

# ALTERNATIVE COOLANTS AND COOLING SYSTEM DESIGNS FOR SAFER FREEZE LINED FURNACE OPERATION

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## Abstract

Water coming in contact with liquid metal is well understood in the metallurgical industry to be an extreme hazard and historically has been at the root cause of many fatal incidents world wide. A wide range of alternative heat transfer fluids exist, which can be used to replace water in both common and special high performance applications. These fluids have a range of physical characteristics leading to different process performances, which can be improved by changes in the configuration and design of the cooling system and furnace cooling elements. This article will examine a number of coolants including natural and synthetic organics, silicones, fluorinated oils, and lead-bismuth eutectic alloy. Peak transient heat fluxes (often where significant damage occurs), Critical Heat Flux and other key copper cooler design parameters will be discussed. Safety tests to determine the suitability of new fluids for use as furnace coolants are discussed and proposed.

## Introduction

Water cooling is used extensively in many types of modern furnace designs to allow for higher operational intensity (i.e. increased throughput) and longer campaign lives (e.g. up to 10 or more years). Blast furnaces use water cooled plate and stove coolers, tap holes, and tuyeres for hot blast injection, amongst other equipment. Electric smelting furnaces use a number of cooled components as shown in Figure 1 [1], from electrode contact clamps, electrode seals, tap holes, feed chutes and cooled lining systems for use in the slag zone and more controversially in the metal or matte zones. Examples of advanced cooler designs are shown in Figure 2 [2]. Ferroalloy furnaces also use water cooled components, particularly in the furnace hoods, off-gas ducts, electrode clamps, slag zone (if slag is present) and around tap holes.

Nearly all commercial furnaces operating today use water as the cooling media due to its abundance, low cost and acceptable heat transfer properties. However, Elkem Solar operates a commercial oil cooled (Therminol<sup>®</sup> 66) furnace supplied by Tenova-Pyromet in their new facility in Kristiansand Norway and an oil cooled (Marlotherm<sup>®</sup> SH) Elkem Multi-Purpose Furnace (EMPF<sup>®</sup>) has been operational for more than 25 years in Iceland at Steinull H.F.

Recently Alcoa (in cooperation with Elkem) have been piloting high intensity (1 MW/m<sup>2</sup>) slag resistance furnaces at temperatures exceeding 2000 °C, as part of the Carbothermic Aluminum

project [3]. Fluorinated oil (Galden<sup>®</sup> HT 200) and currently Mono-Ethylene-Glycol (MEG) have been used by the project for deep cooling of slag/metal furnace panels. The use of coolants other than water has been found to reduce the peak pressure experienced during submerged leakages, avoid most equipment damage and most importantly, prevent injury to personnel.

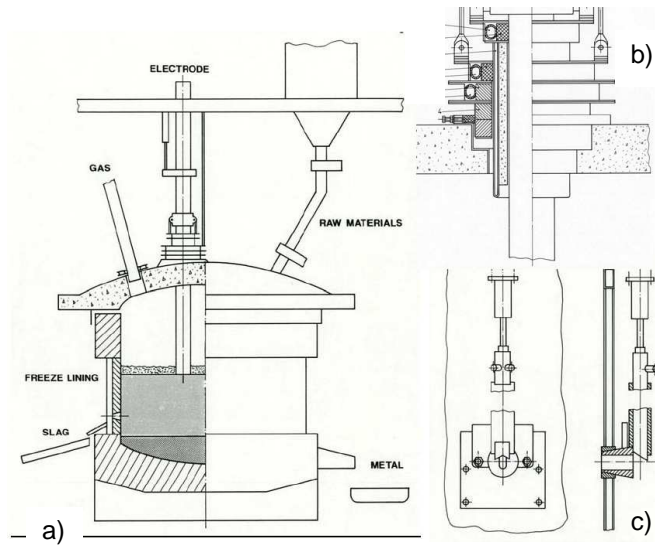
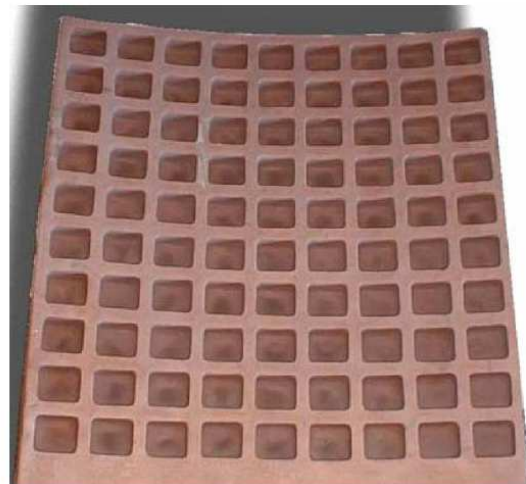
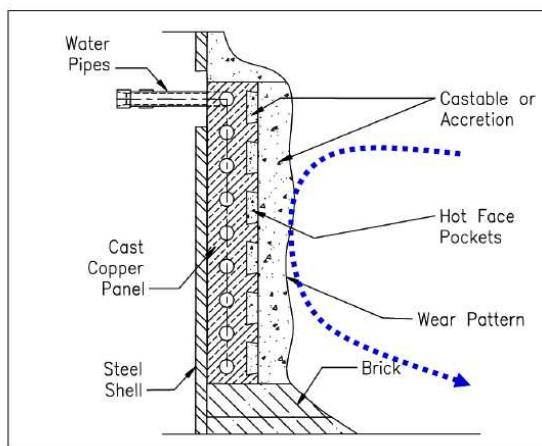


Figure 1. Overview of some cooled smelting furnace structures. a) Elkem Multi-Purpose Furnace<sup>®</sup>, b) electrode seal, and c) slag flow controller [4]. Cooled structures include: freeze-lined sidewalls, electrode clamps and collar, feed chutes, tap hole and slag flow controller.



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Figure 2. (a) Advanced copper cooler with cast-in-pipes and a patterned hot face. Freeze lining and ‘natural’ convective slag flow at the hot face are shown. (b) Photograph of such a cooler [2].

This report will examine some of the safety issues involved in the use of water as a furnace coolant, explore some of the alternative furnace coolants, and the design considerations required to use them successfully. This report will also suggest various active and passive strategies to achieve a higher level of safety for plant equipment and more importantly the personnel.

## Safety Issues Associated with Water Cooled Furnace Components

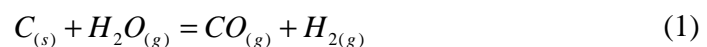
Modern coolers such as pictured in Figure 2, have been installed on second and third generation smelting furnaces [1] and have brought the cooling media deep into the furnace, under the slag and more recently under the matte or metal levels. The use of such panels results in coolant being present only centimeters away from liquid materials with high temperatures and often high superheats.

The explosive potential of water in contact with molten smelting materials (metal, matte or slag) has been graphically displayed in many tragic and often fatal accidents in the metallurgical industry. One well documented incident occurred at Elkem Thamshavn and involved the leakage of large quantities of water from the electrode clamps into a silicon reduction furnace [5]. The resulting structural damage is documented in Figure 3. Similar incidents have occurred in ferroalloy [6] and platinum smelting [7], resulting in multiple fatalities, extensive equipment damage or both.



