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EDITORS



**NATURAL  
DRAUGHT  
COOLING  
TOWERS**

## NATURAL DRAUGHT COOLING TOWERS

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PROCEEDINGS OF THE FIFTH INTERNATIONAL SYMPOSIUM ON NATURAL DRAUGHT  
COOLING TOWERS, 20–22 MAY 2004, ISTANBUL, TURKEY

# Natural Draught Cooling Towers

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## Preface

In our days, natural draught cooling towers have become the symbol of economic generation of electricity taking environmental concerns into account. From the view point of the civil engineering profession, cooling tower shells belong to the most daring structures ever built in reinforced concrete.

In design, all modern and specific computation methods have to be applied in order to find out the linear, nonlinear, static and dynamic behaviours of these very large reinforced concrete shell structures. Moreover, special demands on cooling towers have very often initiated progressive research work on buckling behaviour, wind action, earthquake response and nonlinear material effects with respect to safety, durability and concepts for the extension of their life cycle.

After four previous International Symposia on Natural Draught Cooling Towers, namely the 1st one held in 1978 in Paris, the 2nd one held in 1984 in Bochum, the 3rd one held in 1989 again in Paris and the last one held in 1996 in Kaiserslautern, the Working Group 3 of the International Association for Shells and Spatial Structures (IASS) on Natural Draught Cooling Towers is organizing the present 5th one from May 20 to 22, 2004 in Istanbul, Turkey, in collaboration with Mimar Sinan University where Prof. Mungan who is an active member of the Working Group for nearly 30 years, has been teaching since 1985 after he left Bochum.

The aim of this Symposium is to achieve a broad participation of process, mechanical and civil engineers, of scientists, constructors and suppliers involved in design, construction and operation of cooling towers. To this Symposium, once more the most experienced experts, scientists and engineers, from all over the world have contributed with their 43 papers which will be presented and discussed in 13 sessions during the Symposium. The papers cover all aspects of cooling towers such as research, design, construction, process, maintenance and rehabilitation. A special session is dedicated to the 200 m high and as such world's highest Cooling Tower of Niederaußem, built recently in Germany.

The symposium is gratefully sponsored by Mimar Sinan University, Istanbul, and University of Kaiserslautern. Special supports by BALCKE-MARLEY, ENKA, HEITKAMP, MC BAUCHEMIE, RWE POWER, VATTENFALL EUROPE, ZERNA KÖPPER AND PARTNER are gratefully appreciated.

The organizers feel urgent to thank the members of the scientific committee for their activities, all authors for their contributions and A.A. Balkema Publishers for the willingness to publish these proceedings from the very beginning. Particular thanks are extended to the Executive Members of SANEV, Foundation of Mimar Sinan University, to all members of Mimar Sinan University and to the members of the Institute of Statics at University of Kaiserslautern, involved in the preparation and realization of the Symposium. The great help in editing and the great burden of the organizing work carried out by Dipl.-Ing. Peter Weisenstein in Kaiserslautern have to be accentuated with sincere thanks.

Istanbul and Kaiserslautern, May 2004

I. Mungan and U. Wittek

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## Conference organization

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*Construction heritage*

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## Back to the future of the hyperbolic concrete tower

Hans Damjakob  
*Balcke-Dürr GmbH*

Nic. Tummers  
*Architecture Critic*

**ABSTRACT:** Some of the questions raised during the Symposium held at the Institute of Civil Engineers in London on June 12, 1967 [1] were the incentive to go back another 50 years in time to the place where the first hyperbolic concrete tower was conceived as the chimney for a natural draught cooling tower: Heerlen, Province of Limburg, the Netherlands. From that vantage point we view this tall, yet also elegant and fragile structure's future which is always in the here and now.

