Always one step ahead

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New inductor concept for channel furnaces

Channel induction furnaces are more and more often being used for melting purposes because their efficiency is considerably better than that of crucible furnaces. This results in the demand for more and more powerful inductors. Research projects over the last few decades have been aimed at obtaining an optimal type of channel for high power inductors. The requirements of such inductors with regard to heat transmission from the channel into the furnace and the circulation of molten metal within the furnace can be met by the purposeful use of electromagnetic forces. A practical example illustrates the advantages that can be obtained by optimization measures, such as modification of the channel shape and type of connection and optimization of the complete inductor. In spite of the higher melting power of the inductor the optimized channel shape also ensures a longer lining life. The condition of the optimized channel can be assessed by the simultaneous evaluation of its wear diagram and temperature measurements at the bushing.

Comparison between the economics of channel and crucible induction furnaces

The channel induction furnace has many advantages and, especially on account of energy management, will find increasing use in the future.

Power consumption for the melting of 1 t of copper alloy amounts to 188 kWh, this having been measured on a 24 t channel furnace melting Cu58Zn38Pb4 with two 1200 kW inductors. The furnace has an efficiency

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of 89 to 90% with a melting capacity of 12.8 t/h [1].

The main frequency crucible furnace with the same size, nominal rating and operating conditions, requires around 250 kWh/t, i.e. the efficiency is 68% with a melting capacity of 9.6 t/h. In order for this furnace to achieve the same 12.8 t/h melting capacity the nominal rating would have to be increased to at least 3 200 kW, which means both higher capital and power consumption costs.

Up to now, the advantages of the channel furnace were countered by its disadvantages, the latter particularly being:

- no or only weak bath circulation in the furnace,
- insufficient exchange of heat between channel and furnace, leading to overheating of the channel ceramics, as well as
- the pinch effect due to excessive electrodynamic forces which led to unpredictable break-throughs of the melt into the inductor.

The disadvantages increased with a higher inductor power. Modifications to the channel shapes did in fact result in improvements but could not be looked upon as being optimal.

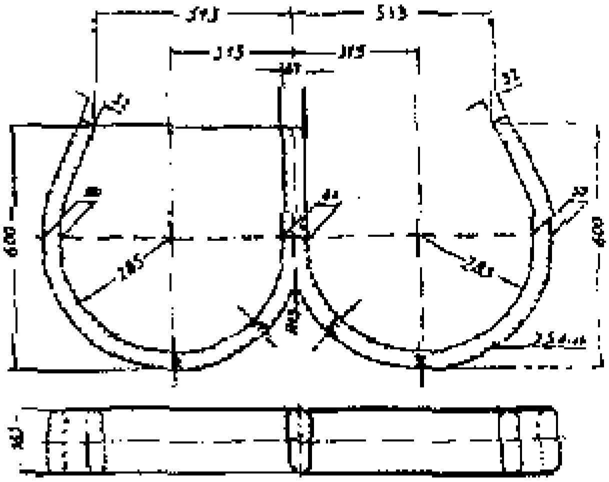
Channel concept, lining and measurements for monitoring inductor condition

Theory

Experimental research work has been going on for years for the purpose of optimizing the channel shape [2 to 4]. Special attention was given to different channel shapes and cross-sections [2, 4] in order to achieve a directional flow of the melt in the channel (transit flow [4]).

A number of papers have been published regarding the theory of the optimal design of channel inductors, of which the contributions in [5 to 7] can be considered to be the most informative with regard to dimensioning. Nevertheless, up to now, a large number of inductors with channels as shown in Figure 1a. are in use, although these already have a tendency towards strong pinching with liquid heel and medium powers of 300 to 400 kW. Pinching is the main cause of unsatisfactory melting capacity and a poor life of the channel inductor ceramics.
The dynamic effect of the electric currents in the induction coil and the channel exerts a pressure on the melt which, with insufficient counterpressure, leads to breaking of the column (pinch effect). It is possible to calculate the minimum height of melt in the furnace that is required in order to avoid pinching [7]. Theoretical calculations [5, 6] show that optimal relationships between power and force can only be achieved with a single phase inductor and a double channel. Based on this knowledge, without any need for experiments, the channel can be calculated and designed for both existing and new furnaces in such a way that ensures sufficient transit flow of the heat exchange between channel and furnace and provides for melt circulation, avoids overheating of the channel ceramics, avoids pinching even after pouring, i.e. minimum molten heel, the furnace can be continuously run at its nominal rating.

