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TEMCO F1 operation on freeze lining 2001–2017

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Abstract – The Tasmanian Electrometallurgical Company (TEMCO) is part of the relatively newly formed company South32. South32 has several operations producing aluminium, nickel, coal, and manganese. TEMCO operates four furnaces and a sinter plant with an annual production capacity of approximately 270 000 tonnes of ferro-alloys and up to 325 000 t of manganese sinter. TEMCO Furnace 1 was rebuilt in 2001 with a freeze lining concept from UCAR/Graftec to improve safe operation by effectively testing the longevity of the new lining design. The aim of the furnace installation was to reach a minimum of 15 years of operation with a target design load of 20 MW and production of HC FeMn and SiMn alloys. This paper presents the operating envelope of the furnace, and the performance outcomes achieved over the 2001–2017 operating period.

Keywords: safety, freeze lining, thermocouples

INTRODUCTION

Furnace operations at TEMCO have been managed historically using conventional thermal insulating refractory configurations of a carbonaceous material encapsulated within an insulation (alumina) brick placed within a steel shell. The conventional design was primarily to reduce thermal losses, and to reduce the consumption of power required in the carbo-thermal reduction process within the submerged arc furnace operation. The refractory configurations used at TEMCO from 1962 to 2001 included using hot ramming carbon paste, big blocks in the hearth, and cold ramming monolithic designs in hearths and sidewalls. The effective life of furnace linings for HC FeMn production was 8–12 years, with failures occurring under tap-holes and through sidewalls in the past 2–3 years of campaign, with monitoring techniques using thermocouples and thermal imaging being used to monitor hot spots on the shell. It is noted that the power density (MW/m^2) of F1 had increased almost two-fold over the years (De Kievit *et al.*, 2004).

The freeze lining design concept was proposed to be installed in 2001 to improve the safe operation of furnaces. The concept is well understood today, across the world, as many ferro-alloy smelters have adopted the design principle which uses high-conductivity carbon materials to promote the build-up of a protective accretion on the hot face of the lining refractory. This insulates the lining, and results in refractory temperatures being below critical reaction temperatures for all wear mechanisms, and potentially results in a lining that will not deteriorate with time, thereby extending the safe operating life of the furnace.

The F1 Rebuild Project included the replacement of the original shell, new under-hearth air cooling, water cooling on the shell, sidewall modifications, and changes to the tapping floor launders and to the raw materials handling systems. The intention of the TEMCO metallurgical team was to apply the learnings from lining development at TEMCO and develop an on-line lining management system to monitor and control the wear rate of the furnace by using an array of thermocouples in the sidewalls and hearth, with the information alarming management automated by the process control system.

The approach adopted by TEMCO was not only to test the market for various freeze lining refractory configurations and furnace designs, but also to apply theoretical rule-based design (RBD) principles (see Figure 1) to understand the important relationships between the reactor and the refractory design. The issues with freeze lining that TEMCO has envisaged were: targeting a minimum lining life of fifteen years for its financial viability, the nature and degree of deterioration of bricks and tap-holes, the impact to the lining in case of loss of water cooling for an extended period, and a proper method for control of the thickness of the freeze lining during normal operation. The success of the F1 Rebuild Project in 2001 has led TEMCO to install freeze linings in all furnaces (F3 in 2007, and F2/F5 in 2009).

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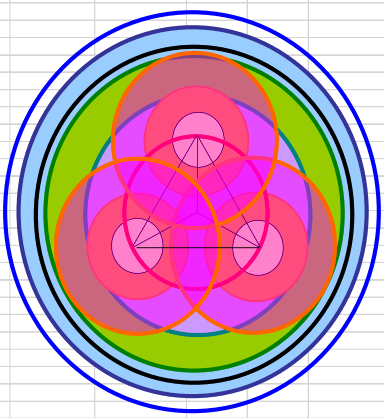
	TEMCO F1 Stnd		TEMCO F1 Modified		TEMCO Mod. UCAR 17/3/00	
TRF Capacity	kVA	29000		29000		29000
Furnace Power	MW	20		20		20
Power Factor	Cos o	0.68		0.68		0.68
Electrode Current	kA	90		90		90
Electrode to Ground Voltage	V	150-235		150-235		150-235
Electrode Diameter	D	1420	D	1420	D	1420
Parabola of Revolution@1D below electrode	2	2840	2	2840	2	2840
El centre to Shell centre	2	1965	2	1965	2	1965
Pitch Circle Diameter PCD	2.77	3930	2.77	3930	2.77	3930
Reaction Zone	4.77	6770	4.77	6770	4.77	6770
Protection Zone	5.77	8190	5.77	8190	5.77	8190
Calculated Minimum Refractory Diameter (ID)	6.77	9610	6.77	9610	6.77	9610
Actual Minimum Refractory Diameter (ID)	5.35	7600	5.60	7958	6.15	8740
Actual Max Carbon Refractory Diameter (ID)	5.92	8400	6.17	8758	6.15	8740
Steel Sheel Diameter (ID)	7.05	10008	7.30	10366	7.30	10366
Effective Carbon and Ceramic Lining		1608	0.00	1608	0.00	1626
kW/m2 of Hearth		440.9		401.9		333.2
ELC:D ratio						
Roof to Electrode tip distance	2	2840	2	2840	2	2840
Electrode Tip to Bottom Refractory distance	1	1420	1	1420	1	1420
Taphole height (above bottom refractory)mm						



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Steel Sheel Diameter (ID)	7.30	10366
		1626
Reaction Zone...Minimum	4.40	6253
Reaction Zone...Maximum	6.20	8819
Actual Cruc Diia .....Front		7810
Actual Cruc Diia .....Back		8953

Figure 1: Rule-Based Design (RBD) of refractory configuration

Since commissioning the new furnace in 2001, the highlights/lowlights of operations will be described including:

- Capacity improvements from incremental load increases, from 20 MW to current 22 MW
- Lining Management System and performance
- Shut and restart from market downturns
- Variable load operations during state power shortages
- No tap-hole repairs after 16 years
- Challenges to maintenance program from extended furnace life
- Key Performance Indicators

A failure of the refractory lining in TEMCO furnaces is treated as a material risk, and there are critical controls in place to maintain the risk within a 'well controlled' state. The well-designed risk-control philosophy of South32 is discussed together with work in progress to manage the furnace until the next rebuild in 2021.