### 1 THE WRONG SORT OF STRUCTURE?

“The thickness of an eggshell ... is about 0.011 in ... When aerodynamic effects are of major significance, then possibly a thing which is a third of the thickness of an eggshell is not the right way of dealing with it. With such random loads, perhaps we are using the wrong sort of structure” [1,1: 1.44, 50]. Or another remark:

“Nothing was produced at the Symposium to show that the general shape of cooling towers had been developed for proved reasons of thermal efficiency due to venturi effects. Prior to the meeting I had been led to believe that in fact the shape was purely historical, and that the shapes had been developed because prior to computer solutions this was the only shape which could be realistically analysed structurally by resolving loads down the generator lines. If these facts are true, this must add considerable weight to ... the request for an examination of alternative structures” [1,1: 1.90].

What had happened? “On Monday, 1 November, 1965, during severe westerly wind conditions, three of eight cooling tower shells, all of which had been completed, collapsed at the Ferrybridge “C” Power Station. (Ferrybridge, Yorkshire, UK, Authors pers. comm.) Tower 1B collapsed at about 10.30 a.m., Tower 1A about 10min later and Tower 2A at 11.20 a.m. Each of the eight towers was 375 ft high with a base diameter of 300 ft and with shells 5 in. thick ... (Fig. 20). They were sited in a staggered arrangement in two parallel rows 350 ft apart.

... Eye witness reports are available” [1,1,1: 1, 2, 3.] as well as photographs of the collapse (Fig. 1).

The Central Electricity Generating Board (CEGB) as owner immediately appointed a Committee of Inquiry with the following Terms of Reference: “To examine the collapse of the cooling towers at Ferrybridge and make recommendations” [2: *Appendix A*].

The examination covered all aspects from the specification of the towers, the design and construction, meteorological conditions prevailing on 1 November in the locality, aerodynamic and structural research investigations to the mode of failure. Within seven months CEGB issued a report, summarized in four paragraphs, the first being as follows:

“The Committee find that the tower failures ... were primarily caused by a serious underestimate of

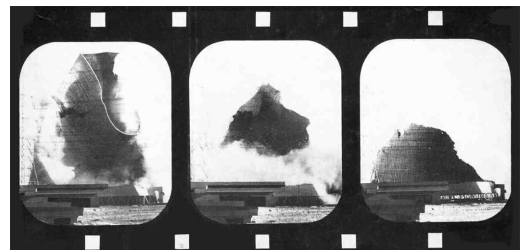


Figure 1. The collapse of Ferrybridge Tower 2A.

the wind loading in the design, which led to tensile failure of the vertical reinforcement in the lower part of the shells. Constructional defects were not significant" [2: 144].

The brevity of this statement conceals the intensive and thorough survey and research work which, for the first time, describes all the conditions required for the structural integrity of this type of building: the specific capabilities of the elastic body to absorb loads and transfer them to the foundations as well as the specifics of the wind, whose fluctuating forces acting on the structure are influenced by the shape and the surface condition of the structure itself and by the arrangement of the eight towers and the power station buildings in the vicinity.

Details on this can best be found in the proceedings of the one-day symposium – “the first of its kind” [1,4: 4.107] – under the title “Ferrybridge and After”, a title “to induce a progressive note into this discussion” [1,1: 1.3], held on June 12, 1967 by the Institute of Civil Engineers which the CEGB, as owner, agreed to contribute to and attend. The following quotations from the Opening Address for Discussion are intended to set the scene for the “Ferrybridge” play, with text projected on the stage curtain calling on us to “examine the collapse of the cooling towers and make recommendations”.

“It is a very rare occasion when we have the opportunity of analysing and ... fully discussing the causes and lessons to be learned from collapse or failure. Since November 1965 when the collapse of the cooling towers at Ferrybridge occurred the Central Electricity Generating Board has been made aware of world-wide interest. It was evident that there were many protagonists of differing theories covering the cause of the collapse ... The important object of this symposium is to highlight the fundamental aspects of structural design against wind loading where data are deficient. To achieve this object, the Committee invited all the members of the Ferrybridge Committee of Inquiry and several specialists who assisted the Committee’s deliberations to produce papers which provide an up-to-date springboard from which to start and stimulate discussions. (Krätzig reports: ‘All parts of the symposium were stamped by extraordinary lively discussions.’ [3].)