1a. previous channel shape



1b new channel shape

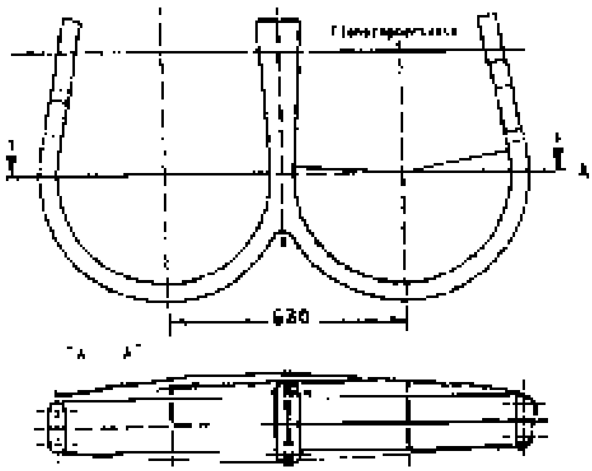


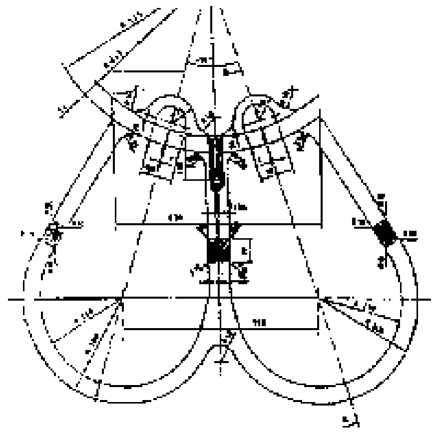
Figure 1. Optimization of the channel shape increased melting capacity by 11% and reduced power consumption by 10%

Practical experience with optimized channel inductors

On account of the theoretical principals channel shapes and inductors were firstly developed for melting furnaces for aluminium and copper alloys, such furnaces fully meeting all the operational requirements concerning capacity and lining life. **Figure 1** shows an example for the optimization of the channel shape; all the other parts of the inductor remain unchanged. With the old channel shape **(Figure 1a.)** the nominal rating of the inductor could only be used when the furnace was more than 80% full because of the strong pinching effect that occurred with a lower level of the melt.

The turbulence of the melt in the channel leads to formation of cavities in the channel wall and after only a few months to breaking-through of the melt into the bushing. The use of the optimized channel shown in **Figure 1b** eliminated the pinch effect, enabled the use of the nominal rating throughout the melting period, led to an 1 1 % increase in the melting capacity and a 10% reduction of power consumption [8].

2b previous channel shape



2b new channel shape

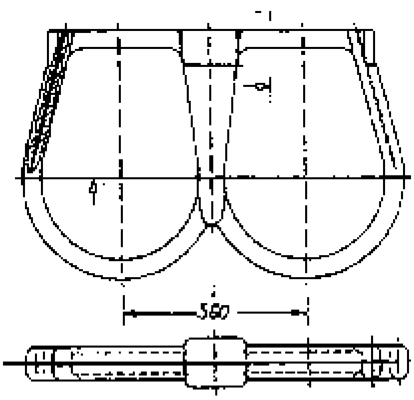


Figure 2. Optimization of the channel shape and the inductor for an existing melting furnace increased the power and melting capacity by around 60%:

Figure 2 shows an example of the optimization of the complete channel inductor. The modification of the inductor from a Scott connection with the channel shape in **Figure 2a** to a single phase connection with the channel shape in **Figure 2b** resulted in a more than 60% increase in the inductor and melting capacity, the durability of the ceramics increasing from 4 months to over 1 year [9]. The substitution of a single 500 kW inductor with single channel by a single phase inductor with double loop channel **(Figure 2b)** led to a 24% increase in the melting capacity and 6% reduction in power consumption [10].

