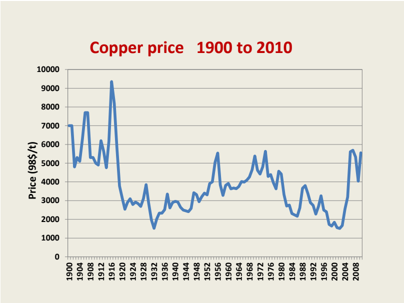
MINERAL PROCESSING DURING THE 20TH CENTURY:

THE HIGHLIGHTS, WHY THEY OCCURRED, WHAT COMES NEXT.

Henry Hodges, writing about Technology in the Ancient World, concluded that *Nowhere was the rate of technological advance a steady, even, upward climb. Always one seems to be confronted with sudden bursts of technological innovation followed by long periods of virtual stagnation*.

Mineral processing was no different. Between the early 1880s and the mid 1990s there were two periods of innovation and two of relative stagnation each lasting about 30 years. They roughly coincided with the so-called "supercycles" of global demand for metals, innovation with high growth, stagnation with low growth. My examples will refer to copper and cement, copper sets the trend in technology, cement is the high growth product.



This figure shows the trend in real copper prices since 1900. A rising trend indicates that global demand is rising, a falling trend indicates that demand is unable to soak up available supply and is slowing. Global price was high in the decades before the First World War, the trigger for demand being the Industrial Revolution and the chemical and electrical inventions which accompanied it. By 1880 they had created all manner of new and attractive products. The railway, the telegraph, the telephone and electrical networks were just some of the developments taking hold in North America and Europe. Metals were needed as never before but the processes and equipment to produce them from ores needed renewal. It prompted what can fairly be called an Age of Metallurgical Invention which was from 1880 to 1920. In the 1870s breakage was by gunpowder and stamp mills and concentration was by gravity. By 1920 dynamite and air-driven hammer drills were used for initial breakage; steam driven crushers and ball and roller mills for finer comminution; rake classifiers and centrifugal separators for classification; and Wilfley tables, flotation and cyanidation for concentration. Between 1880 and 1920 the metallurgical flowsheet was transformed and the most important development was flotation. I will speak briefly about its early years.

Guillaume Delprat, who is commemorated in this lecture, was General Manager of BHP in Broken Hill in 1902 when it was in trouble because the secondary ore high in lead and silver had gone and engineers could not concentrate the fine primary sulphides despite building large plants. The rich bounty of Broken Hill was being lost in fines to the tailings. In 1902 Delprat stumbled on flotation in his laboratory and built a plant to float zinc using acid pulp at high temperature. Success led to a larger plant and in short order other companies on the line of lode were using different versions of the process. Flotation not only rescued Broken Hill, it changed the metallurgical world when it crossed the Pacific and was used in the 15000 tons per day plant Anaconda built at Inspiration in Arizona to float low grade, fine grained porphyries. The high recoveries it achieved led directly to the great copper mines in southwest USA and Chile.

Flotation was a success because company managers knew that a completely new process was necessary to recover metal from low grade, fine grained ores. Flotation was fairly easy to achieve in a laboratory but far more challenging to get right in a commercial plant. It needed skill, experience and time. And of course two other things: sustained management support, and a worthwhile pay-off if it was successful. All these elements came together at Broken Hill. The lesson is applicable now as it was then: engineering skills, management support and time can solve any problem which limits mineral production.

The cyanide process did for gold what flotation did for base metals. Cyanidation was an old idea which MacArthur and the Forrest brothers turned into commercial reality. High losses of gold to tailings had created a crisis for the South African mines similar to that being faced in Broken Hill. They turned to the MacArthur-Forrest process and quickly saw the benefits. But this was a two-part problem. Cyanide was effective but there remained high losses to tailings due to composite particles. Ball milling was a technique in widespread use in the cement industry and it was adapted to gold plants. These rotating mechanised mills greatly improved liberation and gold recovery. The combination of cyanide and ball milling saved the South African mines and created fabulous wealth for their owners. It was another example of using new technology, and adapted technology, to solve a pressing metallurgical problem.

The initial ball milling operations used the ore itself as the grinding media. Autogenous grinding was only much later adopted by the wider metallurgical industry and even lost favour for many decades in South Africa itself. This highlights a more general point: successful metallurgical advances often consist of taking overlooked ideas already in existence and persisting with them.

Cement and coal also benefited from inventions in the late 19th century. Rotary kilns replaced shaft furnaces for cement clinker because of their speed and efficiency and it was not long before pulverized coal replaced oil, gypsum was added to control the setting of the cement, and ball mills and air separators were invented to grind the clinker. Roller mills were developed for coal - vertical mills for furnaces, horizontal mills for briquettes. The vertical roller mill in use today is similar to the mill of 90 years ago.

The Age of Metallurgical Invention ended during the depression years following the First World War. The incentive had gone because the demand was weak and prices fell by 50%. The metallurgical world was geared to supply far more metal than anyone wanted so the focus switched from finding new ways to produce more metal to finding ways to reduce the workforce.