One of the earliest examples of the use of concrete cooling towers in this country for power generation purposes was the Lister Drive Power Station in Liverpool, where hyperbolic towers 100 ft high, 100 ft base dia., each associated with a 10 MW set were built 40 years ago by Liverpool Corporation and are still in use today.

At the present time ... 40% of the country’s total generating capacity is tower-cooled, employing 241 cooling towers of various capacities ... a further 66 cooling towers ... are planned for commissioning by 1971” [1,1: 1.1–6].

The background curtain of our stage slowly starts to depict a global landscape revealing many different sites with completed cooling towers and others under construction: the UK, as mentioned above, South Africa, where more than 130 towers have sprung up since the 1930s [4], the USA, where the first hyperbolic tower is built in 1963 [5] and nine towers are under construction [2,4: 4.25], the continent of Europe, all these towers being vitally linked to the base load power supply of their respective countries.

In Germany, for example, some 40 towers of this kind with a maximum height of 65 m had been built since 1938 and the construction of the first tower with a height of more than 100 m had just been completed at the end of the year 1965 [6]. More towers are under construction or planned.

Let us consider the 40-year cooling tower landscape in the UK as described above: we can see the number of shell structures virtually identical in shape constantly increasing by approximately 6 units per annum, at the same time growing in height from around 30 m to over 100 m, i.e. by a factor greater than 3; the other details such as the thickness of the shell wall remained unchanged at 5 in. or 13 cm as did the single layer reinforcement in the shell. Despite the collapse of three towers of a group of eight on 1 November 1965, the story is rather that of the success of an unusual type of structure than that of the necessity for an examination of alternative structures. What went wrong with the Ferrybridge towers whose shells sole function as a chimney was to resist the wind load and the climate influences as well as its inherent weight? Was the wind load correctly assessed or were the wind forces exceptional and unforeseeably great? In this respect the Committee established the following:

The “basic wind requirement was less rigorous than had been specified for any of the preceding cooling tower stations” [2: 22]. And: “General wind conditions in the Ferrybridge area on 1 November 1965 when the towers collapsed, were severe, but were very considerably lower than the probable maximum values. There is a high probability of these conditions recurring within five years” [2: 101]. And further: “The wind speed in the inquiry specification was ill-defined, in that no average period and no return period were included. It is assumed that the intention was to stipulate a maximum mean one minute speed, ...” [2: 105].

Or had the amount of steel reinforcement designed to prevent the concrete shell from cracking under tensile forces not been appropriately determined because there were no precise calculation methods available to do this? The following was established in this respect:

“The Committee find that the calculations of the towers to resist the specified wind loading were completed by the most modern analysis then available. All doubts on the validity of the analysis methods which have been raised since the collapse have been

resolved. The Committee have no doubt that the calculation method used in the original design to convert wind loading to stresses did not introduce any significant error. Comparison with more recent bending solutions has shown only minor variations from the equivalent stresses derived by membrane solution, ...” [2: 112]. It can therefore be said:

“The fact that, while three towers collapsed ... and five did not, and also that the difference in loading, as influenced by the grouping and the internal packing of the towers, was not great in relation to other possible influences on loading, justifies the assumption that the global safety factor of the towers in relation to the gale of 1 November, 1965, was about 1” [1,1,3: 4]. Any underestimate of either the loads or the structural conditions of the shell structure therefore was to the detriment of any load reserves still available. Obviously no safety margins were allowed for unknown influences. The findings are therefore as follows:

“The Committee found the design to be open for criticism on three main counts:

- (a) The presumed use of a 1 min maximum mean wind speed for the Ferrybridge design loadings was in error. Tower structures are clearly vulnerable to sustained steady wind conditions of very much shorter duration and the design should have included a suitable conversion factor.
- (b) Although the reinforcement provided in the Ferrybridge shells was correctly proportioned to correspond with the requirements of the design, no margins were allowed to cover uncertainties in the definition of the steady wind loading or dynamic effects due either to local gust loadings or fluctuating loadings. ...
- (c) The sensitivity of the design to minor changes in the pressure coefficient distribution was not appreciated. The important membrane stresses in the shells of towers are the resultant of compressive stresses due to dead-weight and tensile stresses due to wind uplift; this resultant tensile membrane stress, being the difference of two stresses nearly numerical equal, is very sensitive to small variations in wind uplift stresses. This effect was exaggerated by the adoption of a design philosophy which applied safety factors to the strength of materials instead of the load” [1,1,1: 17].