A 14 t channel furnace with two 1000 kW inductors with Scott system for the melting of copper-zinc alloys equipped with new 1000 kW inductors according to **Figure 3** and a channel according to **Figure 4** with single phase Steinmetz connection achieved the comparable values as shown in **Table 1** [11]. **Figures 3** and **4** show a single phase inductor which in this form can be optimally used for both copper alloys and cast iron.

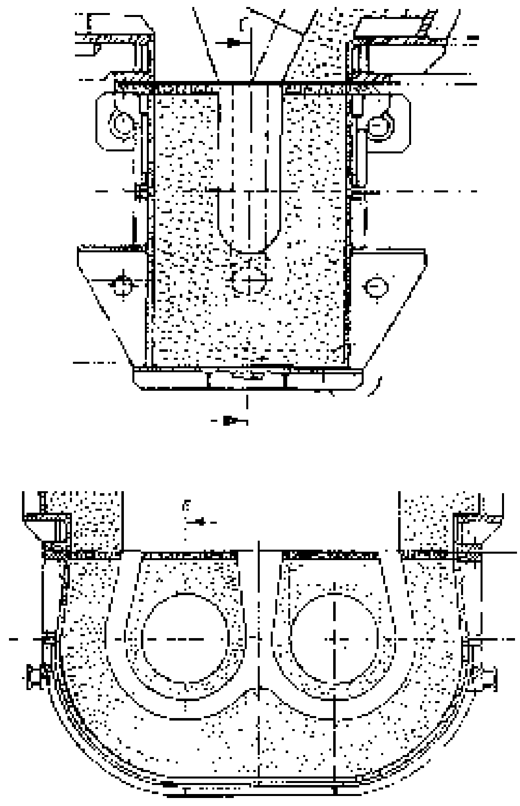


Figure 3. Example of a new channel and inductor design

Table1. Results after substitution of two 1.000 KW inductors (Scott system) by two optimized single-phase parallel feeding inductors

Charge material	Cu-granulate + Zn-ingots	Cu58Zn38Pb4 chips	Cu58Zn38Pb4 scrap
Average inductor power	+ 36,71 %	+ 32,53 %	+ 25,22 %
Power consumption	- 24,52 %	- 07,63 %	- 01,08 %
Melting rate	+ 76,73 %	+ 44,4 %	+ 34,91 %

Possibilities of monitoring the channel condition

One of the main advantages of the optimized channel shape examples **(Figures 1b, 2b** and **4)** is the continuous wear behavior of the channel, which allows monitoring of its condition by means of a wear diagram and temperature measurement at the inductor bushing. Due to the fact that no abrupt changing of the flow and no strong turbulence can occur in the optimized channel it is possible to achieve a longer life of the inductor ceramic wear lining. If the melt flow in the channel is laminar the wear of the ceramics is basically caused by uniform abrasion and/or by uniform clogging of the channel walls. Measurement of the nominal operating values for voltage V, current I and power P after commissioning of the inductor enables calculation of a wear diagram for these changes in the channel **(Figure 5)**.

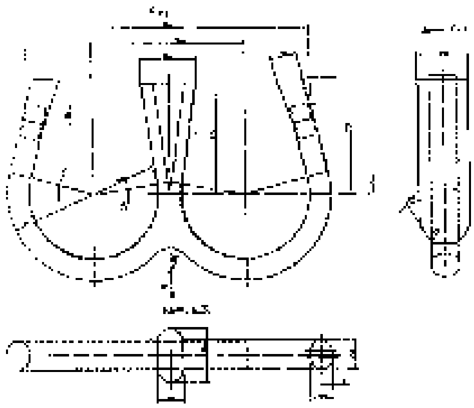


Figure 4 Channel former for inductor in Figure 3 (wear diagram in Figure 5)