FURNACE RELINING 2001

The Furnace 1 Reline included the replacement of the furnace shell, a new under-hearth air cooling system, water cooling on the shell, and modifications to the tapping floor and the raw materials handling systems. The project was completed in 64 days, from May 2001 to July 2001. The UCAR® Chill-Kote™ freeze lining design was modified for Furnace 1 by TEMCO to accommodate three tap-holes, a thicker abutment wall surrounding the tap-holes, and additional ceramic refractory layer in the hearth.

The final design was justified through a detailed thermal finite element analysis (FEA) carried out by Bateman Titaco (Marx & Henning, 2000). Several options of refractory configuration and cooling scenarios were investigated using the FEA methodology. The temperature contours of the TEMCO conventional and UCAR proposed Option 1 freeze lining (without freeze formation) are presented in Figure 2. The FEA concludes that the graphite layer in the hearth induces a high energy sink towards the side-wall, which prevents the hearth bottom from overheating. This is a positive phenomenon, as the water cooling on the side-walls is better able to disperse the thermal energy.

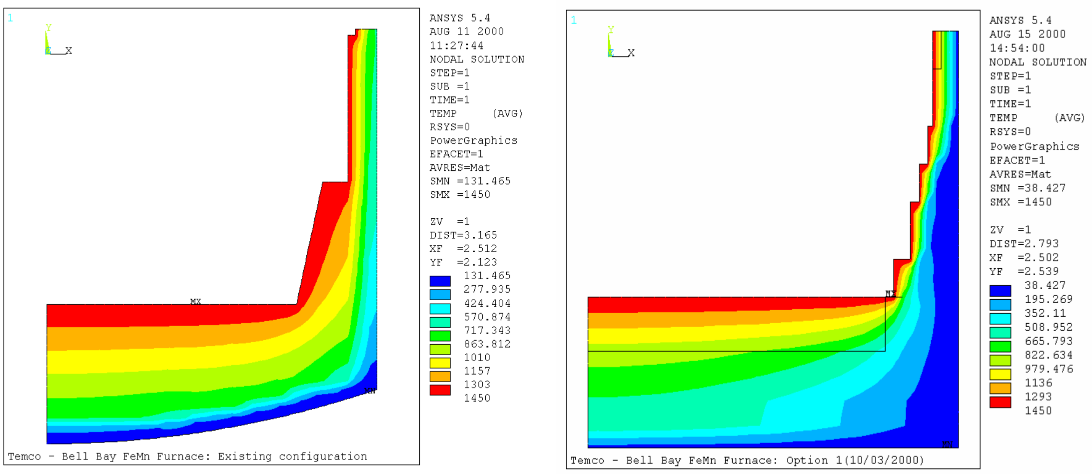

Figure 2: Comparison of conventional lining with freeze lining

The higher initial energy flux obtained for the freeze lining design implies that the effectiveness of the formation of a freeze lining in the furnace, protecting the refractories, is higher than for the conventional design, which will lead to less refractory wear and inherently more stable refractories.

The tap-hole model indicates a high graphite core temperature, which will be favourable for tapping, thus reducing the need for frequent oxygen lancing. The carbon in the tap-hole area provides a sufficient thermal conduction path for adequate cooling, as presented in Figure 3.

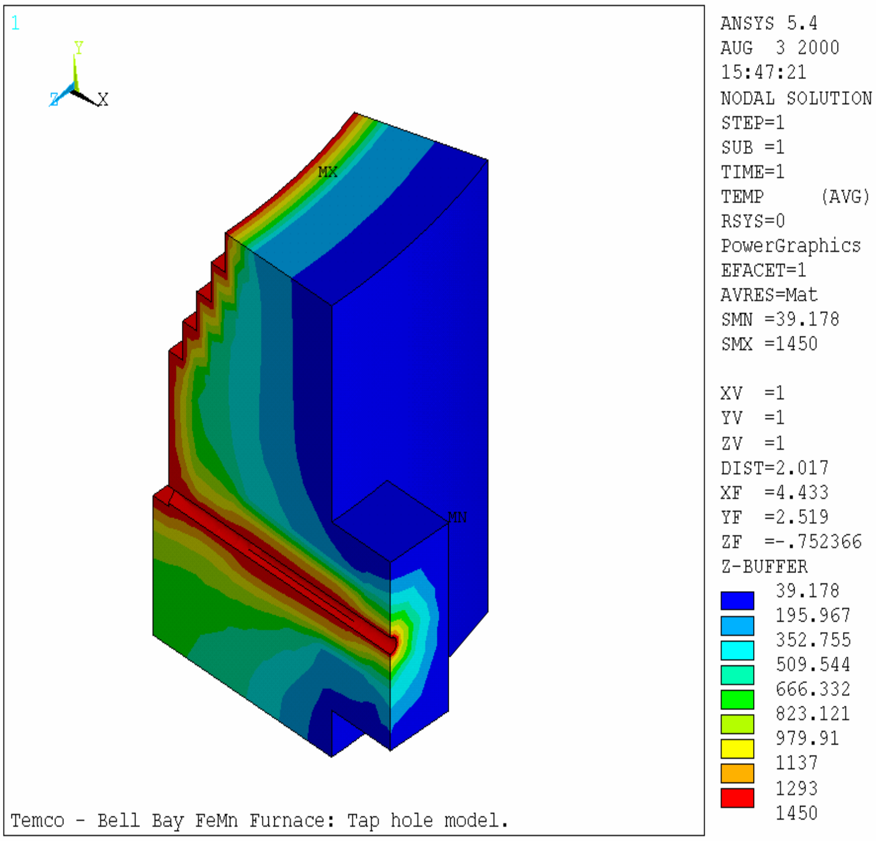

Figure 3: Temperature contour distribution in the 3D tap-hole model

The Furnace 1 design basis is described in Figure 4, and the furnace was installed with three tap-holes due to the experimental approach to the project.