Figure 3. Photograph showing structural damage suffered by Elkem Thamshavn silicon furnace in 2006 water-metal explosion, which resulted in 1 fatality. Photograph by S. Fugelsøy [8].

Investigations have taken place primarily in the nuclear industry, to study the interaction between molten metal/oxide, e.g. liquefied fuel, fuel cladding or primary reactor coolant (e.g. liquid sodium), with water [9-11]. In some cases, metal and water are known to react to produce hydrogen gas, which adds to the explosion hazard [11]. This hazard was graphically illustrated by the recent events at Fukushima Japan beginning on March 11, 2011, where the build up of hydrogen gas lead to the explosion and failure of the reactor containment vessels and reactor buildings [12]. Similar effects have been reported in titanium and other reactive metal production [13, 14]. In vessels containing carbon and low oxygen, hydrogen can be produced by gasification from the water-gas reaction:



Reaction (1) may have played a role in a multiple fatality resulting from melted water cooled components in a modern water cooled blast furnace. The root cause of this accident was operation without proper back up cooling systems in place and the subsequent reduction of cooling water flow during mechanical maintenance of the pumping system [15].

Few investigations have taken place in the metallurgical industry looking at the interaction of water even with common materials like steel and aluminum. One notable exception with high quality empirical data on the explosive potential of water falling onto liquid metal, has been published by Babaitsev and Kuznetsov [16]. Their data have been summarized in Tables I and II, showing that in many cases, water dropped onto liquid metal results in explosions with a force equal to 1 kg of TNT equivalent per kg of water, or higher.

Table I. TNT Equivalent of Explosion Resulting from the Specified Mass of Water Interacting with 1000 kg of a Given Molten Metal [16].

Metal	TNT equivalent of specified mass of water				
	1 kg	5 kg	10 kg	50 kg	100 kg
Steel 12Kh18N9T	0.82	4	7.8	33	57
Aluminum	3.17	15.9	32	176	200

Table II summarizes the resulting damage from an 80 kg equivalent explosion caused by 26 kg of water interacting with molten aluminum. Table II clearly indicates the inadvisability of placing control rooms next to furnaces, as graphically illustrated in the recent deaths of 6 people at a ferroalloy facility [6].

Table II. Effects due to 26 kg of Water Interacting with 1000 kg of Liquid Aluminum [16].

After-effects of explosion	Distance, m	Pressure, kPa
Breakage of glass	250	2
Collapse of roof	41	14
Destruction of interior walls	23	28

The physics of water thermal explosions, so called ‘steam explosions’ are complex and beyond the scope of this document. They often appear to act the same as Boiling Liquid Expanding Vapor Explosions (BLEVE’s) [17, 18], but typically occur in open systems with no clear means to superheat the water prior to the phase change. They do however, involve a complex interaction of boiling heat transfer (e.g. film boiling), phase changes (vapor formation and solidification), contact area (droplet fragmentation), etc. Extremely rapid gas expansions are produced under the correct conditions of mutual phase dispersions (high interfacial area) and high metal superheats. Self-propagating (sonic) shock waves can then result [9, 10] with or without a triggering event. Due to the hazards associated with deep cooling using water, it behooves us to explore economically viable alternative cooling media, which have lower explosion potential in contact with liquid material and most particularly molten matte or metal.

## Heat Transfer Theory and Design Considerations for Metallurgical Furnace Coolers

Before alternative coolants can be discussed, it is first necessary to have a firm grasp of the heat transfer theory and design considerations associated with metallurgical furnace coolers. The largest heat loss in a modern high intensity smelting furnace is from the bath-line coolers that are used to maintain furnace integrity below the slag level. These coolers also carry the greatest possibility of creating an explosion, due to the immediate proximity of the melt and the probability of releasing coolant below the upper surface of the molten material. Therefore bath-line cooler design (see Figure 2) will be discussed in detail. A review on modern furnace cooler technology is available by Verscheure *et al.* [19] and recommended for further information.

From an energy balance stand point, the most important design factor is the average cooler heat flux. The heat flux experienced by a given cooler can be calculated by:

$$\frac{Q_c}{A_c} = h(T_{bath} - T_{hotface}) \quad [1]$$

where  $Q_c$  is the heat flow [W],  $A_c$  is the cooler area [m<sup>2</sup>],  $h$  is the heat transfer coefficient between the melt and the cooler [W/m<sup>2</sup>·K],  $T_{bath}$  is the temperature of the bath material arriving immediately adjacent to the ‘stagnant’ zone near the wall [K] and  $T_{hotface}$  is the hot face temperature of the cooler [K]. Often  $T_{hotface}$  is taken as the liquidus temperature,  $T_{liquidus}$ .

If the hot face is below the liquidus temperature, then  $h$  will contain both a convective component and an added heat flux due to the heat associated with solidification of the melt. Under dynamic conditions, such as exist during recovery from a slag spall (see Figure 4) or after a significant change (increase or decrease) in furnace power, the heat of solidification will add or subtract significantly to the convective heat flux component. Under steady state conditions it is conceivable to solidify some of the melt in the proximity to the wall, e.g. solidified onto suspended solid nuclei and convect such solid material back into the bulk liquid phase, where it is re-melted, i.e. it is possible to operate with a  $T_{hotface}$  between the liquidus and the solidus of the bath material [20] creating a mushy zone. The mushy zone on the hot face of a copper cooler is a complex and dynamic system that is a topic for current study [21, 22].

For the purpose of discussion, it can however, be assumed that at steady state  $T_{hotface} = T_{liquidus}$  in which case  $h$  becomes the heat transfer coefficient for a vertical plate undergoing natural convection heating. The magnitude of  $h$  is then of the order of 425 [W/m<sup>2</sup>·K] for a cooler immersed in only ‘silicate’ slag. More precise estimates accounting for different material properties can be made using [20, 23, 24]:

$$Nu_{m-c} = 0.32(Gr_{m-c}Pr_m)^{0.3} \quad [2]$$

where  $Nu_{m-c}$  is the Nusselt number at the melt-cooler interface [unitless],  $Gr_{m-c}$  is the Grashof number [unitless], and  $Pr_m$  is the Prandtl number [unitless].

$$Nu_{m-c} = \frac{h_{m-c}L}{k_m}, [3] \quad Gr_{m-c} = \frac{g\rho_m^2\beta(T_{bath} - T_{hotface})L^3}{\mu_m^2}, [4] \quad Pr_m = \frac{C_p\mu_m}{k_m}, [5]$$

where  $h_{m-c}$  is the natural convection heat transfer coefficient at the melt-cooler interface [W/m<sup>2</sup>·K],  $L$  is a characteristic length, i.e. the height along the cooler [m],  $k_m$  is the thermal

conductivity of the molten material [W/m·K],  $g$  is the acceleration due to gravity, 9.81 [m/s<sup>2</sup>],  $\rho_m$  is the melt density [kg/m<sup>3</sup>],  $\beta$  is the melt volumetric expansion coefficient [m<sup>3</sup>/m<sup>3</sup>·K],  $\mu_m$  is the viscosity [Pa·s] and  $C_p$  is the heat capacity of the liquid melt [J/kg·K].