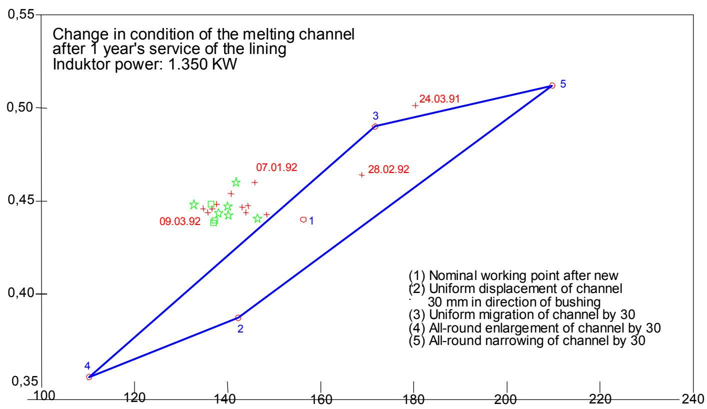


Figure 5. Wear diagram for inductor and channel

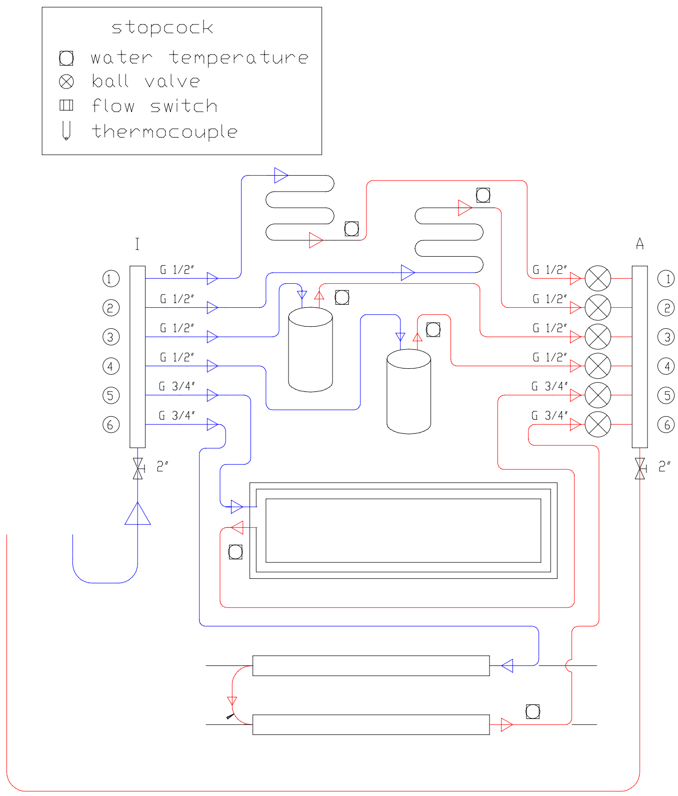
The wear diagram contains the plotted values of the compensating resistance and reactance of the electrical operating data of the inductor for the channel conditions:

- 1) nominal operating point (new channel),
- (2) uniform displacement of the (new) channel in the direction of the bushing,
- (3) uniform migration of the (new) channel away from the bushing,
- (4) all around enlargement (wall abrasion) of the channel and
- (5) all around narrowing (clogging) of the channel.

Figure 5 shows the wear diagram for the inductor in **Figure 3** with the channel in **Figure 4** (nominal rating 1350 kW). The inductor was commissioned on 29th February 1991 and taken out of service on the 9th of March 1992. From the last registered operating points of the inductor and their position in the wear diagram it can be concluded that abrasion of the ceramics took place on the external wall and clogging on the inner wall of the channel, which was confirmed after inspection of the removed inductor.

High power inductors are basically water cooled. Use of a water cooled copper bushing is advantageous because it ensures the best possible heat distribution in the ceramics and the temperature is almost constant over the whole length of the bushing.

