STRIP SHAPE and PROFILES & the UNKNOWN "DEVILS" [1]

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Abstract

Many of the hot strip mill operators have used many "unkind" words about the strip shape and profiles coming off their mill because it keeps changing. Most of them forget a hot strip mill is a "lady" who does what she wants, when she wants, and how she wants it; and immediately changes her mind. The problem is the strip shape and profile is controlled by unknown "devils". Some mill operators learn something about these "devils" and how to control them, but other mill operators just go "crazy" with the constantly changing shape and strip profiles.

Key words: Thermal crowns; Cooling patterns; Heat balance; Shape.

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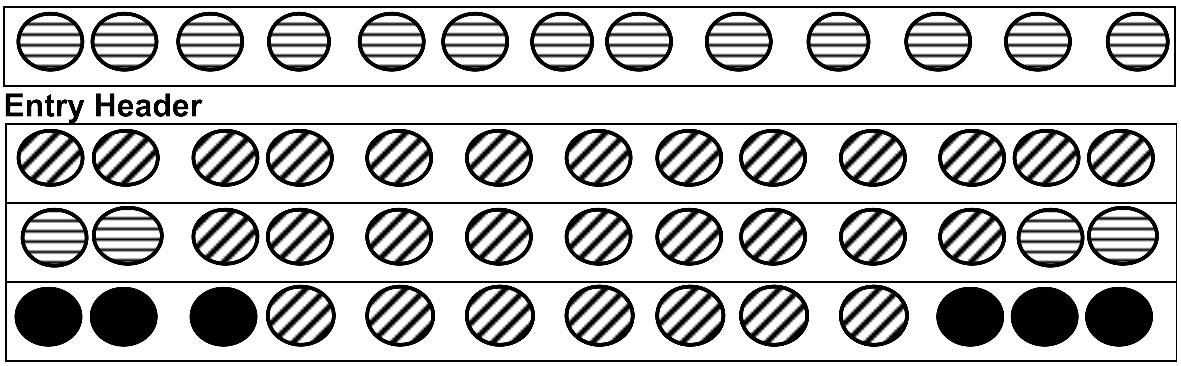
A. Roll Cooling Designs

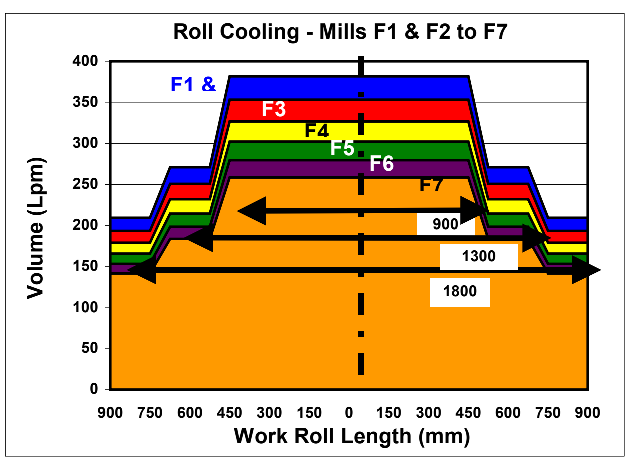


Exit Header **Figure 1 – Typical Roll Cooling Headers (1)**

Figure 1 is a typical roll cooling design used on many mills with these features:

1. All the nozzle arrangements in each mill stand are the same with the cross –hatching indicating different nozzle sizes.
2. All the nozzles are usually offset in the same direction
3. More cooling volume is applied on the exit side of the mill
4. The nozzles **(black)** are plugged to decrease the cooling volume at the ends
5. The length of the cooling spray coverage is less than the length of the work rolls

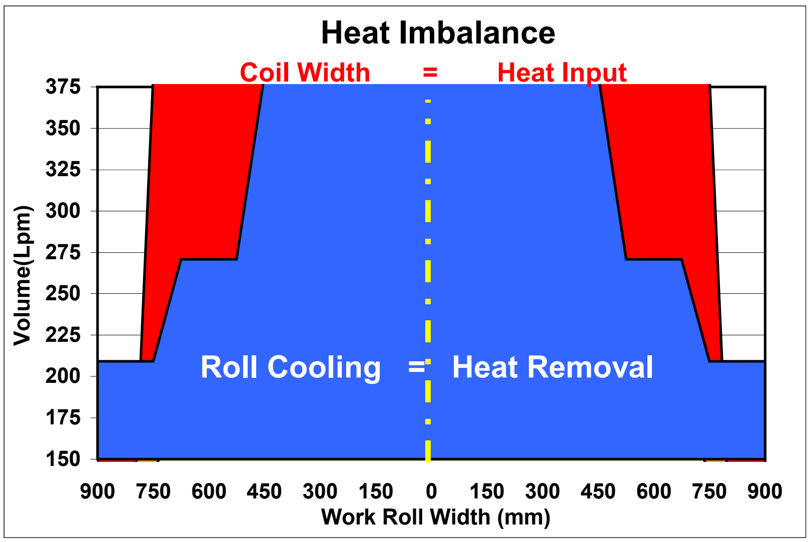
The total roll cooling volume is modified in each mill stand by using larger or smaller nozzles with the greatest volume used in F1 and F2 mills, and less volume used in each mill stand from F3 to F7 is shown in Graph 1. The header and nozzle arrangements in Figure 1 look good on the engineering drawings and inside the mill, but there are a number of "devils" in this design. Do you recognize them? To understand the affects of such a design it is necessary to look at both the **general** and **narrow** thermal crown variations. Graph 1 shows the general roll cooling volume and distribution across the work rolls on each mill stand.