The furnace shell is cooled by a water curtain on the sidewall, and by forced air on the under-hearth steel plate. The initial design brief of 'splash-free' water flow has never been reached due to the poor access to the upper water tundishes, but extensive splash shields contain the water to ensure that water does not pool on the ground.

From 2001, a strong culture of maintaining water on the shell has been embedded into the TEMCO community, and the water system has been installed with three levels of redundancy, including standby pumps, an emergency generator, and, in case of complete power failure, a fresh-water valve will automatically open to ensure there is always water on the shell.

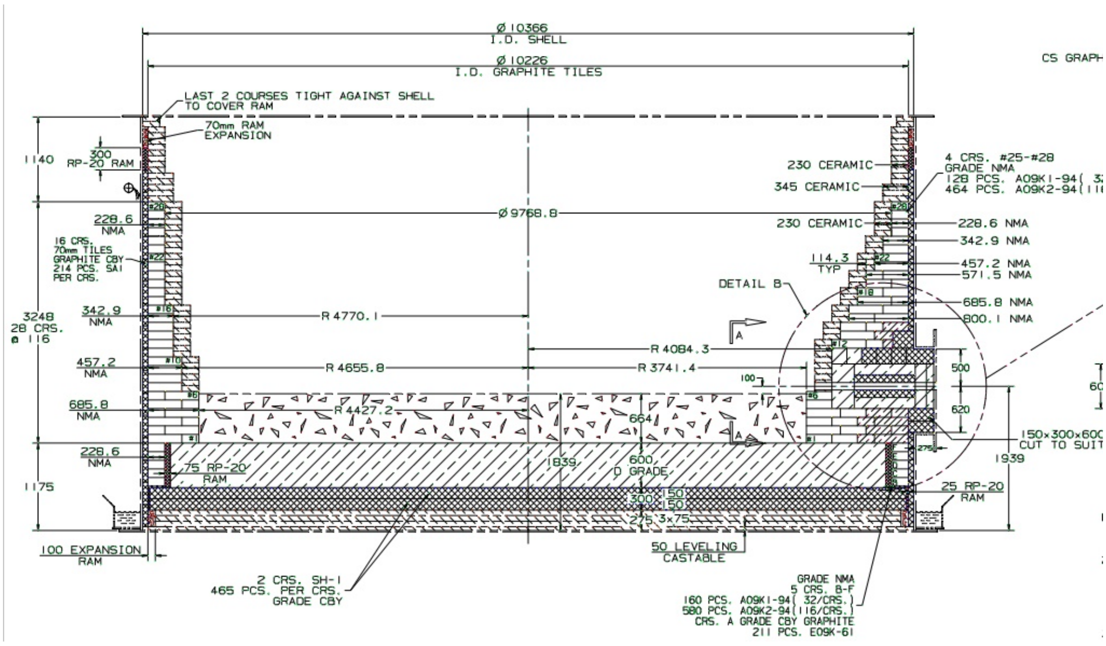

Figure 4: Furnace 1 general arrangement

OPERATING ENVELOPE

The furnace transformer was upgraded from 29 MVA to a 36 MVA power rating in 2012. The maximum technical capacity (MTC) of the furnace is 23 MW, due to the bottlenecks in gas scrubbers and the raw material feed system (Table I). The operating load set point is targeted at 22 MW, with a secondary current of 88–90 kA, by controlling to a resistance set point of 0.80–0.95 milliohms. The raw materials used for HC FeMn production at TEMCO include GEMCO lump ore, a blend of South African ores, and TEMCO sinter. The ore blend is generally adjusted to minimize the slag volume, which has been climbing steadily from a slag : alloy ratio of 0.55 to around 0.65 currently. The increase in slag volumes is primarily due to the steadily increasing silica levels in the GEMCO ores (both lump and fines). However, the blending of ores has resulted in smelting temperatures being reduced from an average of 1375ºC to currently around 1345ºC, which supports the promotion of freeze formation within the smelting crucible.

Table I: The detailed operating envelope of Furnace 1

Product	HC FeMn / SiMn
Furnace load (Max MW)	23 MW
Total transformer (MVA)	36 MVA
Annual production (tonnes/year)	72 kt HC FeMn
Transformer	ABB / 2012 (install)
Primary amperes (max A)	545–583
Line amperes (max A)	656–689
Incoming voltage (kV)	22
Electrode current (max kA)	94
Large capacitor bank (MVar)	15
Small capacitor bank (MVar)	7.1
Electrodes	
Clamp type	Elkem Modular Holder
Case design	14 sections – electrode case 2000 mm high
Current density A/cm²	2.58 A/cm²

Tap-holes	
Number of tap-holes	3
Angular distance between tap-holes	35^o
Tap-hole length (mm)	1420 mm
Tap-hole block (mm)	820 mm
Lining management	
Thermocouple type	Type K
Thermocouple limit (^{o}C)	0–1200^{o}C
Hearth thermocouples – distance from base	
Level 3	575 mm
Level 2	275 mm
Level 1	50 mm
Sidewall locations – distance from base (mm)	
Level 3	3712 mm
Level 2	2519 mm
Level 1	1939 mm
Hearth cooling fan air flowrate (m/s)	15 m/s
Cooling water flowrate (m^3/hr)	75–130 m^3/h
Cooling water temperature	< 60^{o}C
Electrodes	
Baking constants for slipping	2800 kA^2/cm
Operating resistance (mohm)	0.75–1.0 mohm
Operating current (kA)	50–94 kA
Raw materials	
Available oxygen	12% max.
% Sinter	20–70%
Basicity (BAR-1) (CaO + MgO / SiO_2)	0.5–0.70
Mn in slag (HC FeMn)	30–35%

TEMCO has historically used thermal modelling in the furnace control system. The Furnace 1 installation in 2001 included multiple thermocouples at strategic points in the sidewalls, hearth, and tap-hole locations. Contact thermocouples are also located on the shell. The process control system will alert, alarm, and action when temperatures exceed the calculated operating range. The furnace load power set point is the ultimate control that is used to reduce or trip furnace power in the event of significant thermal exceedances. The sidewall uses duplex thermocouples that have been developed in-house by TEMCO; these are inserted in the sidewall/tap-hole locations (duplex type encapsulated in a ceramic tube).