Figure 6 shows the measuring point for the cooling water temperature. Monitoring of the water temperature at the bushing in conjunction with the wear diagram provides information concerning changes in the channel. In the condition of the channel as shown in **Figure 5** it can hardly be expected that there will be any variation in the cooling water temperature. If the actual operating points tended clearly towards the corner point (4), this would indicate a progressive increase of the cooling water temperature.



	l/min	bar	
①	2.2	36.0	bushing
②	2.2	36.0	bushing
③	1.4	36.0	inductor coil
④	1.4	36.0	inductor coil
⑤	2.7	36.0	inductor flange / water tracing
⑥		36.0	water cooled leads

Figure 6. Measuring points for cooling water temperature

Optimization of the channel shape and the conductor in existing channel furnaces enables a considerable increase in the melting capacity without incurring high costs and simultaneously lengthens the life of the ceramics which, in turn, leads to a further reduction in melting costs. The wear diagram can only sensibly be used for optimized conductors and, in conjunction with monitoring of the cooling water temperature at the bushing, ensures full utilization of the longer inductor lining life.

Concrete example of melting cost reduction

Elkhart Corp., Fayetteville, AR/USA, a renowned manufacturer of copper tubes and fittings, was operating with channel induction furnaces that were uneconomical with regard to service life and the introduction of power into the melt. The exacting quality requirements (tight tolerances) and different diameters resulted in corresponding demands on the melting process. Potential improvements were sought on account of the continuously increasing costs.

Previous conditions

The 400 kW plant had been upgraded to 500 kW. Inductor

problems already existed with the previous 400 kW rating, its service life being no longer than 3 months.

At a later point in time the old power feed via transformer and choke, based on 60 Hz, was re-equipped with a converter that then can be loaded with 500 kW (60 Hz, single phase).

However, on account of the strong pinching and thus of the unacceptable service life of the inductor, it was only possible to operate with 420 kW. In service life of the inductor remained at a maximum of 3 months.

The inductor was a single phase unit equipped with a coil and a channel, having cooling only on the sides. Misled to unequal heat distribution with local overheating. The previous use of a stainless steel water-cooled bushing also led to insufficient heat distribution within the ceramics, thereby pre-programming stress cracks.

Checks revealed that the power density of the inductor and its dimensioning were not in accordance with optimal conditions.

Use of a new inductor

Evaluation of the functional requirement and direct onsite investigations resulted in development of a new single phase, 500 kW (at 620 V, 60 Hz and 3000 A) double channel inductor **(Figure 1),** with the possibility to increase the nominal rate up to 600 kW. The copper bushing was water cooled in order to improve transmission of heat into the ceramics. The new channel consisted of heavy cast copper, the flow being so adapted to enable orientated melt circulation.

Operational experience

Duration of operation. The inductor was firstly commissioned on 7th June 1995 and purposely taken out of service at the beginning of August 1996 after around 14 months uninterrupted service. The channel was in an as new condition (**Figures 8** and **9**) with no wear and no partial washouts or accumulations, showing that the inductor power was converted into directional laminar flow of the melt in the channel. On account of the channel condition after 14 months it could be assumed that the lining would last a further 2 to 3 years.

Figure 7. Channel inductor (nominal ratings; 500 kW, 550/620 V, 50/60Hz, system Marx)

Figure 8. Channel condition after 14 months operation (side channel)

Figure 9. Channel condition after 14 months operation (side and middle channel)

Table 2. Measurement recorded during sintering and commissioning of the reserve inductor