“For years the advocates of load factor design have lacked a practical example to demonstrate the superiority of their philosophy over the permissible stress design. Ferrybridge provided one in full measure... perhaps all the other deficiencies could have been tolerated without causing collapse if only load factor philosophy had been adopted” [1,1: 1.20, 21].

Were hyperbolic concrete towers the wrong sort of structure? Not the structure was wrong, but the wind load assumptions in conjunction with the reinforced

concrete design philosophy applied at that time. It was left to this particular structure to force this topic, not only important to reinforced concrete construction but also to the engineering sector in general, on to the agenda. For the time being we would like to close the scene of the “Ferrybridge” play, although not without quoting the following surprising concluding remark made by the President of the Institution of Structural Engineers at the close of the symposium, alluding that one should never be certain: there was “a new approach to the problem we have been discussing – that it was the structure which was wrong. I have a deep sympathy with this view and I hope that some more naturally stable form of construction will be possible” [1,4: 4.106]. We want to keep this in mind.

## 2 COOLING TOWERS

Cooling is required to get rid of waste heat. We all apply it by sweating: wet cooling. Elephants apply it by wafting their ears for ventilation: dry cooling. Industry applies it in wet, dry or hybrid cooling systems, which finally pass all waste heat into the air.

The development of cooling systems follows the development of steam engines. Non-condensing steam engines are provided with condensers. Cooling water used to cool condensers becomes warm. Cooling systems re-cool warm cooling water thus enabling cooling water circuits to be used as a substitute for fresh water resources and this allows fresh water resources to be preserved.

In the year 1891 Klein reported on several of the stages in the development of cooling systems for condenser units. His speech before the Palatinate/Saarbrücken section of the Verein deutscher Ingenieure (VDI: Association of German Engineers) is entitled “Gradirwerke zur Wiedergewinnung des Kühlwassers für Kondensations-Dampfmaschinen und andere gewerbliche Zwecke” (Graduation works to recover the cooling water for condensing steam machines and other industrial purposes) and can be read in [7]. Klein first mentions cooling ponds or a 60 m long, 8 m wide and 8 m high graduation work for a 1500 horse power mechanical plant belonging to the “Bochumer Verein”, and then makes reference to the essay “Traité de la Chaleur” by E. Péclet, Paris 1843. In this essay, Péclet describes vessels in which metal disks or rotating mesh baskets are immersed in a liquid and are then subjected to air or an air flow causing, part of the liquid to evaporate whilst the rest cools. ... Professor Linde has perfected such vessels. ... Theissen ... made these vessels more efficient by enclosing rotating disks in a casing and blowing air passed the rotating disks at great velocity through a propeller-type fan. (Fig. 2). “The cooling

systems described here are still in direct contact with the condenser because, for example, the rotating disks are immersed in the condenser water space between the tubes through which the steam flows and consequently they are referred to as “condensers with evaporative cooling.”

Klein then continues: “I started out from the generally recognized perception that hot soup can be quickly cooled by blowing it. If water is dispersed in very thin extensive films and air is continuously blown passed these at a velocity of some 6.5 m (/s), then a high level of cooling must be achieved.” Based on this, Klein constructs a square timber box, 1900 mm long, 1300 mm wide and 7500 mm high in which he suspends 6m long timber plank walls at intervals of 10 cm; hot water runs down both sides of these planks and a strong air flow is blown in laterally by a propeller-type fan. The plank walls are arranged in two groups, one above the other and at right-angles to one another. The cooling apparatus described by Klein can be broken down into the following sections one above the other (from top to bottom, see Fig. 3):

- (a) the water distribution and ventilation level,
- (b) the cooling pack (the laminar planks),
- (c) the air injection or inlet section and
- (d) the collecting basin for the cooled water.