Graph 1 - Roll Cooling Volume per Mill Stand

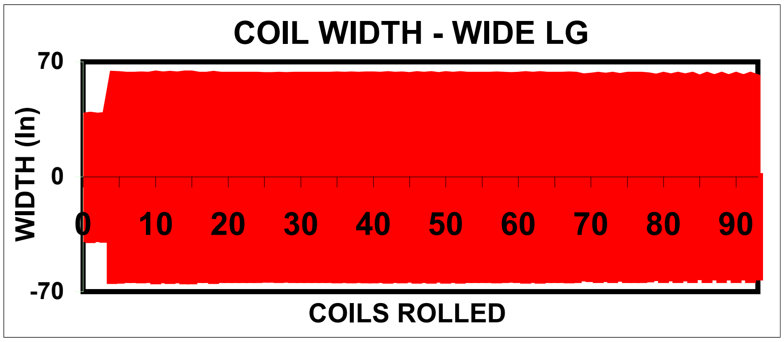
B. Shape Devils

Devil #1 – This roll cooling design originated in the 1950's and 60's when rolling "coffin" shape schedules. The author doubts if anyone here has ever seen every rolling schedule being a "coffin" shape. "Coffin" shape rolling schedules require: **[a]** about 300,000 tons of slab inventory of various widths, **[b]** customers who order many different coil widths, and **[c]** customers who will wait or take delivery ahead of time. How many hot strip mills enjoy the luxury of these three items. Today the rolling schedules are built because **[a]** customers order many coils of the same width from the "low cost" hot mill, **[b]** the customers want "just in time" delivery every week, and **[c]** this results in "barrel" shaped rolling schedules of many coils relatively the same width.



When rolling a "barrel" schedule with different roll cooling volume across the width of the work rolls creates a "heat imbalance". At the beginning heat is removed by the roll cooling water and/or is conducted into the roll body. Eventually the work roll temperature increases until a "heat" balance is reached between the work roll and cooling volume in the middle of the roll. After this occurs the work roll surface becomes hotter near the ends of the rolls because of a lower amount of work roll cooling water is removing the heat. Graph 2 shows the "imbalance" between the **heat input (red)** and the **heat removal (blue)** when a "heat balance" is reached in the middle of the work roll. Now the heat from the middle cannot flow outward to the roll ends, and ends of the rolls get hotter because of the imbalance created by putting the same amount of heat into the work rolls where the roll cooling volume is lower. The result is the middle temperature in the work rolls must rise until the **▲T** between the work rolls and roll cooling water reaches a new "balance". At the same time the work roll temperature at the widest coil widths increases to a higher **▲T** to reach a 'balance' between the **heat input** and **removal**.

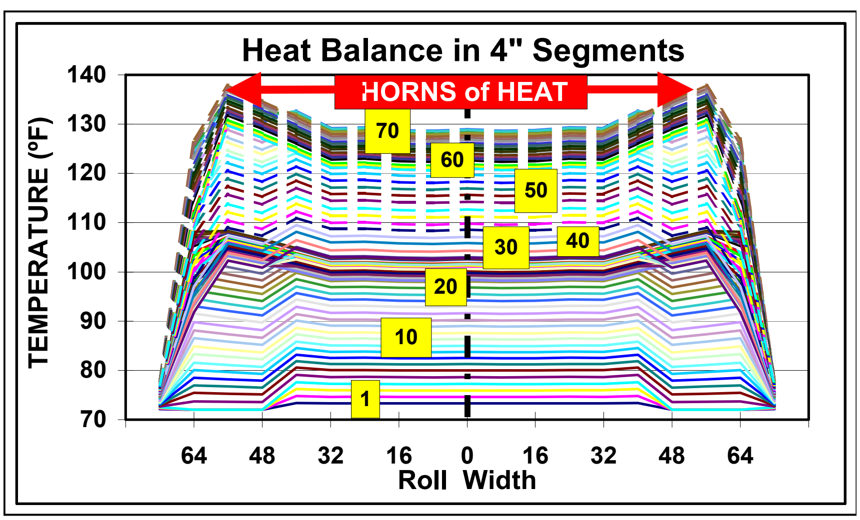
Most mill operators believe a "coffin" schedule starts with narrow coils to build up a thermal crown to roll better shape. Up to a point in the rolling schedule they are correct, but after rolling for 1-1/2 hours the thermal crown begins to change based on the coil widths being rolled, the uneven roll cooling volume, and the rolling pace. Then these things happen: [a] the roll gets hotter near the edges of the strip and the maximum amount of heat flows outward to the roll ends, [b] the area in the middle is colder than the near the edges and the heat begins to flow toward the middle of the work roll, [c] the existing roll cooling volume in the middle cannot remove more heat unless the roll temperature rises to create a greater ▲T, [d] the hotter areas near the edges of the coils cannot send more heat to the middle of the roll and the area near the strip edges becomes hotter, [e] the result is the entire work roll temperature increases, and [f] the different temperature on the work roll creates an uneven thermal crown.