FURNACE PERFORMANCE

Production

Furnace 1 produced 1 083 649 tapped tonnes of combined liquid alloy from July 2001 to June 2017 (Figure 5). The average on-time load (AOTL) for the same period was 19.81 MW, with an overall availability of 92%. The best production of 80 563 t/a was achieved in financial year 2015, with an AOTL of 20.9 MW and availability of 96.7% (Figures 6–7). The low production in 2005/2006 was primarily due to switching the furnace to SiMn production; in 2009 due to the global financial crisis (GFC); and in 2012 due to temporary production suspension for management review of the operation.

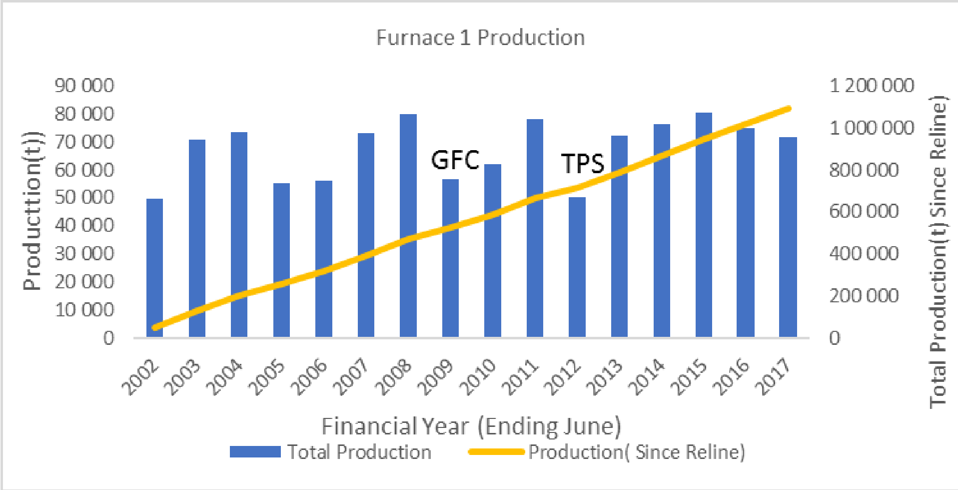

Figure 5: Furnace 1 annual production (t/a)
(GFC: Global financial crisis TPS: Temporary production suspension)

Operating load

The furnace freeze lining was designed for the furnace to operate at a load of 20 MW. This was the load at the time of the shutdown on the conventional lining in 2001. The freeze lining design uses less carbon in the sidewalls, and effectively increased the internal smelting crucible by approximately 13%. This supports the increase in load to 22–23 MW that has been achieved by adjusting raw materials and a new transformer installation. Furnace load was increased by using detailed change management and measurement of key operating variables, including the lining temperatures to take incremental increases. Scrubber capacity and tapping floor procedures were important considerations. Before the change to the freeze lining, the average on-time load (AOTL) was 17.27 MW, against an AOTL of 19.81 MW after the freeze lining (in combination with other improvement efforts discussed later in section capacity improvement from incremental load increase).

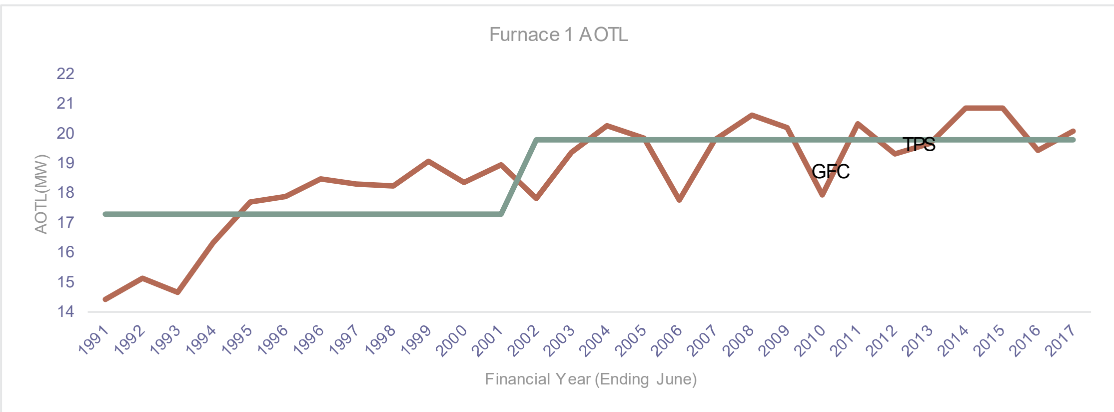

Figure 6: Furnace 1 yearly average on-time load (AOTL)

Availability

The overall availability for the period is 92%, including the reline period, and the two major outages in 2009 and 2012 (see Figure 7). The major cause for downtime on the operating furnace has been the failures associated with the modular electrode holders. Modular electrode holders have contact clamps, and require intensive maintenance work to repair, and complex recovery procedures such as blasting and long slipping of electrodes to establish normal smelting conditions on the furnace.