Equation [1] implies that the sidewall heat flux will increase with bath superheat, and superheat increases significantly at higher smelting rates in many smelting processes [25]. With typical slag superheats in the range of 50-250 K, a heat transfer coefficient of 425 [23] [W/m<sup>2</sup>·K] implies a  $Q_c/A_c$  of about 21-106 kW/m<sup>2</sup>. These fluxes are in the range typically experienced by slag coolers, which are not in contact with metal or matte or experiencing forced convection, due to poor furnace design or operating practices. Molten metal and matte typically produce about one order of magnitude higher heat fluxes and require refractory to be placed in front of the coolers, i.e. direct contact between matte/metal and coolers should be avoided.

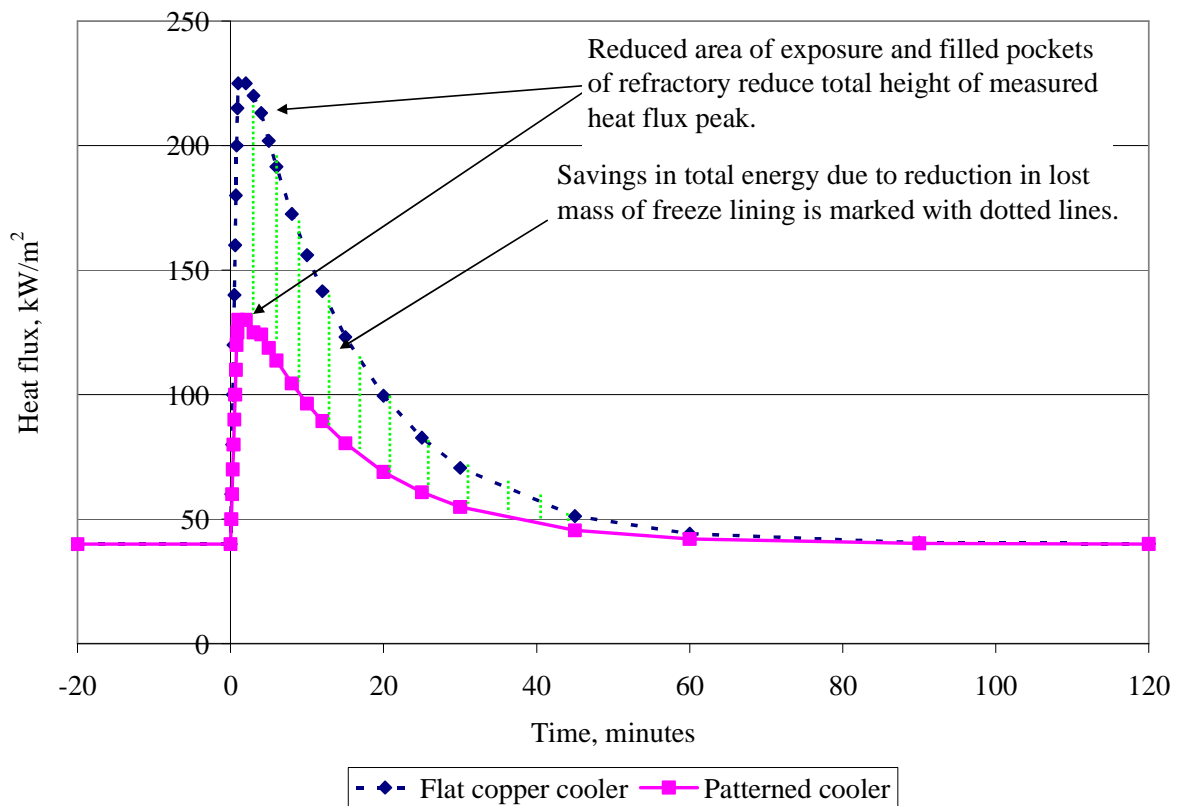


Figure 4. Illustrative example of the dynamic responses of a flat copper cooler and copper cooler with a hot face pattern, due to a slag spall occurring at time zero. A reduced peak heat flux and lower total energy loss are indicated for a copper cooler with a hot face pattern.

### **Safety Considerations in Advanced Furnace Cooler Design**

In designing a forced convection cooled furnace component, the most critical factor is the expected peak heat load or heat flux that it is expected to withstand under emergency conditions, as visualized for a slag spall in Figure 4. Peak heat flux is often difficult to estimate and is scenario dependent. Not all emergency scenarios can be identified a priori. If previous operational data for similar furnaces are available (for at least one entire smelting campaign),



then the design or peak heat flux, should be specified as being equal to the expected average plus  $4.5 \sigma$  (standard deviations), as this should result in a failure rate of  $<1$  in the life of a typical smelting plant due to excessive heat flux.

Bath-line coolers can experience several common types of emergency situations:

- 1) Contact with matte or metal at the hot face (e.g. for coolers designed for slag operation),
- 2) Transition from natural convection to forced convection heat transfer at the hot face,
- 3) Corrosion of the material of construction (typically copper),
- 4) Spontaneous and catastrophic loss of hot face protective layer (either refractory or frozen bath material, i.e. a spall as shown previously in Figure 4),
- 5) Damage due to the conduction of electric current (steel panels are particularly susceptible), and
- 6) Loss or reduction of coolant flow.

Furnace level control is critical to preventing metal or matte from rising onto a slag cooler and leading to extreme heat flux. Failure under abnormal heat flux conditions can also be encountered due to transition to forced convection, e.g. due to a slag 'boil', combined with highly superheated liquid [26]. Corrosion of copper coolers by sulfur [27-29] resulting in water leaks and explosions have also been reported [27, 28, 30, 31]. Monitoring systems are available to detect corrosion, leaking water passages and extreme local heat fluxes in copper coolers and particularly in tap hole blocks, which see especially severe service [32-38].

Refractory failures sometimes occur, particularly when the thickness of the residual refractory or frozen slag is thin (e.g.  $< 25$  mm) and it becomes mechanically unstable. The use of a high conductivity refractory lining will result in a thicker more mechanically sound hot face protection for a given heat flux boundary condition and can provide added protection against chemical corrosion, due to reduced mass-transport by diffusion [28]. A thick highly conductive refractory also provides added thermal mass in a critical near 'burn-out' heat flux condition, by absorbing more total energy in the process of melting.

Rapid changes in furnace power can result in spalling of the freeze lining from the hot face of the coolers due to mechanical stresses induced by thermal expansion. Such spalls result in a characteristic spike, followed by a first order exponential decay on a panel's heat flux with time. Refractory pockets as shown in Figure 2, reduce both the height of the spike (the peak emergency heat flux) and the area under the response curve (total heat loss), due to the fact that less slag must be refrozen and less heat of fusion must be withdrawn as illustrated in Figure 4. A hot face pattern also improves the mechanical adhesion of slag to a panel and reduces both the probability and severity (total area) of a spall. Panels with no hot face pattern can therefore not be recommended for use in a modern furnace design. If "dove-tail" grooves are used in the hot face, these can also be used as a means of securing refractory to the cooler, for added integrity in the lining system.