In conclusion, Klein then reports: “The cooling apparatus can also be constructed without a fan and perform the same service provided that the cooling surface area is five times greater than the area provided when using a fan. The air adopts a rapidly ascending motion as it heats up. These simplified graduation works are now being used more frequently because there is normally enough space out-of-the-way of the machinery house for the cooling apparatus which is to be enlarged.”

Klein, Johannes, 1845–1917, set up the company Klein, Schanzlin und Becker in Frankenthal in 1871, now KSB.

On 1 October 1894, Hans Joachim Balcke, born 1862 in Oberhausen Rhineland, together with Otto

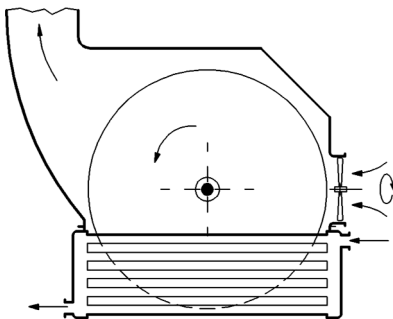


Figure 2. Theissen's condenser with evaporative cooling.

Kleinschmidt, established the company Balcke & Co. in Bochum; in 1905 it was transformed into Maschinenbau AG Balcke. The reason for setting up the company was to launch the chimney cooler on the market as the first natural draught cooling tower. After completing his studies at the Institute of Technology in Berlin-Charlottenburg, Balcke was employed for a time at the pump-making factory Klein, Schanzlin & Becker A.-G., Frankenthal.

In a special catalogue for water cooling towers from Messrs. Balcke & Co. from the year 1905 we can read: “Water cooling plants serve to redress a lack of water for manufacturing purposes by constantly recooling a small available existing volume of water. This primarily involves water to operate condensation systems. Whilst in the early years mechanical draught cooling towers and free-standing structures with brush-wood or lattice fill were used without exception, the chimney coolers which we invented and introduced in 1894 now enjoy general superiority. Chimney coolers are cooling towers with artificial ventilation through a stack-like superstructure, the chimney. Their functioning is not affected by the wind as is also the case with the mechanical draught cooling towers”. And in a certificate we can read: “We are pleased to

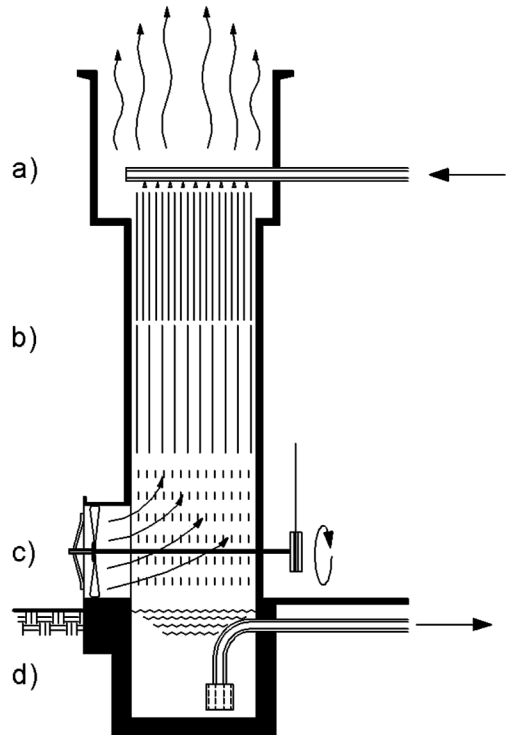


Figure 3. Cooling apparatus as described by Klein, 1891.

certify that we are up to now very satisfied with the output of the chimney cooler installed underground at our works which was commissioned in December 1896. Your chimney cooler receives general approval due to its pleasing appearance compared to other similar systems" (Fig. 4).