Graph 3 – "Barrel" Shaped Rolling Schedule (1)

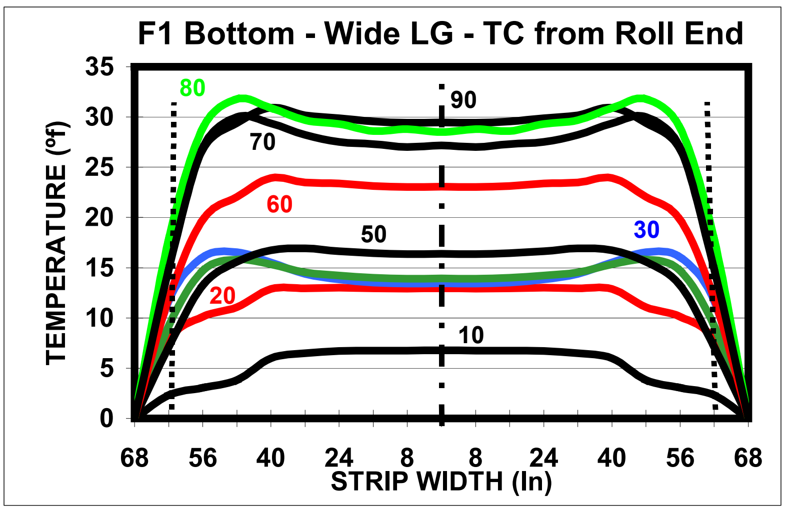
The graphs and thermal profiles are in English or Metric depending on the actual data from different mills. Graph 3 is an actual rolling schedule on a compact mill. The vertical axis is the coil width, and the horizontal axis is the number of coils rolled (1). The first few narrow coils build a thermal crown, but after those coils are rolled the heat input across the work roll width is almost at a constant width. The roll cooling volume shown in Graph 1 represents the heat removal pattern for this hot strip mill. The result of the heat input by coil width and heat removal by the roll cooling volume at each width results in a heat balance shown in Graph 4 (1)(2)(3).

Graph 4 shows the temperature in ºF when a heat balance is reached in each 100mm segment across the work roll width without considering conductivity between the segments (2). The first 25 coils show a heat balance hotter towards the middle and cooler toward the roll ends. After this the heat balance shows a higher temperature near the roll ends compared to the center on coils #30 to #70 forming distinct "horns of heat" at about the 60" strip width. The thermal crown is concave with shoulders for most of the rolling schedule.



Graph 4 – Heat Balance for each Coil Rolled (2)

The computer model predictions in Graph 5 of the thermal crowns on another schedule after adjusts the temperature to for the conductivity between adjacent segments for the heat input and heat removal starting at the 1st coil and for every 10th coil rolled until the end of the rolling schedule at coil #90. Rolling a few narrow coils at the beginning of the schedule allows the heat to go into the cold work roll, and results in semi-convex thermal crown on the 10th, and 20th coils rolled. After #20 coil the work roll cannot absorb more heat toward the edges results in increasing the temperature to form a concave with shoulders (3) thermal crown on coils #30 and #40. These "horns of heat" (3) block the heat coming out from the middle of the work roll toward the roll ends, and the temperature rises in the middle of the work roll as seen in coils #50 and #60 to create a flat thermal crown (2)(3). The continuation of rolling wide coils begins to both increase the temperature in the middle of the roll and ends of the rolls to again create a concave with shoulders (3) thermal crown on coils #70, #80, and #90.



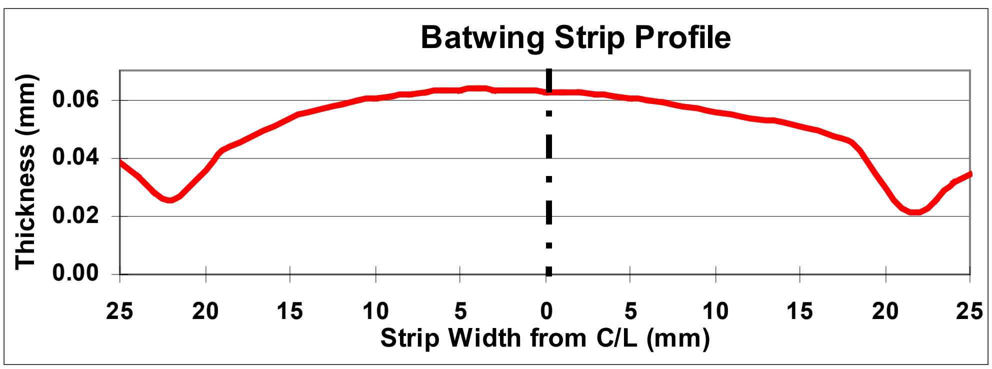
Graph 5 – Computer Model of Thermal Crowns (1)(2)(3)

The **black vertical dotted** lines show the maximum coil width rolled. Do you see the **"devils"** in Graph 5? Rolling the first 20 coils results in a slight **center buckle** for which the typical shape control system can make adjustments. By the time #30 to #40 coils are rolled the shape will have wavy edges due the higher thermal crowns near the edges created by the shoulders (3), and the shape control system will bend the work rolls resulting in **duplex shape** consisting of **wavy edges** and a **center buckle** created by the "horns of heat" and bending of the work rolls. As the rolling continues the **shoulders** (3) become more abrupt creating **batwing** (1) strip profiles in the strip. More often a commonly seen strip shape defect caused by these narrow shape distortions is called **quarter line buckles**.