Time	Inductor data				Inductor temperature°C (Measuring points in Figure 5)					Remarks
	Hz	kW	V	A	1	2	3	4	5	
9th August 1996										
07:42	12	10*	130	310						
08:00	12	10*	130	310	32	28	30	29	29	
12:00	12	10*	130	310	37	30	30	30	30	
14:25	12	10*	130	310	38	30	36	32	31	
14:30	24	20/30*	200	680	38	31	37	35	33	
16:00	20	30*	200	600	40	34	38	35	35	
16:30	20	30*	200	600	40	35	40	36	35	
16:50	20	30*	200	600						
17:00	36	48*	240	950	41	35	40	38	35	
17:02	**Filling-in of liquid copper**									
17:02	40	60*	240	1100	41	35	41	39	35	
17:25	42	80*	260	1250						
17:45	47	160*	320	1500						
10th August 1996										
10:10	44	125*	285	1350	43	38	47	43	39	
10:30	44	125*	285	1350	43	38	47	43	40	Charging
10:40	58	520*	605	2680	43	39	50	50	41	Charging
10:40	57/58	500*	605	2600						Charging
10:45	58	500*	605	2600	47	52	55	58	44	Charging

Heat exchanger temperature, entry/dischange: -primary circuit: 40°C / 58°C

Measurements.

Table 2 shows the measurements made during sintering and commissioning of the reserve inductor on the 9. and 10. August 1996. The cooling water volumes were initially only roughly adjusted. As with commissioning in 1995 the cooling water volumes in the individual circuits have to be so adjusted that the temperatures (1) to (5) are between 60 and 65 'C in order to enable later assessment of the channel condition

Summary of results

1. The operating figures at nominal rating as recorded on 10. August 1996 are almost the same as the measurements made during commissioning from 7^{th} to 13^{th} of June 1995. The small variations of 605 V as against 610 V (around -0,82%) and 2.600 A as against 2.650 A (around -1,89%) are within the range of measurement tolerances and can be ignored for evaluation of the wear diagram, no corrections being necessary for its use in assessment of the channel condition.
2. The cooling water must be adjusted to the same original temperature in all circuits (1 to 5).
3. Monitoring of the channel condition by means of the wear diagram and temperature measurement has proved to be completely successful. Until the end the actual inductor working points indicated an almost new condition of the channel, which was confirmed by inspection of the removed inductor.
4. On account of the findings, under the same operating conditions it can be reckoned that the service life would be at least 2 years.

Evaluation of wear diagram after 14 months operation

In the wear diagram (**Figure 10**) the points 1 to 5 represent the figures for the new inductor after commissioning. Point 1 (nominal working point) is thus applicable for new lining. In the case of displacement of point 1 in directions 2, 3, 4 or 5 the channel wear would amount to up to 10 mm.

By means of the measured data points 6 to 8 it can be clearly seen that, at around 1 mm, the nominal working point 1 remained in the working diagram without any appreciable change.

Costs

Table 3 shows prices and costs as the basis for calculation of the cost saving achieved by Elkhart Corp. through the installation of a high power inductor with high quality refractory [13].

Total lining costs and lining costs per t of copper are shown in **Table 4**. The pre-planned removal of the inductor after 14 months continuous operating time resulted in a surprisingly short amortization period of around 44 days. Because the very good condition of the inductor enabled the assumption of a considerably longer service life, it can be reckoned that the actual amortization time would be less than one month.

Table 2. Basis of calculation by example of Elkhart Corp.

Melting capacity		
- previous inductor (500 KW)	1,2	t/h
- high power inductor (500 KW)	1,8	t/h
Inductor conversion costs	200.000	DM*
Acid dry ramming mix, upper furnace	500	DM/t*
Semi-plastic ramming mix, upper furnace	1.500	DM/t*
T/Cu-MsL for inductor	625	DM/t
80 Sp for upper furnace	2.250	DM/t
Moler insulating bricks	1,40 DM/each	
Lightweight refractory bricks	3,50 DM/each	
Nefalit 16, 10 mm thick	1,50	DM/m^2
Hourly labour costs	50	DM/h*
Pure copper costs	4.000	DM/t*
Provision (10 % of copper price)	400	DM/t*
Service life		
- before conversation	3	months
- after conversation with new refractory material	14	months[1)]
Expected service life	24	months
Working hours		
- 24 h / day		
- 5 day / week		
- 11 months / year		