The objective of chimney coolers i.e. the natural draught cooling towers now entering the stage, is not to achieve the lowest temperature possible, but to continuously discharge waste heat into the atmosphere at the lowest possible cost and at a temperature level which permits the use of cheap materials. The new cooling tower can be divided up into the same superimposed sections as the cooling apparatus previously described by Klein but it has a significantly higher ventilation space above the water distribution and a cooling pack with a greatly reduced thickness. Not only does this save the cost of operating the fan, the cost of pumping in the water to be cooled is also significantly reduced due to the lower distribution level. However, as also reported by Klein, a significantly larger cooling surface or larger cooling pack is required which naturally has to be enclosed by the chimney. Whilst previously a fan drew the cooling air into the cooling tower and forced it out of the cooling tower again via the descending water and the cooling

pack, the weight differential between the colder air column outside the cooling tower and the plume column in the chimney now serves to power the cooling air flow and to overcome all types of resistance which oppose it: the natural draught cooling tower as gravity machine. Its drive force or uplift force depends on the height of the actual air columns outside or inside the chimney structure and additional resistance in the cooling air flow has to be offset by additional chimney height.

The market stimulates the development of steam machines and generators to provide electrical energy and consequently the spread and further development of natural draught cooling towers which, within a very short period, have started appearing in industrial areas throughout the world in widely varying shapes and made of all available and suitable materials such as timber, steel and reinforced concrete.

These developments involve the scientific permeation of the heat transfer phenomenon in conjunction with the invention of high-performance and at the same time low-cost cooling packs on the one hand and with low-cost production of the required civil engineering components on the other, i.e. in particular the chimney structures which are constantly increasing in size.

If the primary aim in developing a cooling pack is its efficiency in relation to the transfer of heat from the cooling water to the cooling air which takes place through radiation, convection and evaporation and which is always connected with a certain residing time for the water in the cooling pack, then the flow resistance for the cooling air should not be too great, otherwise the chimney structure would have to be heightened in order to compensate for the pressure drop. The extension and the thickness of the cooling pack which are determined by the thermodynamic design of the cooling tower for a specified performance at the given boundary conditions, including the geographic and climatic conditions at the site, should be as small as possible, not only to minimize material and erection costs but also because the diameter of the chimney structure depends on this as does the level of the water distribution which in turn influences the pumping costs. The static structure of the cooling pack is also of significance because this in turn determines the type and the cost of the support structure: the reason for this is that the entire area of the cooling pack together with the water distribution system has to be spread out at a relatively high level. In our previous definitions and also in the following description, we perceive the cooling pack as a flat cake over which the cooling water is uniformly distributed and in which the trickling cooling water and the ascending cooling air meet in counter-flow. Both the items considered and also all the other correlations can, however, easily be transferred to a so-called cross-flow cooling tower.

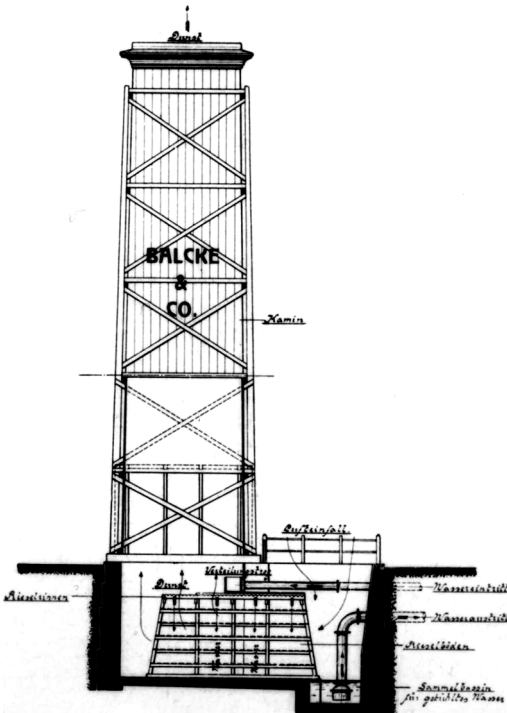


Figure 4. Balcke chimney cooler installed underground, 1896.