How can any shape control system bend the "roll stack" with these thermal crowns to remove the "horns of heat" distortions and roll good shape?

Devil #1 **is the** general **shape and profile defects due to using a roll cooling design made for rolling "coffin" shaped rolling schedules when actually rolling "barrel" shaped rolling schedules.**

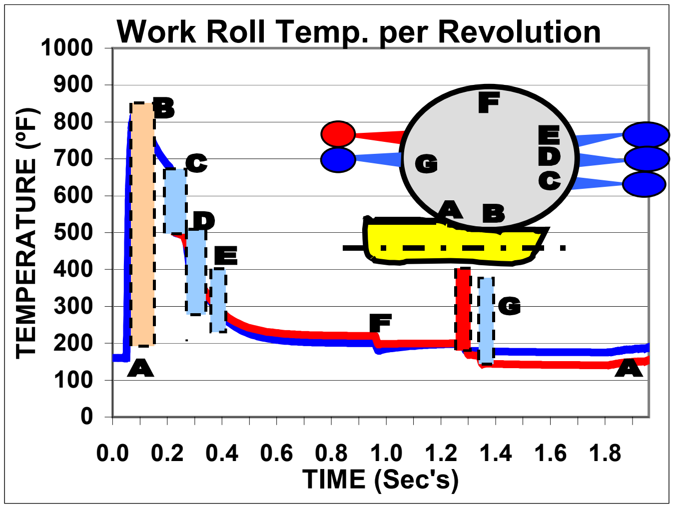
- **Devil #2** produces a **duplex shape** consisting of **wavy edges** and a **center buckle** if the rolling schedule after coil #60 are narrower and the same width of the **"shoulders"**. The thermal crown produces severe **wavy edges**, and the shape control system bends the rolls to create a **duplex shape.**
- **Devil #3** produces an undesirable **"flat"** strip profile on narrow coils at the end of the schedule where the coil width narrows down inside the center cooling area.
- **Devil #4** comes from the roll cooling headers being the same in each mill stand, and carries the same uneven thermal crowns through every mill. Making shape control adjustments or changing work rolls on individual mill stands just creates a new undesirable strip shape. This drives the mill operators "crazy".



Graph 6 – Batwing Strip Profile (1)

- **Devil #5** is a strip profile problem called **batwings** because the strip has a profile as seen in Graph 6 with two distinct "dips" near the edges. **Batwings** do not appear on all coils, but go back to Graph 4 to see the "horns of heat" creating **"peaks"** from #30 to #70 coil. This abnormal profile occurs because all the mill stands have the same roll cooling distribution, but the strip shape looks okay.

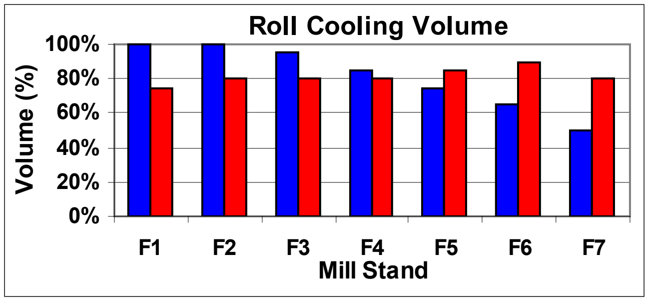
Devil #6 is a variation of the Batwing profile, which results in quarter line buckles. On Graph 5 there are rounded shoulders in the thermal crown inside the edges of the strip on coils #30, #40, #70, #80, and #90. These will produce quarter line buckles if the reduction in each mill stand is not the same.



Graph 7 – Work Roll Temperatures (1)(4)

