 &amp; 8978117711</td>
<td>8.14 &amp; 730228</td>
</tr>
<tr>
<td>16</td>
<td>0.6129 &amp; 3523</td>
<td>27.0 &amp; 32833333333</td>
<td>8.39 &amp; 127556</td>
</tr>
<tr>
<td>17</td>
<td>0.6376 &amp; 8498</td>
<td>24.6 &amp; 6439115225</td>
<td>8.68 &amp; 4583262</td>
</tr>
<tr>
<td>18</td>
<td>0.6623 &amp; 168</td>
<td>22.2 &amp; 1179732225</td>
<td>9.01 &amp; 163089</td>
</tr>
<tr>
<td>19</td>
<td>0.6863 &amp; 5425</td>
<td>19.9 &amp; 9147083333</td>
<td>9.35 &amp; 378121</td>
</tr>
<tr>
<td>20</td>
<td>0.7101 &amp; 0496</td>
<td>18.1 &amp; 0564247972</td>
<td>9.54 &amp; 582344</td>
</tr>
<tr>
<td>21</td>
<td>0.7339 &amp; 3523</td>
<td>16.5 &amp; 49708333333</td>
<td>9.76 &amp; 032663</td>
</tr>
<tr>
<td>22</td>
<td>0.7574 &amp; 1228</td>
<td>15.3 &amp; 9369979500</td>
<td>9.97 &amp; 031759</td>
</tr>
<tr>
<td>23</td>
<td>0.7802 &amp; 4416</td>
<td>13.6 &amp; 6213253231</td>
<td>1.01 &amp; 75916785</td>
</tr>
<tr>
<td>24</td>
<td>0.8024 &amp; 4461</td>
<td>12.1 &amp; 7534133333</td>
<td>1.03 &amp; 77435572</td>
</tr>
<tr>
<td>25</td>
<td>0.8240 &amp; 4461</td>
<td>10.9 &amp; 115212032</td>
<td>1.05 &amp; 53114774</td>
</tr>
<tr>
<td>26</td>
<td>0.8448 &amp; 3523</td>
<td>10.1 &amp; 4823849496</td>
<td>1.07 &amp; 6974347</td>
</tr>
<tr>
<td>27</td>
<td>0.8658 &amp; 1025</td>
<td>9.4 &amp; 41597303</td>
<td>1.09 &amp; 89753482</td>
</tr>
<tr>
<td>28</td>
<td>0.8869 &amp; 0496</td>
<td>8.7 &amp; 1749181418</td>
<td>1.11 &amp; 47153951</td>
</tr>
<tr>
<td>29</td>
<td>0.9074 &amp; 1373</td>
<td>8.1 &amp; 566249965</td>
<td>1.13 &amp; 1416913</td>
</tr>
<tr>
<td>30</td>
<td>0.9279 &amp; 7342</td>
<td>7.6 &amp; 3230703070</td>
<td>1.15 &amp; 124010932</td>
</tr>
<tr>
<td>31</td>
<td>0.9480 &amp; 2428</td>
<td>7.1 &amp; 970833333</td>
<td>1.16 &amp; 9233699</td>
</tr>
<tr>
<td>32</td>
<td>0.9681 &amp; 1228</td>
<td>6.6 &amp; 914639104</td>
<td>1.18 &amp; 7051586</td>
</tr>
<tr>
<td>33</td>
<td>0.9880 &amp; 8498</td>
<td>6.1 &amp; 349933056</td>
<td>1.2 &amp; 9032838</td>
</tr>
<tr>
<td>34</td>
<td>0.8081 &amp; 1024</td>
<td>5.6 &amp; 249564792</td>
<td>1.22 &amp; 78969995</td>
</tr>
<tr>
<td>35</td>
<td>0.8280 &amp; 5046</td>
<td>5.1 &amp; 903677063</td>
<td>1.24 &amp; 1024667</td>
</tr>
<tr>
<td>36</td>
<td>0.8480 &amp; 2458</td>
<td>4.7 &amp; 749038271</td>
<td>1.26 &amp; 15262758</td>
</tr>
<tr>
<td>37</td>
<td>0.8681 &amp; 1234</td>
<td>4.3 &amp; 572610198</td>
<td>1.28 &amp; 8944242</td>
</tr>
<tr>
<td>38</td>
<td>0.8880 &amp; 0316</td>
<td>3.8 &amp; 19275250</td>
<td>1.3 &amp; 9584843</td>
</tr>
<tr>
<td>39</td>
<td>0.9081 &amp; 0109</td>
<td>3.4 &amp; 12470333</td>
<td>1.32 &amp; 4983843</td>
</tr>
<tr>
<td>40</td>
<td>0.9281 &amp; 9480</td>
<td>3.0 &amp; 30653844</td>
<td>1.34 &amp; 652417632</td>
</tr>
<tr>
<td>41</td>
<td>0.9481 &amp; 9046</td>
<td>2.6 &amp; 734344401</td>
<td>1.36 &amp; 32796773</td>
</tr>
<tr>
<td>42</td>
<td>0.9680 &amp; 5784</td>
<td>2.2 &amp; 145714501</td>
<td>1.38 &amp; 32908860</td>
</tr>
<tr>
<td>43</td>
<td>0.9881 &amp; 26751</td>
<td>1.8 &amp; 465331308</td>
<td>1.4 &amp; 15015360</td>
</tr>
<tr>
<td>44</td>
<td>0.8092 &amp; 5773</td>
<td>1.4 &amp; 325526197</td>
<td>1.42 &amp; 424677899</td>
</tr>
<tr>
<td>45</td>
<td>0.8292 &amp; 71165</td>
<td>1.0 &amp; 193353333</td>
<td>1.44 &amp; 31601970</td>
</tr>
<tr>
<td>46</td>
<td>0.8491 &amp; 41002</td>
<td>0.6 &amp; 699141914</td>
<td>1.46 &amp; 76791129</td>
</tr>
<tr>
<td>47</td>
<td>0.8691 &amp; 1410122</td>
<td>0.2 &amp; 285020767</td>
<td>1.48 &amp; 931452660</td>
</tr>
<tr>
<td>48</td>
<td>0.8891 &amp; 0112</td>
<td>1.0 &amp; 2731990169</td>
<td>1.5 &amp; 955476394</td>