The steady state heat flux that a cooler must withstand is often known with some accuracy, either due to calculation (e.g. from Equations [1-5]), piloting or previous commercial operation. The peak heat flux can be considered a known-unknown [39], i.e. it is known that it will occur, but the magnitude is uncertain. Estimations can be made using heat transfer modeling for certain dynamic scenarios, such as a simulated spall or partial refractory failure. These values can be compared to the mean heat flux and a suitable safety factor applied to the nominal value for design purposes. It is recommended that peak design heat flux, should be at least 4 times higher

than the nominal heat flux over the full area of the cooler [40]. Where higher ratios can be achieved within conventional design limits, they should be used.

A simple 2D simulation has been performed using COMSOL<sup>®</sup> 4.2a, to model a cast cooler as shown in Figure 5. Copper with 80% of the theoretical copper thermal conductivity, i.e.  $k = 320 \text{ W/m}\cdot\text{K}$ , has been used to simulated phosphorus deoxidized copper. The copper cooler shown in Figure 5 is equipped with ‘dove-tail’ grooves containing refractory with a  $k = 1.8 \text{ W/m}\cdot\text{K}$ . A heat flux of  $1 \text{ MW/m}^2$  has been applied to the hot face, by manipulating the hot face temperature (set to  $1100 \text{ }^\circ\text{C}$ ). It can be seen that the sharp tips of the copper at the hot face are at incipient melting and are well above the recommended  $400 \text{ }^\circ\text{C}$  maximum copper hot face temperature for continuous cooler operation without oxidation [41].

Figure 5 clearly indicates that if embedded thermocouples or other sensors are to be used to monitor copper cooler temperature or estimate local heat fluxes, that they must extend past the plane of the cooling passages. Outside this plane, the copper has essentially the temperature of the cooling media;  $120 \text{ }^\circ\text{C}$  in the example shown. The copper cold face has been modeled as undergoing combined natural convection and radiative heat loss ( $\sim 5.6 \text{ kW/m}^2$ ), while the other sides of the cooler are perfectly insulated to simulate the presence of similar coolers. The modeling of the cooling channels has been simplified to be a constant  $120 \text{ }^\circ\text{C}$  (simulating high velocity forced convective cooling).

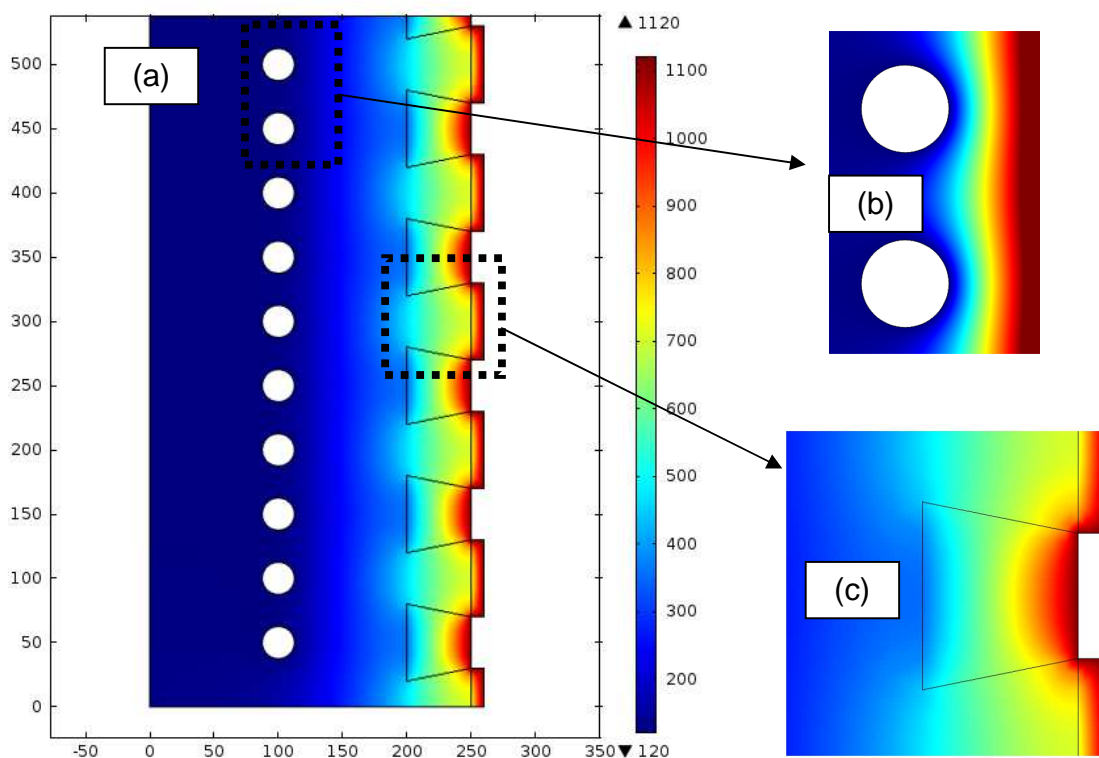


Figure 5. (a) Simplified 2D FEM model of a furnace cooler (half section shown) at steady state, simulating a critical ‘emergency’ heat flux of  $1 \text{ MW/m}^2$ ,  $1100 \text{ }^\circ\text{C}$  hot face temperature, 10 mm of frozen slag on the copper, and exposed refractory lined dove-tail grooves on the hot face. (b) Close up of a cooler, where the color scale has been modified such that red indicates  $200 \text{ }^\circ\text{C}$  and dark blue  $120 \text{ }^\circ\text{C}$ . (c) Close up of one refractory lined pocket showing incipient melting of the copper in the corners at the hot face.



## Critical Heat Flux (CHF) and Cooler ‘Burn-Out’

It is highly recommended to design such that the peak heat flux can be transferred into the cooling media without boiling. The concern is that if boiling takes place that vapor can obstruct the flow of coolant or that the heat flux will exceed the Critical Heat Flux (CHF). At CHF, nucleate boiling transitions to film boiling, where the heat transfer surface becomes blanketed with gas, insulating the surface and reducing heat transfer, as indicated in Figure 6. Past the CHF the furnace cooler temperatures increase rapidly and ‘burn-out’ quickly ensues.

The cooling channel heat transfer coefficient and total heat flow can increase by orders of magnitude before the transition to film boiling occurs as indicated in Figure 6 [42], due to the enhancement of heat transfer by vapor bubble agitation. Figure 6 shows a CHF of 1 MW/m<sup>2</sup> for water under stagnant or ‘pool boiling’ conditions. Using forced convection cooling, the coolant velocity can be used to increase CHF by one or more orders of magnitude, by stripping away vapor before it can insulate the heat transfer surface. Methods for predicting and enhancing CHF have been extensively studied by those designing modern nuclear reactors [43].