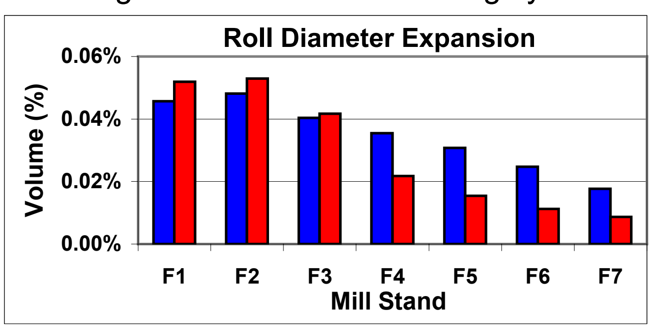
Devil #7 comes from the work roll cooling water distribution on each mill stand on the entry and exit side of the work rolls. The letters **"A"** to **"G"** to **"A"** in the sketch and temperature curves indicate the temperature during one revolution of the work roll. The horizontal axis is time in seconds, and the vertical axis is temperature in **ºF**. The mill in Graph 7 has 75% of the work roll cooling water on the exit side of the work rolls, but results in a higher thermal crown as seen in the **blue curve**. The **blue curve** is the surface temperature on the work roll using three **blue** headers on the exit side and one **blue** header on the entry side. The **blue curve** shows **[a]** the temperature rise from **A** to **B** due to contact with the hot strip, **[b]** a decrease in temperature from **B** to **C** from surface water cooling, **[c]** a decrease in temperature from the three cooling sprays **C, D,** and **E**, **[d]** a decrease in temperature from points **E** to **F** by surface water cooling and contact with the colder backup roll, **[e]** the entry side cooling spray **G** decreases the temperature again, and **[h]** finally the temperature stays constant and rises a little ahead of point **A**. The **red curve** is the surface temperature with two headers on each side of the roll. From point **A** to **D** the temperature is shown by the **blue curve**. The **red curve** begins at point **D** and **[a]** decreases rapidly from the two sprays **C** and **D**, and more from surface water cooling to point **F**, **[b]** the two headers at **"G"** on the exit side reduces the surface temperature (**red curve)** below the **blue curve** because more heat has been conducted to the roll surface resulting in more heat removal, and **[c]** the result is the average roll temperature is lower when the cooling is equal on both sides of the work roll. If there are any "uneven" thermal crown problems as discussed in **Devils #1 to #6**, a higher thermal crown will make the shape and strip profiles worse.

The maximum work roll temperature at each mill stand is due to the **heat input** (contact time) and **heat removal** (non-contact time) during each revolution of the work roll plus the cooling time between coils rolled (rolling pace) depending on the volume of cooling water used in each mill stand. Graph 8 shows the amount of cooling water in percent compared to F1 mill using the maximum at 100% per mill stand. The **blue columns** are the existing work roll cooling volumes in this illustration resulting in a maximum temperature of 65ºC in F1 and F2 mills using the maximum (100%) cooling; and the volume decreasing to 50% at F7 mill. The **red columns** use a new concept of 75% of the cooling water on F1 mill, and increases the volume on each mill stand to F6 mill and decreases a little at F7 mill. The new cooling pattern in the **red columns** results in F1 and F2 mills work rolls reaching the maximum of 85ºC, but reduces the thermal crowns on F4 to F7 mills.



Graph 8 – Cooling Volume per Mill Stand

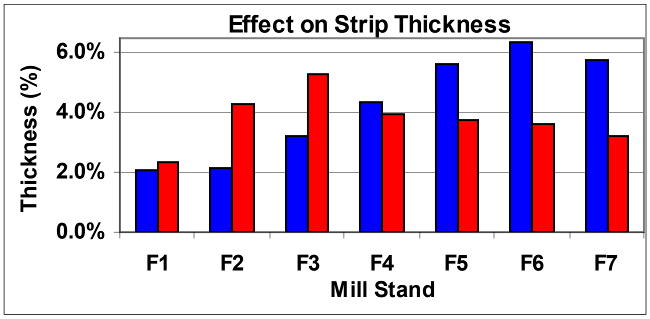
These two different roll cooling concepts per mill stand affect the work roll temperature and expansion of the roll diameter. Graph 9 is an approximation of the work roll expansion in percent of the work roll diameters. Since most mills "cascade" the work roll diameters from maximum to minimum the affect on the thermal crown expansion is both affected by the maximum work roll temperature and work roll diameter. The **blue columns** show the existing expansion is the highest in F1 and F2 mills and decreases toward F7 mill. The **red columns** show the affect of the new concept of roll cooling making the first mills have a greater expansion because less cooling water is used, and the last three mill stands have a lower work roll expansion. The difference is relatively small, in fact the only "person" interested in the thermal expansion is the computer model to modify the roll bending or shape control system to produce a specific "roll stack" bend in each mill stand. However the lower thermal crowns in the last three mill stands provides a greater range for the work roll bending systems to operate.



Graph 9 – Roll Diameter Expansion in %

Both of the roll cooling distribution volume **(blue or red columns)** effects the work roll's thermal expansion about 0.05% or less, which indicates comparing the thermal expansion to the work roll diameter <u>does not provide</u> any indication of the affects on the strip shape or profile.