</tr>
<tr>
<td>49</td>
<td>0.9092 &amp; 4951</td>
<td>1.6 &amp; 2639333333</td>
<td>1.52 &amp; 9311780</td>
</tr>
<tr>
<td>50</td>
<td>0.9292 &amp; 3059</td>
<td>2.2 &amp; 5461059736</td>
<td>1.54 &amp; 22914696</td>
</tr>
<tr>
<td>Width</td>
<td>Gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.0</td>
<td>.100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 2

Calculation of air velocity (at the end of the nozzle), air pressure and air horsepower for various strip width, jet separation and strip gauge.

<table>
<thead>
<tr>
<th>WIDTH</th>
<th>CAUSE</th>
<th>PRESSURE</th>
<th>HP AIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00000E+01</td>
<td>5.00000E-02</td>
<td>2.952E+00</td>
<td>2.541E+01</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>4.564E+00</td>
<td>7.187E+01</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>6.758E+00</td>
<td>1.325E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>9.214E+00</td>
<td>2.031E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.1766E+00</td>
<td>2.641E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.351E+00</td>
<td>3.093E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.677E+00</td>
<td>4.069E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.821E+00</td>
<td>5.756E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.075E+00</td>
<td>6.601E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.202E+00</td>
<td>8.034E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.302E+00</td>
<td>2.637E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>4.183E+00</td>
<td>4.923E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>6.275E+00</td>
<td>7.741E+02</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>8.164E+00</td>
<td>1.374E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.177E+01</td>
<td>1.757E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.351E+01</td>
<td>2.339E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.677E+01</td>
<td>3.333E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.820E+01</td>
<td>4.060E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.074E+01</td>
<td>4.923E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.201E+01</td>
<td>5.756E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.301E+01</td>
<td>6.601E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.400E+01</td>
<td>8.034E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.637E+01</td>
<td>2.637E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>2.832E+01</td>
<td>4.923E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>3.133E+01</td>
<td>7.741E+03</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>3.400E+01</td>
<td>1.374E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>3.857E+01</td>
<td>1.757E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>4.351E+01</td>
<td>2.339E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>4.923E+01</td>
<td>3.333E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>5.756E+01</td>
<td>4.923E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>6.601E+01</td>
<td>6.601E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>8.034E+01</td>
<td>8.034E+04</td>
</tr>
<tr>
<td>4.00000E+01</td>
<td>1.00000E-01</td>
<td>1.000E+02</td>
<td>1.000E+05</td>
</tr>
<tr>
<td>WIDTH</td>
<td>GAUGE</td>
<td>PRESSURE</td>
<td>HP AIR</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>----------</td>
<td>--------</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>5.000E-02</td>
<td>2.590E+00</td>
<td>3.143E-01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>1.000E-01</td>
<td>5.181E+00</td>