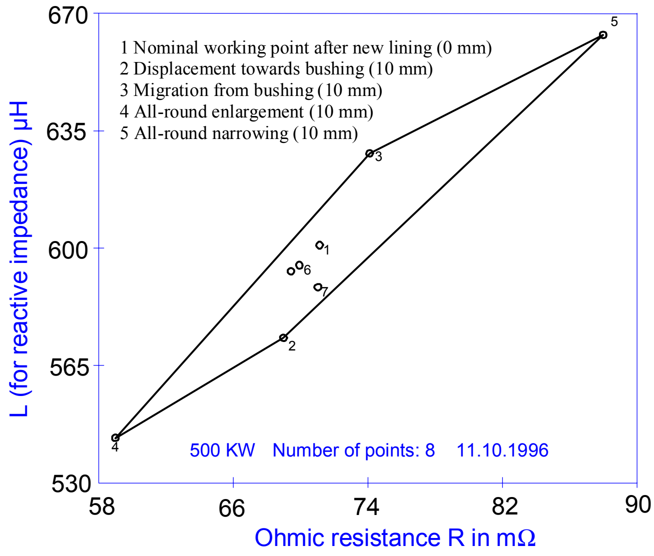
* assumed figures
[1)] The inductor was purposely changed although the electrical conditions gave no cause for changing it, this being confirmed after removal

Table 4. Comparison of the total lining costs for the previous inductor with those of the high power inductor with high quality refractory and its amortization period

Total costs for a lining	
- previous inductor	212.620 DM
- high power inductor with high quality refractory	218.810 DM
Lining costs per t of copper	
- previous inductor	123,05 DM/t Cu
- high power inductor with high quality refractory	18,09 DM/t Cu
- saving	104,96 DM/t Cu
armortization (14 months)	44,1 working days [1)]

[1)] Allowing for the fact that the furnace has operated for 24 months the armortization period would then be around 25.7 working days.

This cost calculation was based on some assumed values, indicated in **Table 3** by means of an asterisk(*), but are included for the purpose of this calculation. The information in **Table 3** should also



No.	Date	f [Hz]	U [V]	I [A]	P [KW]	R [mΩ]	L [µH]
1	13.06.95	58	610	2.650	500	71,2	600,7
2	13.06.95	58	610	2.772	530	69,0	573,5
3	13.06.95	58	610	2.535	475	74,0	628,4
4	13.06.95	58	610	2.953	514	59,0	543,3
5	13.06.95	58	610	2.369	494	88,0	664,1
6	26.02.96	58	610	2.675	500	69,9	595,6
7	04.03.96	58	610	2.650	500	71,2	589,8
8	11.03.96	58	610	2.680	500	69,6	594,6

Figure 10. Channel inductor wear diagramm (Elkhart Corp.)

only be regarded as an aid to enable foundries to correctly determine their actual costs.

At this point it should be clarified what the refractory manufacturer should correctly understand as a high power inductor. Today, it is frequently the case that inductors are referred to as high power when they have a rating in excess of 600 kW. This is not correct because it is not the power but the melting capacity per kW that indicates whether or not they are "high power". Consequently, 1.000 kW inductors that on account of the pinch effect only have a melting capacity of 1,2 t/h, cannot be classified as high power units because, as a rule, only the melt is superheated, which not only results in metallurgical but also refractory problems.

Contrary to this, a 500 kW inductor that, inclusive of ancillary time, has a melting capacity of 1,8 t/h, must be regarded as high power unit. There should therefore always be close cooperation between the furnace and refractory manufacturers as well as the foundry.

Conclusions

The knowledge that the channel represents a closed secondary winding of a transformer for the transmission of energy into the melt is of decisive importance for the optimal design. It is also decisively important that the furnace and refractory manufacturers work closely together to achieve long service lives. Only in this way is it possible to solve the most important questions of costs in the interest of each individual foundry, e.g. decreased melting times, energy-saving and optimal service lives.

The example here for channel furnaces for nonferrous metals foundries is also basically convertible to iron foundries. Allowance must naturally be made for the special features regarding the higher processing temperature and electromagnetic coupling.

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