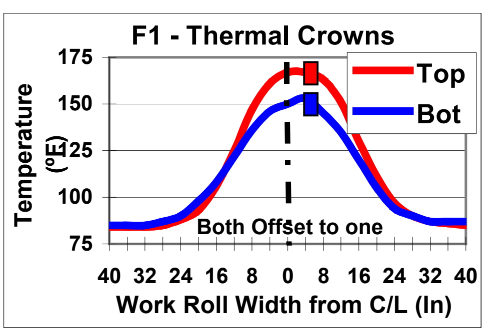
What is important is the thermal crown expansion compared to the strip thickness as seen in Graph 10. The existing work roll cooling distribution **(blue columns)** by mill stand shows an increasing affect from 2% to 6% on F1 to F6 mills and a little less on F7 mill. With the amount of roll cooling is only limited by the maximum work roll



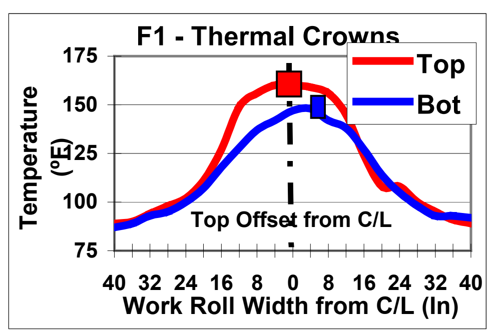
Graph 10 – Roll Expansion vs Strip Thickness

temperature of 85ºC allowed in F1 and F2 mills, the extra roll cooling volume is shifted toward the F4 to F7 mill stands to reduce the affect of the thermal crown expansion on the strip shape as seen in the **red columns** in Graph 10. The new cooling distribution keeps the expansion affect on the strip to 2% to 5% on F1 to F3 mills, and then decreases the affect from 4% to 3% on the final three mills to minimize the affect in relation to the strip gage. The roll cooling effectiveness is increased by using higher offset angles (1)(5), and applying equal cooling on both sides of the work rolls (1). The first three mill stands create the strip profile, and the last four mill stands determines the strip shape. With lower thermal crowns on the last mill stands the probability of **narrow shape** distortions such as **build up** and **quarter line buckles**, etc. occurring is greatly reduced.

Devil #8 is the result of the roll cooling offset angles set in one direction resulting in more surface water cooling toward one end of the work rolls. Graphs 11 and 12 were from the best roll cooling system investigated. The top roll had 45% and the bottom roll had 55% of the cooling water on each mill stand. The **red curve** shows the higher top roll temperature due to a lower cooling volume than used on the bottom roll as shown by the **blue curve**. The **red** and **blue rectangles** show the centerline of the thermal crowns compared to each other and the work roll centerline. Graph 11 had the nozzles offset 15º in the same direction, and Graph 12 is with the top work roll cooling sprays offset from the centerline.



Graph 11 – Offset to One Side



Graph 12 – Top Offset from Centerline

Because every rolling schedule creates different maximum roll temperatures and thermal crowns, this mill was an ideal place to see the affect of both more roll cooling water on one work roll, and using two different offset angle arrangements. There were many thermal crowns taken on different rolling schedules, and these two are representative of the results. Graph 11 shows the bottom roll was cooler because it had 22% more cooling water than the top roll. The thermal crown centerline was toward the drive side (right side in these graphs) when the nozzle angles were offset in one direction. Since the top and bottom thermal crowns followed each other, it was decided to offset the top work roll nozzles from the work roll centerline and leave the bottom work roll as a reference. Graph 12 shows the typical results of the experiments. More experiments were made using 30º and 60º offset angles showed they reduced the work roll temperatures. The conclusions were **[a]** applying more water to one work roll lowers the maximum roll temperature, but the average thermal crown for both the top and bottom rolls is the same, **[b] does not improve** the thermal crown's profile, and **[c]** offsetting the nozzles in one direction creates an off center thermal profile resulting in **wedge shaped profiles** and **torn tail ends** in the strip. More confusing is any tapered roll cooling causes defects such as **quarter line buckles** to be seen more often on one side of the strip.

Devil #9 is the maintenance required on the roll cooling headers is overwhelming. Typically some mills have as many as 1400 nozzles in the mill consisting of 3 different size nozzles. Just getting into a mill stand and checking 200 nozzles and replacing or clearing plugged sprays is time consuming. Assume the nozzles become plugged at a rate of 0.20% per day of operation with 10 days between repair days would result in 28 plugged nozzles or 4 nozzles per mill stand. Consider after the 1st nozzle is plugged the probability of the next nozzle being plugged is in same location from the work roll centerline. It is not 1:1400 chances, but 1:25 chances the next nozzle plugged will be in the same location in relation to the work roll width because there are 25 nozzles in each header. With eight roll cooling headers in each mill stand a single nozzle plugged reduces the cooling 12.5% resulting in raising the F1 work roll temperature **1.5ºC** in a narrow band (2). In most cases the next mill would eliminate any narrow shape distortions, but if two or three mills have a hotter band in the work rolls in the same area it would result in **build up (ridges)**. In the author's experience 100% of the roll cooling systems using different nozzle sizes are used had wrong size nozzles in every mill stand. Reducing the number of nozzles by using wider sprays or reducing the number headers by using larger nozzles reduces both the nozzle costs and the number of plugged sprays. This automatically reduces the problems with this **"devil"**.