The 1920s started a steady refinement of existing techniques. Xanthates were patented in 1925, and with depressants and activators improved sulphide flotation dramatically; and many universities had programmes on flotation fundamentals, notably Columbia with Taggart, Melbourne with Wark, Idaho with Fahrenwald, and MIT with Gaudin. Their debates led to a good understanding of how the ‘upside down’ process of flotation worked. Pulverised black coal was used in a power station in Milwaukee in 1918 and in 1925 pulverized brown coal was used in Leipzig. The ultrafines caused problems and to understand their formation better Paul Rosin and Erich Rammler at the Freiberg Mining Academy derived an equation to define size distributions. Years later this equation would become the basis of grinding mill models. Late in the 1920s Fred Bond started his classic work with Allis Chalmers on the equations linking feed rate, ore hardness and power consumption, and the Work Index he developed became part of grinding technology.

The October 1929 stock market crash triggered heavy falls in commodity prices but the metallurgical challenges continued. At CSIRO the eminent geologist Frank Stillwell used the new technique of mineragraphy to understand the nature of mill products and he and Austin Edwards used mineragraphy for thirty years to solve the problems of many mining companies, often working with CSIRO Ore Dressing. This link is now called geometallurgy.

By 1950 the dark years of depression and war were over, and consumer confidence returned in the industrialised countries. It seemed that everyone wanted a new motor vehicle, refrigerator, airconditioner and, by the end of the 1950s, a television set. This kick-started a global economic boom which was to last 25 years. Real copper prices started to rise in the early 1950s and continued through the 1970s. Companies looked for new ways to increase production and first off the rank were the advances achieved but not utilised during the 1920s and 1930s. But more was needed, and metallurgists increasingly drew their inspiration from outside their traditional field, turning to electronics and mechanical engineering which had seen much development during the war.

Some companies were adventurous enough to use autogenous mills and found that addition of 5-10% of balls improved their performance. Mills increased in size, in 1970 the largest ball and SAG mills required 3 and 5 mw motors, by 2010 these had increased to 15 and 30 mw. The first Gearless Mill Drive was installed on a cement mill driven by a 6.5 mw motor in a plant in Le Havre in France in 1969. GMDs were subsequently used on many cement mills but it was 12 years before the first unit was installed on a mill grinding ore. That was in an iron ore plant at Sydvaranger, Norway, on an 8.1 mw ball mill commissioned in 1981. GMDs are now common on ore mills.

In 1945 the Asahi Glass Company in Japan used a vertical stirred mill with small balls to produce powder, this evolved into Tower mills and IsaMill. In the 1950s high capacity pumps allowed centrifugal force to replace gravity: the O-Sepa separator for cement, hydrocyclones for ores, and heavy media cyclones for coal. In the late 1960s two Denver 300 flotation cells were joined to make a 17 m^3 unit, and sizes were then increased regularly. By 2000 FL Schmidt and Outotec were both building 300 m^3 cells and it was these cells and the large SAG and ball mills that made 150000+ tons per day plants possible. Columns and high intensity cells were tried again in the 1950s, and microbial leaching became a viable source of copper when SX/EW replaced cementation in the 1980s.

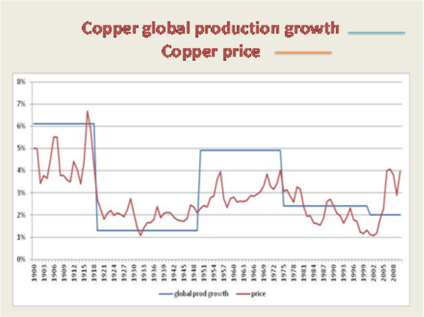
In 1958 AMIRA was established, it was inspired by Maurice Mawby, Managing Director of CRA and a brilliant mineral engineer and manager. Modelling and control was the first AMIRA project and by the mid 1960s grinding models were available. Process control required on-stream analysis and new techniques had to be developed but by the early 1970s OSA systems were available.

Cement production grew rapidly after 1950 to meet the demand for new infrastructure. In 1957 Hans Rumpf moved from research director at Alpine to Karlsruhe University to investigate and improve the efficiency with which energy is used in comminution. In 1982 his colleague Dr Klaus Schonert patented HPGRs which reduced grinding energy by more than 15% and were adopted by many cement companies. Fifteen years would elapse before they were used in ore plants.

The buoyant demand of the 1950s and 1960s era inevitably came to an end. The immediate causes were the global oil shocks but the underlying problem was that consumer demand in industrialised economies had run its course. From the mid 1970s the focus of household expenditure turned to items such as education and tourism, the demand for metals slowed and overcapacity once more became a feature of the industry. Real copper prices fell, also the rate of metallurgical innovation. The slump would last to the late 1990s when China started to make its presence felt. During the 80s and 90s the dominant feature of operations was “austerity” measures as managers sought to drive their costs down in the face of continually falling real prices.