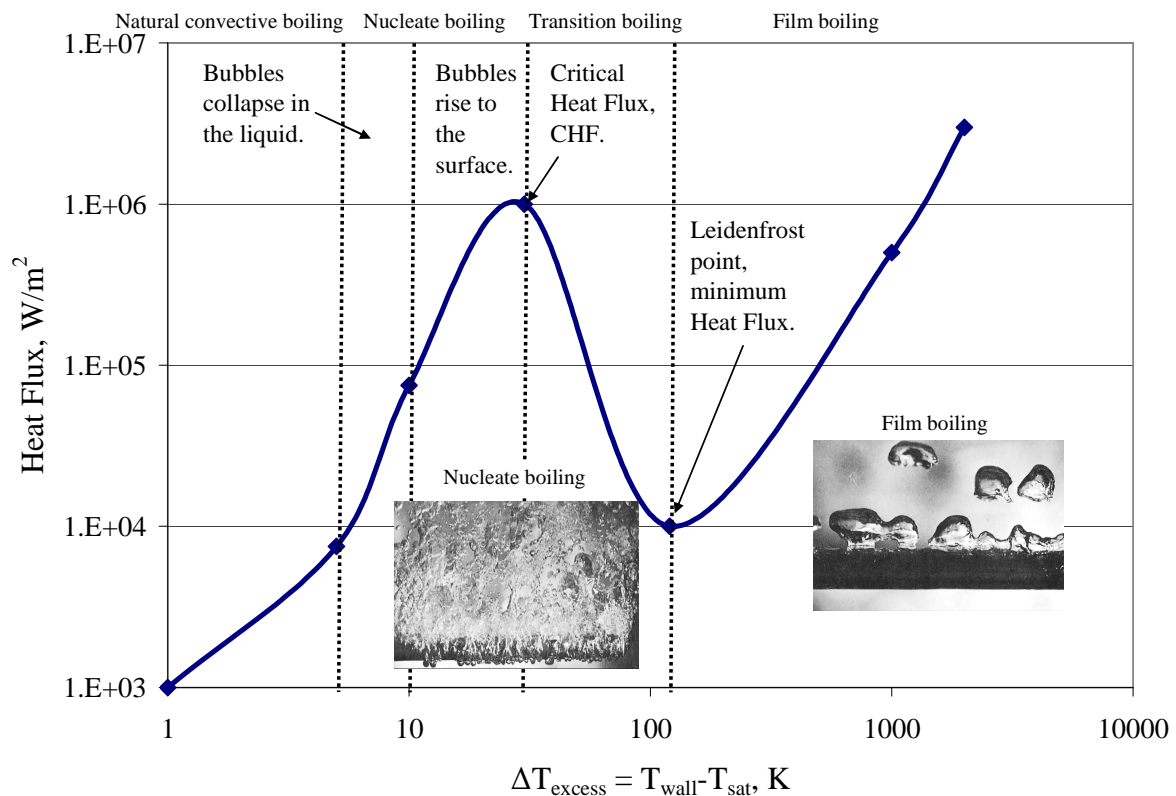


Figure 6. ‘Pool’ boiling heat transfer for water as a function of excess temperature  $T_{\text{wall}} - T_{\text{sat}}$ , showing improved heat transfer (and heat transfer coefficients) up to the Critical Heat Flux (CHF), [42] often referred to as the “Burnout Heat Flux” in furnace literature. Past the CHF, film boiling blankets the inner heat transfer surface as shown in the inserted photo, causing the furnace cooler to rapidly heat and melt.

If care is taken in the panel design to prevent low velocity regions near the tops of panels, which can become easily blocked by vapor, and if a sufficiently high coolant velocity is used (>1 m/s

and preferably between 2 and 3 m/s or even higher for extreme conditions), then film boiling and ‘vapor lock’ can be prevented until heat fluxes are so high, that the copper approaches melting temperatures as indicated in Figure 5. It must be understood that such a ‘boiling’ case represents a critical emergency and not a normal ‘design case’. Permanent loss of copper due to melting is the ‘true’ limiting factor for well designed copper cooling elements. Maximizing the Copper Melting Heat Flux and not the Burn-Out Heat Flux is the most reasonable target in modern cooler design.

For the transition to film boiling, the location of the critical heat flux is not at the panel hot face, but at the internal cooling channels. Therefore to design robust panels, the maximum internal to external surface area should be created. The panel picture in Figure 5 uses 25 mm bored passages, on 50 mm centers, resulting in a ratio of internal/external heat transfer areas of 1.5. So hot face heat flux of 1 MW/m<sup>2</sup> is reduced to an average of 667 kW/m<sup>2</sup> over the area of the internal cooling channels. Figure 5 b) shows that it is unlikely that the side of the cooling channels opposite the cooler hot face will fully participate in cooling, emphasizing the importance of a very large total area, particularly facing the hot face (alternate shapes e.g. triangular, square or oval channels could conceivably be used if the panel were of an extruded design).

### **Internal Cooling Channel Heat Transfer Coefficient Estimation**

For fully developed forced convective cooling in smooth internal passages, at turbulent Reynolds numbers, the Colburn equation [44] can be used to estimate the Nusselt number:

$$Nu_{w-c} = 0.023 Re_i^{0.8} Pr_c^{1/3} \quad [6]$$

where  $Nu_{w-c}$  is now the internal wall-coolant Nusselt number,  $Re_i$  is the cooling channel Reynolds number [unitless] and the  $Pr_c$  is the coolant Prandtl number, all evaluated using the average bulk fluid properties. Average properties are evaluated at  $(T_{inlet} + T_{outlet})/2$ . Equation [6]

is sometimes multiplied by the Sieder-Tate viscosity relation  $\left(\frac{\mu_c}{\mu_w}\right)^{0.14}$  [45], when large

temperature differences are experienced between the wall and bulk of the fluid.  $\mu_c$  is the average bulk coolant viscosity and  $\mu_w$  is the coolant viscosity [Pa·s] evaluated at the average wall temperature. With use of the Sieder-Tate relation the calculation becomes iterative in nature.

$$Nu_{w-c} = \frac{h_{w-c} D_h}{k_c}, [7] \quad D_h = 4 \frac{\text{Channel area}}{\text{Channel perimeter}}, [8] \quad Pr_c = \frac{C_p \mu_c}{k_c}, [9] \quad Re_i = \frac{\rho_c v_i D_h}{\mu_c}, [10]$$

where  $h_{w-c}$  is the average turbulent forced convection heat transfer coefficient between the channel wall and the bulk coolant [W/m<sup>2</sup>·K],  $D_h$  is the hydraulic diameter of the channel [m],  $k_c$  is the average thermal conductivity of the coolant [W/m·K],  $C_p$  is now the mean heat capacity of the coolant [J/kg·K],  $\rho_c$  is the average bulk coolant density [kg/m<sup>3</sup>], and  $v_i$  is the average velocity in the cooling channel [m/s].

## Comparison between the Cooling Effectiveness of Water and Alternative Coolants

A number of heat transfer fluids can be considered to replace water as a cooling media. Natural and synthetic organic oils (one or two phase) or other organic compounds (e.g. Mono-Ethylene-Glycol), silicones, fluorinated oils and even liquid metals (such as Pb-Bi) can be considered. A 2-phase heat transfer fluid is a substance, which boils before decomposition takes place.