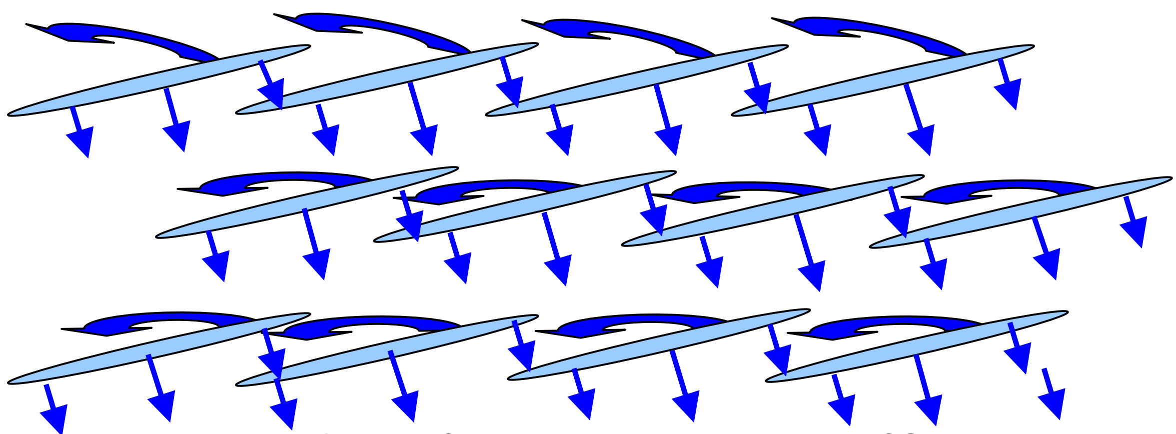


Figure 2 – Interference with Multiple Rows of Sprays

Devil #10 is the roll cooling sprays across the roll width creating interference between the rows of sprays. The spray impact pattern for each row is shown by the **light blue ovals** in Figure 2. When the spray impacts the roll, the water flows 90º away from the impact pattern, and the amount of water going in each direction depends on the impact angle to the work roll. The **dark blue curved arrows** show the flow climbing the upper curvature of the work roll, and flowing in one direction to cool the roll more toward one side of the work roll. The downward flow of the top row of sprays **(dark blue arrows)** impacts the upward flow from the middle row to curve the flow sideways. The flow between the top and middle row combines into a larger mass and along with the pull of gravity will interfere with the middle row's spray impact. This repeats between the middle and bottom row until there is a "hodge-podge" of interfering water flowing down the work roll surface. This affects the work roll cooling these ways: **[a]** the sprays drive "hotter" water from other spray's to reduce the cooling efficiency, **[b]** the average water temperature flowing down the roll increases, and **[c]** the flow is directed by the offset angle to cool one side of the roll more than the other side. Multiple rows of nozzles decrease the cooling efficiency, and result in more plugged sprays due to using smaller spray nozzles.

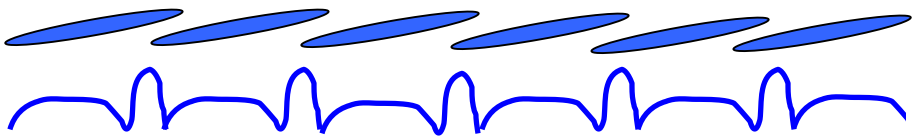
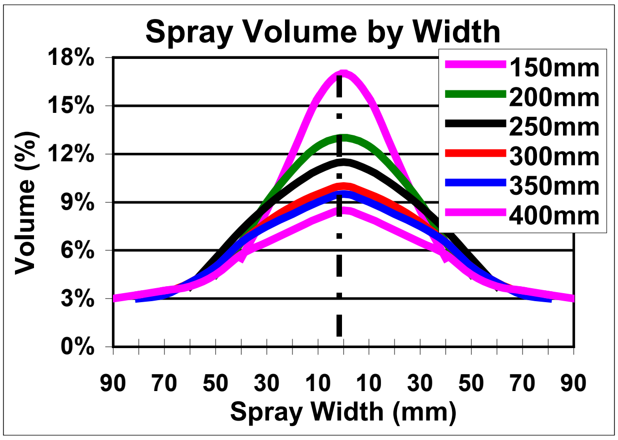


Figure 3 – Spray Cooling Pattern for Overlapped Sprays (1)

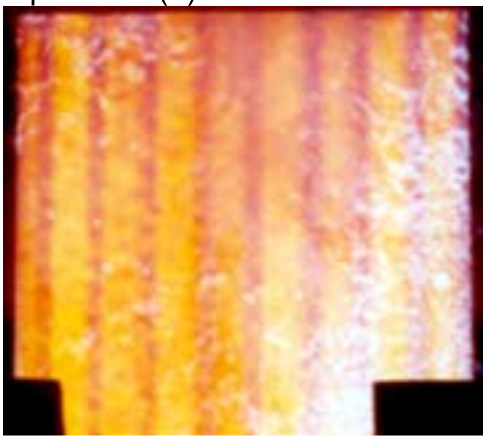
The typical "V" jet cooling nozzle distributes the water across the spray about 30% less on the edges compared to the center of the spray. The result is the typical roll cooling engineer overlaps the sprays about 15% resulting in a spray cooling pattern as shown in Figure 3. This represents 40% more direct spray cooling in the overlap areas compared to the center of the spray.