<td>3.864E-01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>1.500E-01</td>
<td>7.724E+00</td>
<td>2.625E+00</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>2.000E-01</td>
<td>1.363E+01</td>
<td>1.924E-01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>2.500E-01</td>
<td>2.245E+01</td>
<td>1.505E+00</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>3.000E-01</td>
<td>3.136E+01</td>
<td>1.206E+01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>3.500E-01</td>
<td>4.724E+01</td>
<td>1.618E+01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>4.000E-01</td>
<td>2.324E+01</td>
<td>1.519E+01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>4.500E-01</td>
<td>2.471E+01</td>
<td>1.410E+01</td>
</tr>
<tr>
<td>4.600E+01</td>
<td>5.000E-01</td>
<td>2.808E+01</td>
<td>1.311E+01</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>1.000E-01</td>
<td>2.742E+00</td>
<td>9.155E-01</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>1.500E-01</td>
<td>2.413E+00</td>
<td>1.601E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>2.000E-01</td>
<td>7.583E+00</td>
<td>2.956E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>2.500E-01</td>
<td>3.261E+00</td>
<td>4.573E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>3.000E-01</td>
<td>1.177E+01</td>
<td>5.349E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>3.500E-01</td>
<td>3.326E+00</td>
<td>7.324E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>4.000E-01</td>
<td>6.471E+00</td>
<td>3.739E+00</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>4.500E-01</td>
<td>1.627E+01</td>
<td>1.236E+01</td>
</tr>
<tr>
<td>4.700E+01</td>
<td>5.000E-01</td>
<td>1.226E+01</td>
<td>1.817E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>1.000E-01</td>
<td>6.276E+00</td>
<td>7.556E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>1.500E-01</td>
<td>6.331E+00</td>
<td>7.974E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>2.000E-01</td>
<td>2.759E+00</td>
<td>6.797E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>2.500E-01</td>
<td>7.931E+00</td>
<td>5.856E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>3.000E-01</td>
<td>1.134E+01</td>
<td>1.022E+00</td>
</tr>
<tr>
<td>4.800E+01</td>
<td>3.500E-01</td>
<td>1.264E+01</td>
<td>1.971E+00</td>
</tr>
<tr>
<td>4.900E+01</td>
<td>1.000E-01</td>
<td>6.385E+00</td>
<td>8.541E+00</td>
</tr>
<tr>
<td>4.900E+01</td>
<td>1.500E-01</td>
<td>1.699E+00</td>
<td>5.576E+00</td>
</tr>
<tr>
<td>4.900E+01</td>
<td>2.000E-01</td>
<td>1.255E+00</td>
<td>4.936E+00</td>
</tr>
<tr>
<td>4.900E+01</td>
<td>2.500E-01</td>
<td>1.263E+00</td>
<td>4.926E+00</td>
</tr>
<tr>
<td>4.900E+01</td>
<td>3.000E-01</td>
<td>1.263E+00</td>
<td>4.926E+00</td>
</tr>
<tr>
<td>5.000E+01</td>
<td>1.000E-01</td>
<td>6.385E+00</td>
<td>8.541E+00</td>
</tr>
<tr>
<td>5.000E+01</td>
<td>1.500E-01</td>
<td>1.699E+00</td>
<td>5.576E+00</td>
</tr>
<tr>
<td>5.000E+01</td>
<td>2.000E-01</td>
<td>1.255E+00</td>
<td>4.936E+00</td>
</tr>
<tr>
<td>5.000E+01</td>
<td>2.500E-01</td>
<td>1.263E+00</td>
<td>4.926E+00</td>
</tr>
<tr>
<td>5.000E+01</td>
<td>3.000E-01</td>
<td>1.263E+00</td>
<td>4.926E+00</td>
</tr>
</tbody>
</table>
APPENDIX 3

Drawing 1  Section through existing runout table
Drawing 2  Testing equipment
Drawing 3  Air cushioned runout table 1 - section
Drawing 4  Air cushioned runout table 11 - section
Drawing 5  General arrangement of runout table
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE NOTED ARE: (PLUS OR MINUS) MAINTAIN ±0.010"; STRUCTURAL OVERALL ±1/16"; ALL OTHERS ±1/32" NON-ACCUMULATIVE.

SURFACE FINISH UNLESS OTHERWISE NOTED BETWEEN "DY" AND "F".