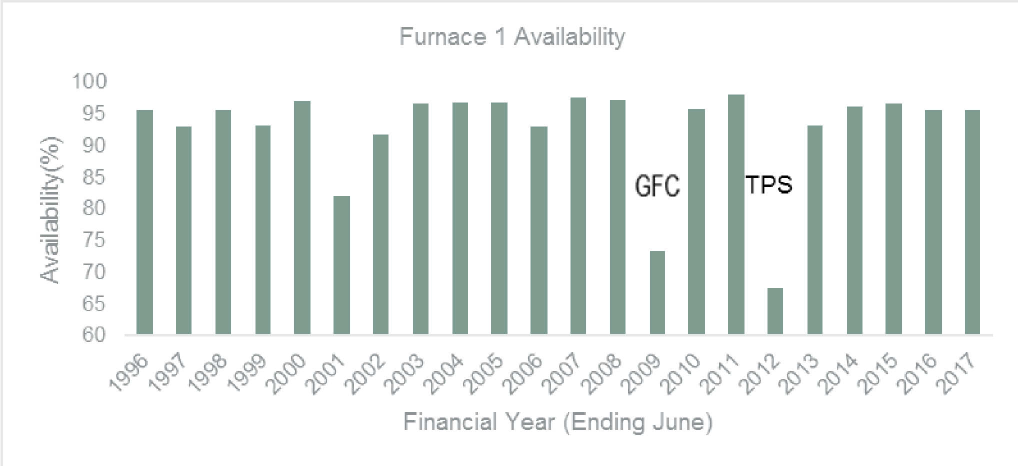

Figure 7: Furnace 1 availability
(GFC: Global financial crisis TPS: Temporary production suspension)

Whilst TEMCO has over 30 years of applied learnings and improvements to the design and monitoring of the modular holders, a recent decision was made to remove the modular holders and replace them with a conventional design on Furnace 2 in March 2017. This is the first stage of standardising electrode equipment at TEMCO, and current planning involves a study of the investment potential for the next reline of Furnace 1.

CAPACITY IMPROVEMENT FROM INCREMENTAL LOAD INCREASE

An incremental increase in load has been achieved due to several changes in equipment design, raw material, and equipment maintenance programmes. The thermal model is used to verify the effect on the lining in real time, and strategies have been developed to maintain the safe operating envelope of the furnace.

Electrical

The transformer changed from 29 MVA to 36 MVA in 2012, with operating limits placed on Primary and Line amps, with a 22 kV incoming load. Electrode / transformer regulation control is from setting resistance to target a secondary current and specific load set point. Maximum transformer MVA during 23 MW operation was 33.6 MVA, which is well below maximum capacity of the F1 transformer (Figure 8).

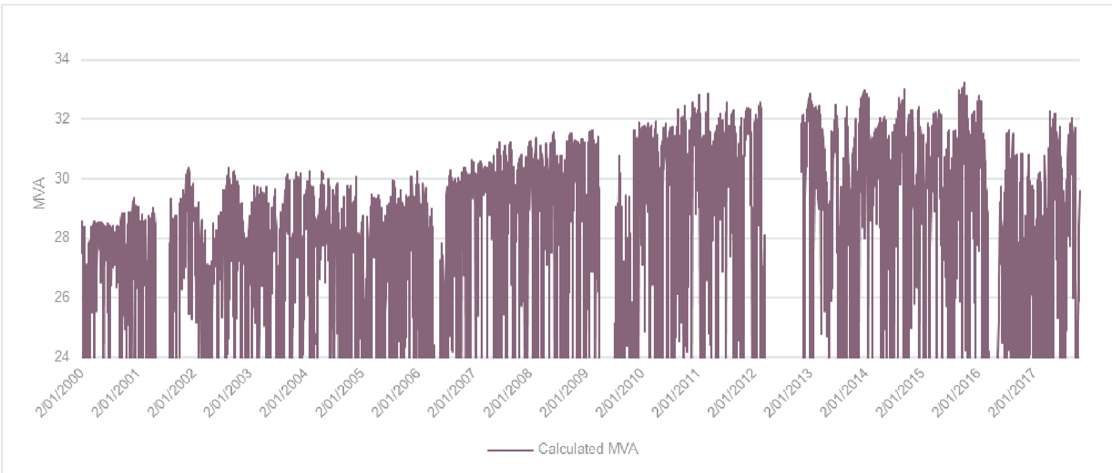

Figure 8: Furnace 1 calculated MVA

Coal discussion
Coal was introduced in 1985 to achieve a higher furnace load at the same secondary current. This improvement was perceived to be from deeper electrode penetration due to increased raw material charge resistivity. The initial coal used was from the NSW Hunter Valley, and was a high volatile and very reactive type with very high swell properties. However, the volatiles resulted in significantly increased gas make, and was limited to a maximum of 30% (on a dry fixed carbon basis). Furnace pressure control can become poor as scrubber gas capacity is reached. The coal has also had an impact on the longevity of the TEMCO asset, when consideration is made of the limited capacity of fume dams and Tasmanian EPA requirements for the site.

Between 2002 and 2009, trials were carried out with differing coal input and types, but the outcome has been that coal has not been used since 2009 in the TEMCO HC FeMn operations. The removal of coal reduced around 94% volatiles going to the off-gas, which has also improved flexibility of operations to increase load and still maintain scrubber capacity. A filter press operation was installed in 2015, to recover all wet scrubber fume for recycling and controlling the long-term legacy issues with fume dams.

Slag volume
Since 2001, TEMCO has been blending South African ores with the GEMCO lump and fines. The Wessels ores have a lower silica content than the GEMCO ore, and these are used to reduce the slag volume, which improves smelting efficiency. The blending of ores is also beneficial for operating the furnace with lower smelting temperatures, which results in promoting 'freeze' on the lining at higher loads. Mn sinter maintains available oxygen below a safe operating limit due to pre-reduction of the ores.

Sinter
TEMCO has been producing manganese sinter since 1975 from GEMCO waste streams, and the benefits of using sinter to improve smelting processes by deeper penetration and high porosity for smelting efficiency have been well documented. Mn sinter maintains high smelting efficiency due to increased pre-reduction of the ores by good gas distribution. The acid-type sinter is strong, and will not break down from standing in stockpiles; it is now being sold to alloy producers to promote stability in the smelting process. TEMCO has used sinter at an addition ratio of 20% to 70% of the manganese ore blend in both FeMn and SiMn production. The sinter is used to improve manganese conversion and reduce manganese losses to slag.

LINING MANAGEMENT SYSTEM AND ITS PERFORMANCE

Lining management system
The Furnace 1 lining is managed by thermocouples inserted into the sidewall and hearth at strategic depths and locations during the refractory installation (see Figure 9). The temperature data is stored in the process control DCS, and used in an on-line monitoring system.