Graph 13 – 50º Spray Width at various Spray Lengths (1)(2)

The spray pattern becomes even more complicated depending on the distance of the spray tip to the work rolls as shown in Graph 13. The same 50º sprays spread the water as shown by these eight curves at distances of 50mm to 400mm away from the work roll. Spray lengths on one modern mill were found to be 155, 170, 210, 220, 165, 360, 190, 180, and 220mm due to the different work roll diameters used and the positions of the cooling headers (1). With special computer programs the variations

in volume on multiple rows of sprays can be isolated. It is necessary to add the total variations on each side of the work roll and the top and bottom work rolls to see the affect on the thermal crown. Finally the pattern out of each mill stand has to be compared with each other.
Compound the roll cooling against the **heat input** from the strip coming out of the F1 descaler with “cold” bands **(purple)** from the descaling overlaps as shown in Photo 1. The actual temperature variation between the “hot” and “cold” bands is shown by the solid curve in Graph 14 was approximately 90ºC from the highest to lowest temperature (6).



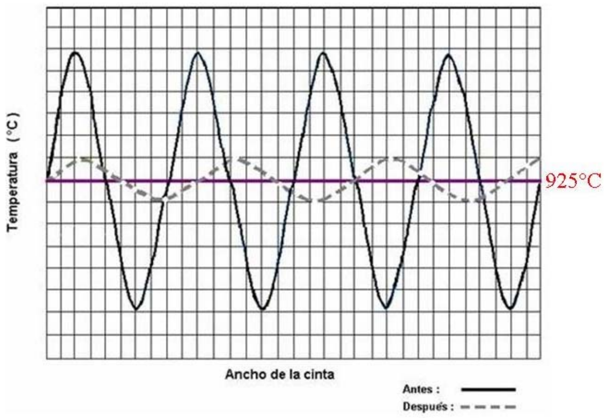
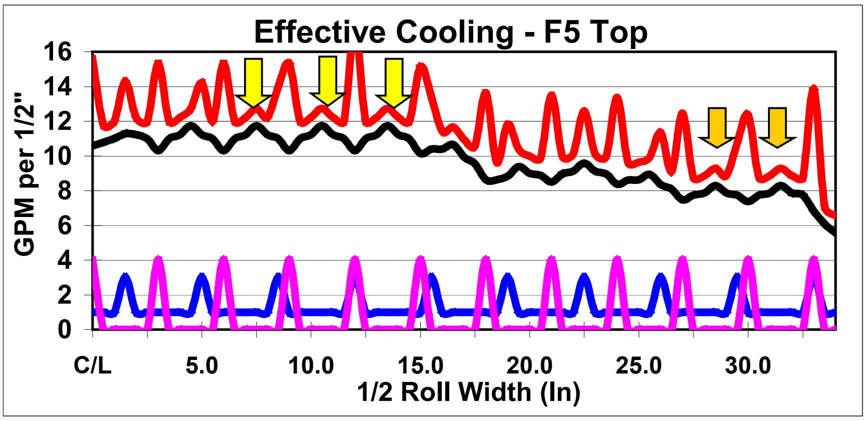


Photo 1 – Overlap Cooling Variation (6) **Graph 14 – Temperature Variation (6)**

It requires different computer programs to see the results of the roll cooling spray’s overlap and spray distribution along with the uneven temperatures on the strip from the finishing mill descaler.



Graph 15 – Equivalent Roll Cooling Volume across ½ of the Work Roll (1)

The results are shown in Graph 15 where the vertical axis is the equivalent cooling volume in Gpm per ½” of roll width, and the horizontal axis is half of the work roll width from the centerline of the work roll to one edge. The **purple peaks** at the bottom of the graph represent the extra cooling in the cooling spray’s overlap area. The **blue curve** represents the reduced cooling of the descaled surface with the peaks showing where the extra overlap cooling occurs. The **black curve** represents the uneven cooling due to the spray characteristics from edge to edge. The **red curve** is the effective cooling affect of these three curves. The descaling sprays and roll cooling sprays do not have the same spacing between the nozzles, and the combinations increase or decrease the total cooling volume in certain locations. The result is the total cooling affect has an irregular pattern from both sides of the centerline to the edge of the work rolls. The thermal crown will increase in narrow bands where there is less roll cooling volume. The **yellow arrows** near the center indicate where a lower roll cooling volume increases the thermal crown to create narrow shape distortions such as **build up (ridges), floppy center,** or **cartoons de huevos**. The **orange arrows** near the edge of the roll is where lower roll cooling increases the thermal crown to create other narrow shape distortions such as **quarter line buckles, wavy edges,** or **featheredges**, and **batwing** strip profiles.

Devil #11 is a narrow shape distortion called **short choppy edge waves**, and when they occur the operators often "level" the mill, which results in camber in the strip. Photo 1 shows the "classic" cause of **short choppy edge waves**. Can you see it? Look carefully at the right edge of the strip, which is "double" cooled by the descaling spray's overlaps. Look at the left edge of the strip where only the single descaling spray is cooling the edge. The difference of a cold band on one edge to the hot band on the other edge is 90ºC (1)(6), and the left edge will elongate into a **short choppy edge wave**.

There are many more **"devils"** in some roll cooling designs, and the wonderful engineering drawings provided by the mill builders of the spray distribution compared to "real" life inside a rolling mill are two different worlds.

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