A number of fluid options are listed in Table III. Heat transfer coefficients have been evaluated using Equations [6] through [10] at 3 m/s velocity, using 25 mm channel diameters and 1.5 surface area ratio, as shown previously in Figure 5. A peak emergency heat flux of 4 times the highest slag heat flux of 106 kW/m<sup>2</sup>, has been selected for discussion purposes. Two phase fluids are highlighted in blue. For reference the copper cooler hot face temperature is ~200 °C higher than the indicated cooling channel surface temperature for the given heat flux.

Table III. Comparison of Different Coolant's Physical and Heat Transfer Properties, Evaluated for 3 m/s, 25 mm Channel Diameter and at a 424 kW/m<sup>2</sup> 'Peak' Design Heat Flux [46-52]

Cooling fluid	Approximate Range of Operation Min/Max °C	Temp for Ref. Data, °C	Density, kg/m <sup>3</sup>	Heat Capacity, J/kg·K	Thermal Conductivity, W/m·K	Viscosity, mPa·s	Prandtl Number	Reynolds Number at 3 m/s	Nusselt Number at 3 m/s	25 mm Tube Forced Convection Heat Transfer Coefficient, W/m <sup>2</sup> ·K	Cooling Channel Surface Temperature, °C for 424 kW/m <sup>2</sup> heat flux	Approximate Copper Hot Face Temperature, °C
Water	0/100	20	1000	4183	0.604	1.0	6.9	75000	348	8414	54	252
MEG	-13/240	60	1087	2343	0.261	5.2	47	15682	188	1964	204	403
Dowtherm A	15/400	60	1028	1687	0.132	1.7	22	44818	339	1790	218	417
Galden HT 200	-85/300	60	1715	1080	0.063	2.1	36	61475	514	1295	278	477
Texatherm HT 22	-50-320	60	885	1936	0.126	7.8	119	8506	158	798	414	613
Marlotherm SH	-5/350	60	1016	1700	0.125	8.2	112	9259	165	826	402	601
Therminol 66	-32/345	60	982	1699	0.116	11.5	169	6388	141	653	493	691
Xceltherm 500	-62/260	60	766	2327	0.134	2.8	49	20487	236	1269	283	482
Syltherm 800	-40/400	60	899	1677	0.128	5.1	67	13181	185	943	360	558
44.5%Pb-55.5%Bi (123.5 °C)	200/600	225	10150	146	14.2	1.4	0.015	535714	215	122304	227	426

The following can be observed from Table III at the selected conditions:

- 1) Water at 3 m/s is well within its design limits, and has a safe heat flux limit of ~1 MW/m<sup>2</sup> under these conditions.
- 2) Eutectic Pb-Bi is more than an order of magnitude improvement over water as a heat transfer fluid.
- 3) Texatherm<sup>®</sup> HT 22, Marlotherm<sup>®</sup> SH and Therminol<sup>®</sup> 66 (marked in yellow) will not maintain the bulk of the copper below the recommended maximum of 400°C, which substantively eliminates long term oxidation [41]; however, as this represents a critical emergency and not a steady state operating condition, this is not a serious design issue.
- 4) MEG, Dowtherm<sup>®</sup> A, and Galden<sup>®</sup> HT 200 (marked in blue) may experience boiling at the copper interface depending on the system operating pressure and local peak heat fluxes, as these are 2-phase fluids.
- 5) Syltherm<sup>®</sup> 800 a silicone based oil, and Xceltherm<sup>®</sup> 500 an organic one phase oil, both show improved performance over the traditional organic based one phase oils.

The combination of high internal surface area (1.5 times larger than the hot face area) and high fluid circulation rate of 3 m/s, has permitted organic and silicone based fluids to perform within thermal limits at 400% of the maximum expected steady state slag only heat flux, thus achieving a good standard of safety. At 3 m/s all of the coolants shown in Table III are capable of protecting the hot face of the copper from melting at heat fluxes up to ~600 kW/m<sup>2</sup>. The reduced

emergency peak heat flux achievable by the use of dove-tail grooves as shown in Figure 4, further improves safety and the technical viability of organic coolants.

While seemingly exotic, Pb-Bi eutectic alloy has been investigated in the laboratory as a cooling media, since 1951 and has previously been used to cool Russian nuclear submarine reactors [52]. 4<sup>th</sup> generation reactor research is currently investigating the use of Pb-Bi coolants and a great volume of design information is available upon which the metallurgical industry could build. At 0.1 m/s circulating velocity, Pb-Bi could satisfactorily maintain the temperature of a copper cooler exposed to a heat flux of up to 4.5 MW/m<sup>2</sup>, while using a fraction of the pumping cost of water (even after considering the high density of the alloy). Pb-Bi eutectic alloy having a 'pour' point of 125 °C, does not represent a significant engineering challenge. At high velocity, e.g. 1 m/s, Pb-Bi would allow metallurgical engineers to construct processes that could not be conceived of otherwise.

In the event of a Pb-Bi leak into or out of the furnace, neither fire nor explosion will occur. Pb-Bi has the advantage of being non-flammable and virtually non-chemically reactive in contact with liquid water, unlike sodium or potassium. The environmental implications of a lead 'leak' into a high temperature smelting vessel require evaluation before such a coolant could be applied in the metallurgical industry.

Some coolants such as MEG, Dowtherm<sup>®</sup> A and Galden<sup>®</sup> HT 200, are 2-phase fluids like water. Under extreme heat transfer conditions, 2-phase fluids will boil, enhancing heat transfer as shown previously in Figure 6. Boiling is preferable to the alternative, which for organic oils is permanent thermal degradation. The most critical emergency that a cooler can experience is a complete loss of coolant circulation. In such an emergency, pool boiling will ensue for 2-phase fluids. The cooled structures will remain at the boiling point of the fluid, until such time as the coolant contained in the equipment and its associated piping has 'boiled dry'. This provides a substantial time for system recovery or plant evacuation. The piping can be designed to ensure that gravity supply of coolant is maximized, by placing reservoirs high within the system and ensuring that the resulting vapor can be vented safely from the system on the return-side headers.

### **Special Safety Issues Associated with Alternative Coolants**

The use of alternative heat transfer fluid to water is often discounted based on assumptions, rather than proper technical analysis. As shown in the previous section, most of the commonly available heat transfer fluids can safely be used for most furnace applications, when combined with advanced cooler designs such as those pictured in Figures 2 and 5, and high fluid circulating velocities. Some coolants, like liquid metals, significantly improve on the performance of water as a heat transfer media, even at greatly reduced circulating velocities.

It is often assumed that oils and other fluids will create BLEVE-like explosions when released under superheated liquid metal in a manner similar to water. Controlled testing by Elkem and Alcoa, have shown that the peak pressure produced by fluids other than water is significantly reduced. Elkem performed relatively small scale experiments (sub-kg scale) using liquid filled metal ampoules plunged into superheated silicon and aluminum. Alcoa has performed larger scale testing (including flammability) with liquid aluminum. Anecdotal experience from leakages in commercial and large scale pilot operation have corroborated the laboratory testing, indicating that organic heat transfer fluids represent a safer alternative based on explosion risk.