Thermal modelling techniques are used, and control is automated to manage alerts and actions from reduced power to furnace tripping capacity, if limits are exceeded. The F1 lining history can be reviewed in varying average time displays from 5 seconds to 24 hours' averages, and the history from the 2001 start-up is available. The data is used to provide a good understanding of performance issues with the smelting processes and their effect on the change in the energy balance of the operation. Tap-hole management with drilling and plugging, furnace liquid tapping efficiency, electrode tip position, coking level, and internal refractory condition can all be assessed by monitoring and studying the temperature and energy flux trending that is available.

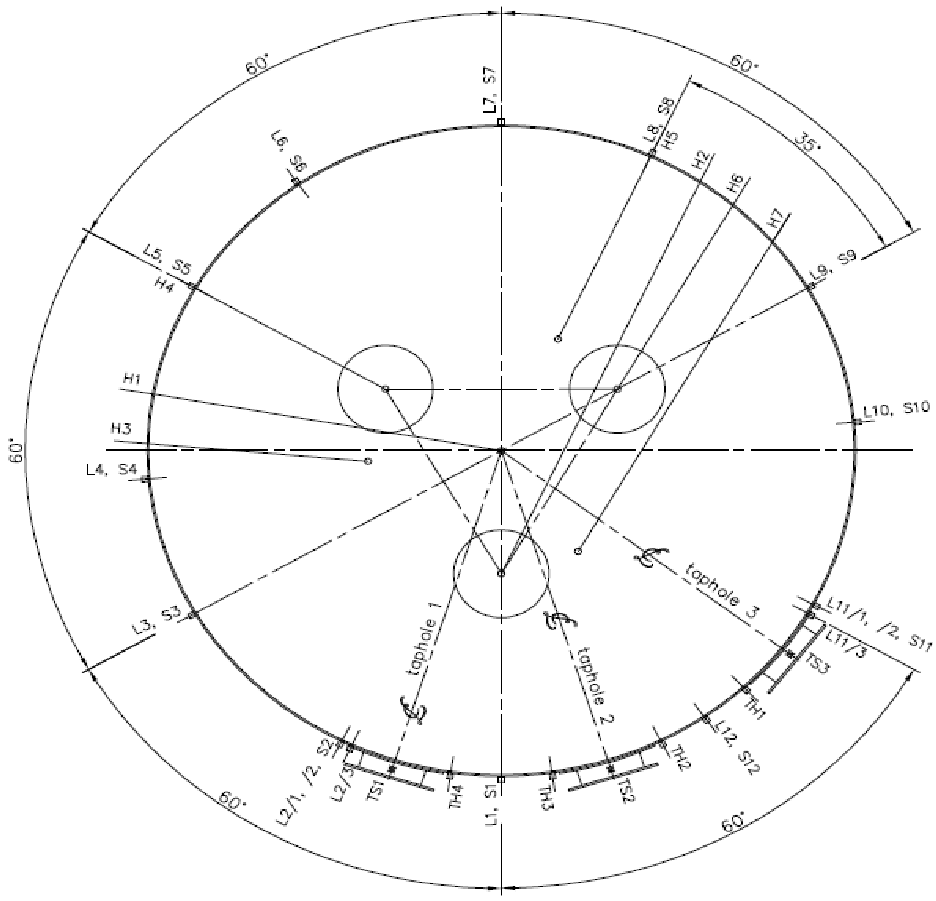

Figure 9: Furnace 1 thermocouple arrangement

Lining performance management

The lining management alarm philosophy at TEMCO is based on a calculated hot-face temperature lower than 800ºC. When the calculated hot face temperature is more than 700ºC an alarm is raised, load is reduced at 750ºC, and the furnace trips on reaching 800ºC. Sidewall thermocouple hot-face calculations are based on a cylindrical model of energy transfer, and hearth thermocouple set-points are based on a straight-line model for energy calculations. The lining management system is to prevent refractory damage, rather than to detect an impending lining breakout.

Historical Temperature Trends

The average hearth temperatures at Level 1 range between 350 and 400ºC (Figure 10), and temperature increases with time due to lining deterioration. The step increase in temperature after the 2009 and 2012 shutdowns is observed to operate at 30–50ºC higher temperature. The hearth thermocouple design has not been satisfactory, and the thermocouples at Level 2 and Level 3 appear to have deteriorated and are recording temperatures that are lower than predicted from modelling. The thermocouples break when removal is attempted, and replacement wire will not reach the original installation point; therefore, readings are not accurate, although they will still show short-term temperature trending.

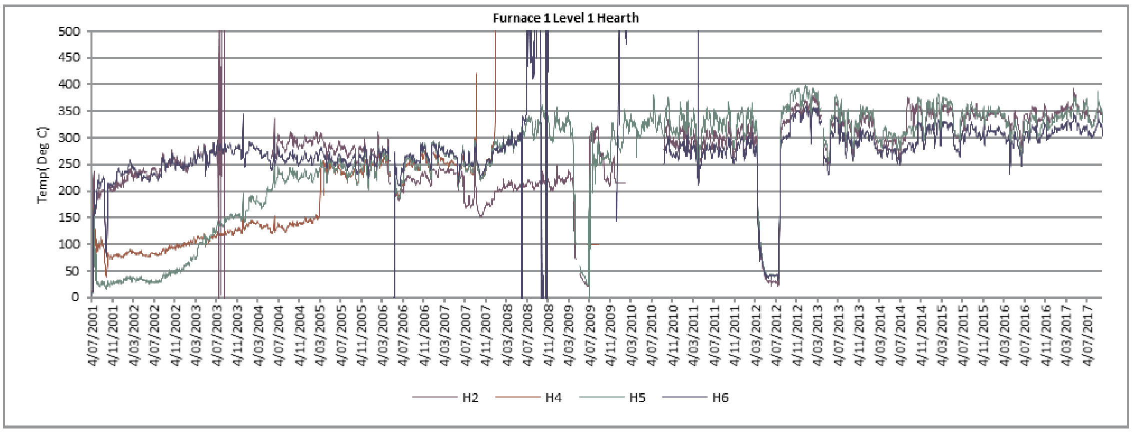

Figure 10: Furnace 1 hearth temperatures at Level 1

The sidewall temperatures trending at Level 1 (tap-hole level) are in the range 200–250ºC (Figure 11). The thermocouples on the sidewall also showed that temperatures increased by 20–30ºC after the 2009 and 2012 shutdowns.