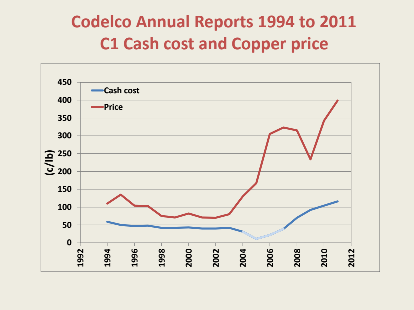
This rather gloomy situation was dramatically changed by the emergence in the second half of the 1990s of China as a large and growing consumer of metals on the global stage. This upswing in demand from China not only halted but reversed the falling price trend. Real copper prices tripled between 2002 and 2004, and there except for a sharp drop during the global financial crisis, they have stayed. It has been the most dramatic metal price rise in modern history, even including the massive jump in prices during the First World

War. If the historical pattern held true, a decade on from this sudden and dramatic rise we should now be seeing a raft of new techniques and significant improvements to existing techniques. Instead, remarkably little has really happened. There have of course been some incremental improvements but where are the types of advances seen in previous periods of rising prices? It cannot be said that the existing production base is adequate to supply the demand. Indeed, it would appear to be manifestly inadequate.



This figure shows that since 2000 the average annual growth in copper production has actually been lower than during the gloomy period of falling prices which preceded it. During 1950 to 1975 prices were high and average global production growth was nearly 5% per year. During the period of falling prices which followed, annual production growth fell to 2.4%. Since 2000, with very high prices it has averaged just 2%. Global production has been unable to respond to the much increased demand. The challenge for metallurgists is clear: it is time to unlock the known resources contained in large and low grade deposits. It is a challenge requiring advances on the scale of flotation and mechanisation.

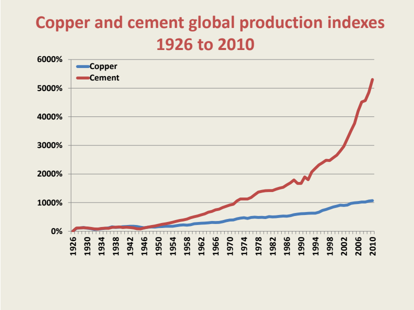
So much for the 20th century. What comes next? The 21st century will be the comminution century just as the 20th century was the flotation century. By 2040 four billion tonnes of cement, ten billion tonnes of copper ore, ten billion tonnes of coal, and huge amounts of other minerals will require fine grinding and this means an immense amount of energy. Practices must change, for example tumbling mills are the dinosaurs of the industry and must be replaced by mills with faster breakage rates, better use of energy and smaller footprints.



Costs will be crucial. The C1 cash costs for Codelco, taken from Annual Reports, are shown in this figure for the last 20 years. They demonstrate Codelco’s success in controlling the cash cost for many years, but the last few years also show the need to reduce the rise in cash cost as grades decline. Energy represents 20-30% of the operating cost for most major copper operations, and breakage typically accounts for 45% of this energy. In a paper entitled Step Change in the Context of Comminution Dr Ted Bearman discussed pre-concentration. He commented that long term decline in grades and the immense feed rates which must ensue will consume far higher levels of energy, test the limits of existing equipment and methods, and require a large increase in water. The alternative is to recognise that the objective is not to break rocks to a size, it is to break only what is necessary to the point at which a saleable product can be made. This is the role of pre-concentration. Its use must be supported by comprehensive knowledge of the geology and metallurgy of the orebody, process models, and true integration of mining and processing.

And energy efficient circuits? There is a surprising lack of comprehensive data about today’s plant circuits but in 2011 John Marsden, President of Metallurgium, gave a presentation to the Procemin Congress in Santiago which was based on data from eight open pit copper mines operated by Freeport-McMoRan and included information about the performance of six different comminution circuits. He concluded that a reduction of 40% of the energy used by a conventional SAG mill/ball mill circuit could be achieved by replacing them with HPGRs and stirred mills, and this could increase to 45% if better classification could be achieved.

By contrast with copper the cement price has been stable in real terms for 90 years, one reason being the unwavering emphasis by producers on using energy efficiently in the grinding circuits because of its high cost. This will continue with ball mills being replaced by HPGRs and high energy bead mills to reduce energy by 50%. In the longer term finer cement is the key to a variety of new products. Cements with Blaine numbers of more than the usual 4000 Blaine number are stronger and have shorter setting times than Portland cement and will lead to more efficient construction techniques. High energy bead mills will be used to make them



The production of copper and cement grew rapidly from 1950 and all credit is due to those who made new technologies work and produced materials which built great industries. The baton is now with us, how well are we travelling? The 2009 paper by Peter Munro and Peter Tilyard entitled *Back to the Future – Why Change Doesn't Necessarily Mean Progress* is relevant. They discussed the modus operandi of metallurgists and noted that the emphasis in the 20th century was on outcomes but that in the early 2000s "*There has been emphasis on process at the expense of outcomes*". This may be one reason that the last ten years of very high prices have brought only incremental changes in technology. Another reason may be that the high level of technical leadership which was evident for much of the 20th century seems to have weakened during recent decades. The opportunity exists to renew innovation because mining and processing system must change as dramatically as they did when flotation arrived 100 years ago and comminution will be at the core. This presents a wonderful chance for today's engineers to drive change.

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