The precise mechanism for the reduced peak pressures from the alternative fluids is not understood, but could be due to the: energy absorbed by cracking of the large molecules, reduced vapor pressures at the metal temperature, or the lower thermal conductivity of the fluids.

Fire risk is an issue associated with organic oils, which is not present with water. The heats of combustion of all of the organics listed in Table III are high and of the same magnitude as 'gasoline'; however, the limited empirical evidence is that they are difficult to combust in open air in the liquid state. Testing should be conducted to determine the energy released per unit area and time [ $\text{W}/\text{m}^2$ ] for these fluids at different initial ignition temperatures. This would simulate the liquid release of hot coolant, followed by subsequent ignition and provide more practical information useful for the selection of furnace coolants. Standardized tests exist to guide metallurgical engineers in the development of targeted methods for such flammability testing [53]. Research has also been published on the use of halogen additives in hydraulic oils for military tanks to reduce flammability [54]. Research into additives for furnace cooling oils (and hydraulic systems) is therefore recommended to reduce the intensity of fires and hopefully produce self extinguishing cooling oils.

Galden<sup>®</sup> is a fluorinated oil and is completely non-flammable. The decomposition products of Galden<sup>®</sup> at extreme temperature and in the absence of oxygen are primarily  $\text{COF}_2$  and  $\text{CF}_4$ . While low levels of HF have been detected during explosion testing, toxic levels of HF have not been observed in practice, although HF can theoretically be produced by the reaction of  $\text{COF}_2$  and water vapor. Concerns about HF formation have led to the replacement of Galden with MEG by Alcoa for the Carbothermic Aluminum project.

### **Conclusions and Recommendations**

Water cooled components have allowed metallurgical vessels to simultaneously achieve greater productivity and longer campaigns; however, the use of water has exposed plant workers to significant risk in the form of 'steam explosions'.

Viable technical alternatives to the use of water exist, in the form of organic and fluorinated fluids and liquid metal. It is recommended that the metallurgical industry take action to explore these alternative heat transfer fluids.

Improved and standardized testing methods for explosivity and flammability should be identified, developed if necessary and adopted to allow systematic analysis of alternatives. Oil additives should be explored that might allow for the creation of self extinguishing cooling (and hydraulic) oils.

Pb-Bi eutectic alloy is perhaps the best alternative to water for the metallurgical industry, offering massively improved cooling capability, lower pumping costs and the elimination of BLEVE-like explosions. The issue of environmental contamination in the event of a leak into a smelting vessel needs to be addressed, and active development is recommended.

## References

1. M.W. Kennedy, H. Haaland, J.A. Aune, and C. Headquarters, "High Intensity Slag Resistance Furnace Design," *Proceedings of the Conference of Metallurgists, Nickel-Cobalt 2009*, CIM, Sudbury, Ontario, (2009) 101-110.
2. G. Slaven, A. MacRae, and L. Valentas, "The Implementation of Ultralife™ Copper Casting Technology in the EAF," *AISE*, Pittsburgh, Pennsylvania, (2003), 1-9.
3. C.V. White, Ø. Mikkelsen, and D. Roha, "Status of the Alcoa Carbothermic Aluminum Project," *Light Metals*, (2012), 81-88.
4. G. Ellefsen and Ø. Hallquist, "The Elkem Multi-Purpose Furnace® Used for Slag Production, Technical Description with Plant Features," *presented at the Elkem seminar*, Bhubaneswar, India, (1989), 1-17.
5. H. Tveit, M. Garcia, H. Delbeck, A.T. Haug, B. Saugestad, and I.J. Eikeland, "Water Leakages in Ferroalloy and Silicon Reduction Furnaces - Experience Gained from a Severe Accident in 2006," *presented at the Silicon for the Chemical and Solar Industry IX*, Oslo, Norway, (2006), 1-16.
6. "Assmang Plant Operations Ban Lifted," in *South African Government News Agency*, SAnews.gov.za, (2008).
7. J. Robinson, "Lonmin Plc - Update on Smelter Incident," *Lonmin Press Release*, (2004).
8. C. Solbakk Johnsen, "Kritisk Etter Thamshavn-Ulykken," in *Adresseavisen*, Trondheim, (2006).
9. M. Rizk, "A Review of Large Scale and Small Scale Underwater Thermal Explosions," *DTIC Document*, (1990), 1-118.
10. P.E. Shick, T.M. Grace, and I. o. P. Chemistry, "Review of Smelt-Water Explosions" *Institute of Paper Chemistry*, (1982), 1-69.
11. D. Cho, D. Armstrong, and R. Anderson, "Combined Vapor and Chemical Explosions of Metals and Water," *Nuclear Engineering and Design*, vol. 155, (1995), 405-412.
12. D. Biello, "Partial Meltdowns Led to Hydrogen Explosions at Fukushima Nuclear Power Plant " in *Scientific American*, (2011).
13. E. Poulsen, "Safety-Related Problems in the Titanium Industry in the Last 50 Years," *JOM Journal of the Minerals, Metals and Materials Society*, vol. 52, (2000), 13-17.
14. S.C. Evans and D.F. McLaughlin, "A Thermodynamic Investigation into Reactive-Metal Melting-Furnace Explosions," *JOM Journal of the Minerals, Metals and Materials Society*, vol. 57, (2005), 49-52.
15. "The Explosion of No. 5 Blast Furnace, Corus Uk Ltd, Port Talbot, 8 November 2001," *Health and Safety Executive*, UK, (2008), 1-60.
16. I. Babaitsev and O. Kuznetsov, "Energy of Explosions Occurring When Water Falls onto a Layer of Molten Metal," *Metallurgist*, vol. 45, (2001), 185-188.
17. T. Abbasi and S. Abbasi, "The Boiling Liquid Expanding Vapour Explosion (BLEVE): Mechanism, Consequence Assessment, Management," *Journal of Hazardous Materials*, vol. 141, (2007), 489-519.
18. J. Venart, G. Rutledge, K. Sumathipala, and K. Sollows, "To BLEVE or Not to BLEVE: Anatomy of a Boiling Liquid Expanding Vapor Explosion," *Process Safety Progress*, vol. 12, (1993), 67-70.
19. K. Verscheure, A.K. Kylo, A. Filzwieser, B. Blanpain, and P. Wollants, "Furnace Cooling Technology in Pyrometallurgical Processes," *Sohn International Symposium, Advanced Processing of Metals and Materials Vol 2.*, Eds. F. Kongoli and R.G. Reddy, TMS, San Diego, California, USA, 27-31 August, (2006), 139-154.