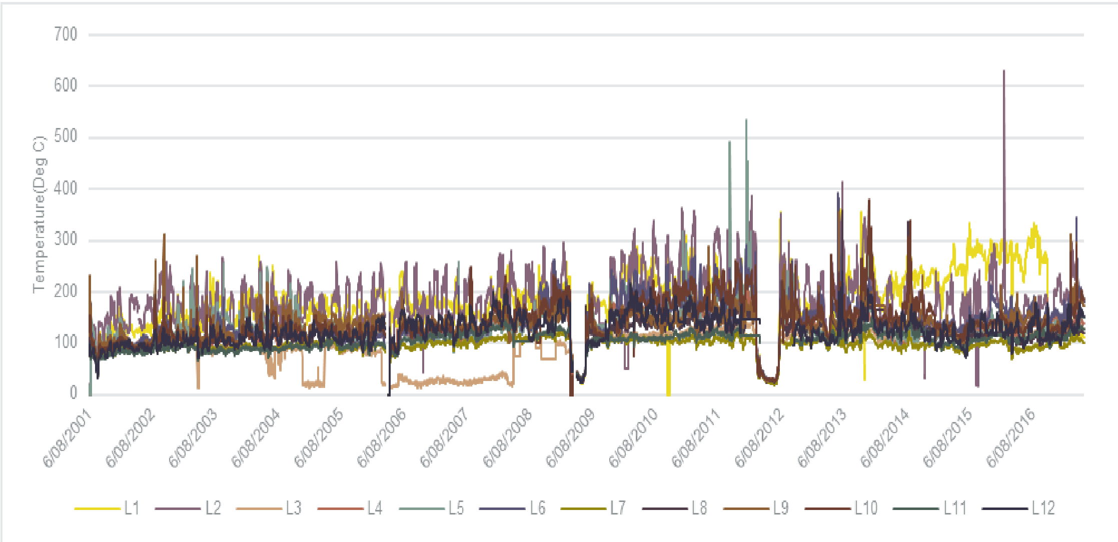

Figure 11: Furnace 1 lining temperature (Level 1)

The Furnace 1 hearth does not have installed contact thermocouples on the external steel plate. These temperatures are physically recorded at monthly intervals to monitor condition, and it is planned to increase the frequency of monitoring as the campaign continues. Maximum base plate temperature was measured at 100ºC, and a project is planned to increase the air flow under the hearth with a bigger fan (see Figure 12). The Furnace 1 hearth has 15 rectangular channels to pass air to cool the base plate. The airflow in each channel is controlled by adjusting the damper position. Figure 12 shows the change in the base-plate temperature by adjusting damper positions.

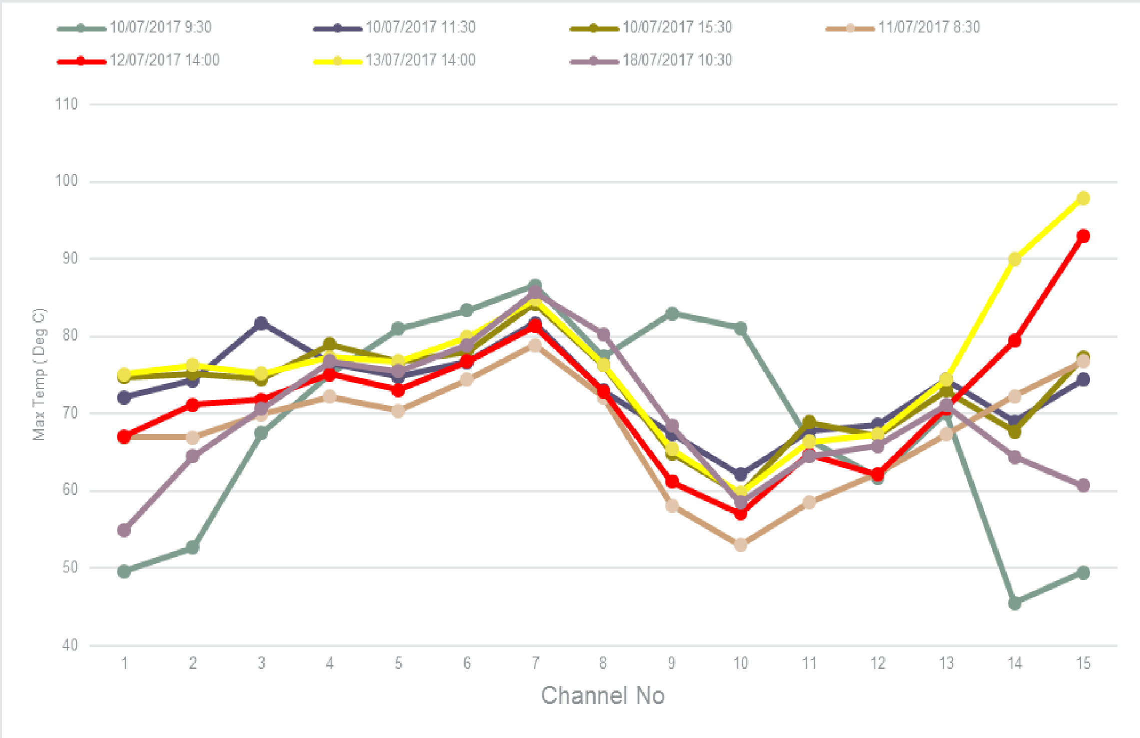

Figure 12: Furnace 1 hearth base-plate temperature variation after adjusting damper positions

EFFECT OF MARKET ON OPERATIONS

Shutdowns due to market downturn

The furnace has been shut down twice for extended durations:

- In 2009, it was off for 86 days during the global financial crisis, when alloy prices were well below production costs, and stockpiles were high due to a poor steel market, and,
- In 2012, the furnace was shut for 124 days due to temporary production suspension for a management review of operation.