20. H. Joubert, "Designing for Slag," "Freeze Linings" on Furnace Sidewalls – an Engineering Perspective," *Molten Slags, Fluxes and Salts*, Stockholm, Eds. S. Seetharaman and DU Sichen, Sweden-Helsinki, (2000), 12-17.
21. F.J. Guevara and G.A. Irons, "Simulation of Slag Freeze Layer Formation: Part I. Experimental Study," *Metallurgical and Materials Transactions B*, (2011), 652-663.
22. F.J. Guevara and G.A. Irons, "Simulation of Slag Freeze Layer Formation: Part II: Numerical Model," *Metallurgical and Materials Transactions B*, (2011), 664-676.
23. D. Robertson and S. Kang, "Model Studies of Heat Transfer and Flow in Slag-Cleaning Furnaces," *Fluid Flow Phenomena in Metals Processing*, (1999), 157-168.
24. S. Kang, "A Model Study of Heat Transfer and Fluid Flow in Slag-Cleaning Furnaces," *Dissertation Abstracts International (USA)*, vol. 52, (1992), 1-182.
25. J. Merry, J. Sarvinis, and N. Voermann, "Designing Modern Furnace Cooling Systems," *JOM Journal of the Minerals, Metals and Materials Society*, vol. 52, (2000), 62-64.
26. L. Nelson, R. Sullivan, P. Jacobs, E. Munnik, P. Lewarne, E. Roos, M. Uys, B. Salt, M. de Vries, and K. McKenna, "Application of a Highintensity Cooling System to Dc-Arc Furnace Production of Ferrocobalt at Chambishi," *SAIMM Journal*, vol. 104, (2004), 551-561.
27. B.M. Thethwayo and A. Garbers-Craig, "Corrosion of Copper Coolers in PGM Smelters," *The 4th International Platinum Conference, Platinum in transition 'Boom or Bust'*, SAIMM, (2010), 187-194.
28. B.M. Thethwayo, "Sulphidation of Copper Coolers in PGM Smelters," *Masters Thesis*, University of Pretoria, (2010).
29. B.M. Thethwayo and A. Garbers-Craig, "Laboratory Scale Investigation into the Corrosion of Copper in a Sulphur-Containing Environment," *Corrosion Science*, (2011), 3068–3074.
30. T. Raymond, "Polokwane Smelter Shutdown Update," *Anglo American Platinum Press Release*, (2005).
31. "Lonmin Shuts Number One Furnace for a Week," *in miningmx*, (2009).
32. A. Sadri, P. Gebiski, H. Ghorbani, G. McGarrie, and T. de Vries, "Monitoring Deterioration of Waffle Cooler Thickness at Polokwane Smelter," *JOM Journal of the Minerals, Metals and Materials Society*, vol. 61, (2009), 69-73.
33. M. Hopf and E. Rossouw, "New Opportunities-Exhaustive Monitored Copper Coolers for Submerged Arc Furnaces," *SAIMM Journal*, vol. 106, (2006), 373-378.
34. J. Eksteen, B. Van Beek, and G. Bezuidenhout, "Cracking a Hard Nut: An Overview of Lonmin's Operations Directed at Smelting of UG2-Rich Concentrate Blends," *SAIMM Journal*, vol. 111, (2011), 681-690.
35. R. MacRosty, S. Nitschke, T. Gerritsen, and C. Crowe, "Advances in Furnace Monitoring: Instrumentation," *Proceedings of the Sixth International Copper-Cobre Conference*, vol VII, August 25–30, Toronto, Canada, (2007), 203–215.
36. T. Plikas, L. Gunnewiek, T. Gerritsen, M. Brothers, and A. Karges, "The Predictive Control of Furnace Tapblock Operation Using CFD and PCA Modeling," *JOM Journal of the Minerals, Metals and Materials Society*, vol. 57, (2005), 37-43.
37. A. Sadri, P. Gebiski, and D. George-Kennedy, "Development of the Taphole Acoustic Monitoring (TAM) System for Water-Cooled Copper Tapblocks," *47th Conference of Metallurgists*, Winnipeg, (2008), 7-19.
38. P. Tracy, R. MacRosty, Q. Zhao, L. Gunnewiek, and T. Gerritsen, "Tapblock Diagnostic System," *Proceedings of the Sixth International Copper-Cobre Conference*, vol. III, August 25–30, Toronto, Canada, (2007), 453–464.
39. W.P. Imrie, "New Technology Developments in the Production of Non-Ferrous Metals," *ERZMETALL*, vol. 59, (2006), 9-18.

40. F. Stober, T. Miraza, A. T. Hidyat, I. Jauhari, K. Belanger, D. Fowler, T. Gerritsen, A. Matyas, C. Nichols, and N. Voermann, "Furnace Upgrade with Hatch Technology at PT Antam Feni-II in Pomalaa, Indonesia," *INFACON XI*, New Delhi, India, (2007), 638-653.
41. U. Aniekwe and T. Utigard, "High-Temperature Oxidation of Nickel-Plated Copper vs. Pure Copper," *Canadian Metallurgical Quarterly*, vol. 38, (1999), 277-281.
42. Y.A. Çengel and A.J. Ghajar, *Heat and Mass Transfer: Fundamentals & Applications*: McGraw-Hill, (2011).
43. S.H. Chang and W.P. Baek, "Understanding, Predicting, and Enhancing Critical Heat Flux," *10th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-10)*, Seoul, Korea, October 5-9, (2003), 1-20.
44. A.P. Colburn, "A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction," *Transactions of the American Institute of Chemical Engineers*, vol. 29, (1933), 174-210.
45. E. Sieder and G.E. Tate, "Heat Transfer and Pressure Drop of Liquids in Tubes," *Industrial & Engineering Chemistry*, vol. 28, (1936), 1429-1435.
46. J.P. Holman, *Heat Transfer*: McGraw-Hill, New York, (1986).
47. Monoethylene Glycol (MEG). Available: <http://www.chem-group.com/services/meg.tpl>, accessed, September 3, 2012.
48. Dow Chemical Co. Supplied Computer Software: "Fluidfile [the Dow Chemical Co.]," (1995).
49. Sasol Product Information Sheet, "Marlotherm SH Heat Transfer Fluid," (2004).
50. Solvay Solexis Product Information Sheet, "Galden PFPE: Heat Transfer Fluids," [www.solvaysolexis.com](http://www.solvaysolexis.com), (2004).
51. SOLUTIA Product Information Sheet, "Therminol 66 Heat Transfer Fluids by SOLUTIA," (2004).
52. P.N. Martynov, A.V. Gulevich, Y.I. Orlov, and V.A. Gulevsky, "Water and Hydrogen in Heavy Liquid Metal Coolant Technology," *State Scientific Center of the Russian Federation – Institute for Physics and Power Engineering*, (2004), 1-20.
53. L. Deleanu, D. Buzoianu, M. Rîpă, Ș. Crăciunoiu, and A. Drug, "Flammability Tests on Hot Surfaces for Industrial Fluids," *The Annals of University "Dunărea de Jos" of Galați, Fascicle VIII, Tribology*, (2007), 22-31.
54. B. Wright, R. Mowery, and M. LePera, "Survivability? It Could Be a Matter of Hydraulic Fluid," *Proc. 11th Annual US Army Ground Vehicle Survivability Symposium*, 27-30 March (2000), 1-14.