Reduced load operation

The failure of the Bass Link cable, together with low rainfall in Tasmania in 2016, resulted in a situation that there was a critical power shortage in Tasmania. Hydro requested TEMCO to reduce load on the furnaces. TEMCO management decided to switch off Furnace 2 and keep Furnace 5 off and reduce load on Furnaces 1 and 3. During this time, Furnace 1 was running on 12–15 MW for two months.

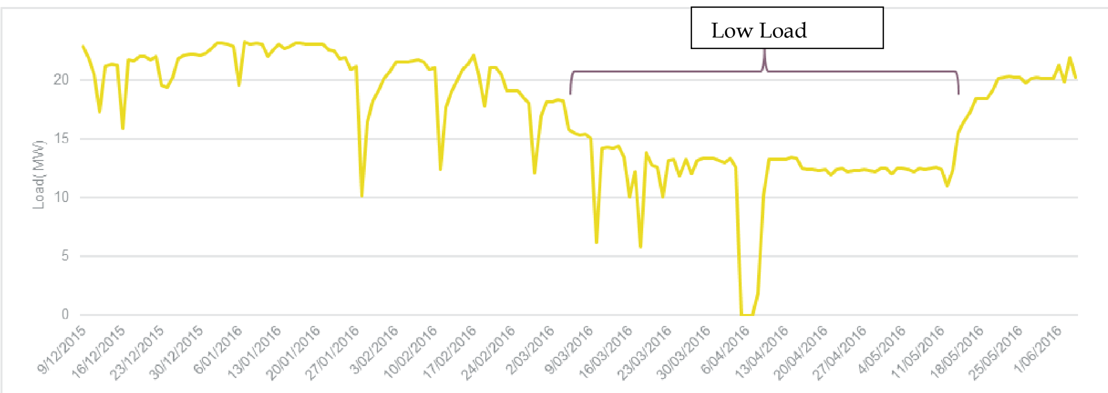

Figure 13: Furnace load during low-load period (Tasmanian power crisis)

The potential issues faced during low-load operations were:

- Narrow smelting zone: the reduced energy input and continued water cooling of the shell has the potential to promote increased freeze formation, which can lead to a narrow smelting zone in the furnace
- Low/high flowrate of alloy/slag from the tap-hole and potential for a metal spill on tapping floor and personal injury
- Short electrode length giving a hot furnace top, and poor smelting conditions.

TAP-HOLE MANAGEMENT

Since relining Furnace 1 in 2001, the tap-holes used on Furnace 1 have not had any major repair or replacement to date. Tap-hole condition is shown in Figure 14 after 11 years of operation. The tap-hole is generally drilled open, and an oxygen pipe is used only after extended shutdowns or opening a new tap-hole. The maintenance of drills and mud guns is considered very important to ensure that a good quantity of tap-hole mud is pumped into the tap-hole cavity when plugging the furnace. A steel plate is used on the front of the hole to make a good contact for the mud-gun nozzle, and is replaced when it begins to warp from exposure to high temperatures.

Figure 14: Tap-hole condition observed during TPS-2012 (after 11 years of service)

The tap-hole spout is cooled by a water spray, with water from the shell cooling flow, and two spray bars are used to push water to the underneath of the tap-hole spout. Lightweight splash shields are used to avoid contact of water with molten materials on the tapping floor. There is a strong culture of awareness of molten material, and the risk with water, as well as needing to keep water on the shell and tap-holes.

CHALLENGES TO MAINTENANCE FROM EXTENDED FURNACE LIFE

Brick movement

Furnace 1 lining bricks have been noted to have undergone some movement.

- In tap-hole regions, it has been seen that thermocouples have become increasingly more difficult to extract from the lining when requiring replacement.
- The upward movement of alumina bricks from inside the furnace crucible has caused significant lifting of the furnace cover. A total of ten rows of alumina bricks have been removed from the front of the furnace mainly, but also from the scrubber offtake adjacent area. This is believed to be due to the process slag replacement of the sacrificial face bricks installed on the inside of the furnace.

These bricks do not show chemical attack or change in original dimensions (see Figure 15).

- There has not been any visible movement of carbon bricks towards the top, as seen with the alumina bricks.

Figure 15: Brick removal from Furnace 1

Equipment failures
The extended life of the furnace caused some maintenance issues, such as maintenance of feed chutes, sprouts, furnace top components, and water pipes. Feed chutes are oxidized, and thinned to a degree that raw mix charge leaked on the furnace top, leading to arcing and component failures. As a temporary measure, chutes are patched from time to time (Figure 16).

Figure 16: Arcing of feed chute due to material leakage

However, in worst-case scenario, chutes are replaced as and when required. To replace these chutes, the furnace needs to shut down for an extended period (10–12 hours) that is longer than for a normal shutdown (5 hours).

Maintaining upper shell cooling troughs has been difficult since the 2001 furnace installation. Limited access to the troughs has led to excessive oxidation of the shell, and poor water control on the furnace shell. In the 2009 GFC, the furnace shutdown presented an opportunity to do repairs to the shell cooling system. It was necessary to replace all of the steelwork with stainless steel, due to the excessive corrosion of the cooling system pipework. The rusting of the shell area in contact with the upper troughs was approximately 8 mm penetrating the 20 mm steel shell plate. All the rust was removed, and waterproof paint applied to prevent further oxidation. This highlighted the importance of a well-designed and maintained system.

CONCLUSIONS

- Safe operations are supported by a lining management system that ensures the risk of lining failure is monitored continuously, and is well controlled.
- The production has exceeded 1.08 million tonnes of tapped metal in the single lining campaign without a breakout or tap-hole repairs.
- The average on-time load achieved is 19.8 MW, with an overall availability of 92% for the 16-year campaign (including the 210 days of extended shutdowns of 2009 and 2012).
- Some brick movement has been observed, with alumina bricks removed, but no carbon upward movement is evident.
- Furnace 1 is expected to be relined / rebuilt in 2021; however, engineering work has not yet commenced. Risk mitigation action is in place with the long lead-time carbon refractories in store at TEMCO.
- Non-destructive assessment of the remaining lining will be carried out by third parties at regular intervals to increase condition monitoring as campaign life extends towards 20 years.

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