The development of a low-cost chimney structure is a purely civil engineering issue. The diameter at the height of the cooling pack (and here we simply assume a circular layout of the cooling pack which is, of course, the optimal shape in larger units) as well as the overall height above the collecting basin for the cooled water has already been determined in the thermodynamic design taking into account also certain other conditions. The overall height of the cooling tower includes the heights of the air inlet into the cooling tower up to just below the cooling pack, a height from there to almost the water distribution level and from that point to the upper edge of the chimney structure. The latter height determines the uplift force.

We now have all the elements required for a fully functional natural draught cooling tower whose chimney initially comprised a prismatic timber structure like the cooling tower illustrated in figure 4, later for larger diameters, a cylindrical steel lattice structure with timber planks which was first based on the concept of gas tanks (Fig. 5), and subsequently the reinforced concrete cylinder previously used for liquid tanks. Figure 6 shows such a cooling tower dating from 1952 with a cylindrical diameter of 53 m and an overall height including circular foundation of 75 m. The wall thickness of the cylindrical shell is 24 cm [8].

Now, however, the cross-section of the plume at the outlet does not have to be the same as the lower cross-section which results from the size of the cooling pack. That is not only unfavorable from a structural engineering point of view but also because of the cost of this part of the structure. Statically it is in any case better to select a smaller outlet diameter which means that the upper chimney section is more rigid and its wall surface is reduced. And as far as the cooling tower function is concerned, it is possible to set the outlet velocity of the plume at a level at which cold air inrushes are prevented by the impetus of the plume by selecting an appropriately sized outlet cross-section [9]. If the plume outlet opening is smaller, the plume velocity in this area must be increased somewhat, this, however, requires additional power from the gravity machine, i.e. a higher chimney.

In the same way it would be possible to reduce the thickness of the cooling pack by increasing its diameter. The velocity of the cooling air in the cooling pack would be reduced somewhat as would the flow resistance in this section. As less power is required for the cooling air flow, the result could be a reduction in the chimney height.

In the case of a natural draught cooling tower, it is unfortunately not possible to compensate the additional flow resistance generated by the throat at a lower level by subsequently widening the cross-section again. This has frequently been attempted but it has not been possible to prove the success of this measure.

The geometry of the chimney structure of a natural draught cooling tower can therefore be described with the parameters (Fig. 7)

- HAI height of air inlet,
- HWD height of water distribution,
- HTOT total height of chimney structure,
- DSYS system diameter,
- DMIN minimum inner diameter of the chimney

whose values are determined for a specific application using a thermodynamic design calculation; this means that the chimney structure can be designed in a variety of proportions whilst the cooling tower performance remains the same.

As it is not possible to calculate the technical optimum for a cooling tower, only an optimum in relation to overall costs: when designing a cooling tower, in particular a natural draught cooling tower, it is necessary to toy with these parameters which at a first glance represent the geometrical dimensions of the chimney structure but which in fact conceal the characteristic features of the selected cooling components

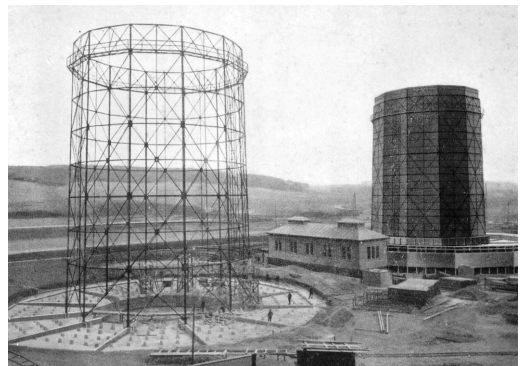


Figure 5. Steel girders for cross flow chimney coolers.

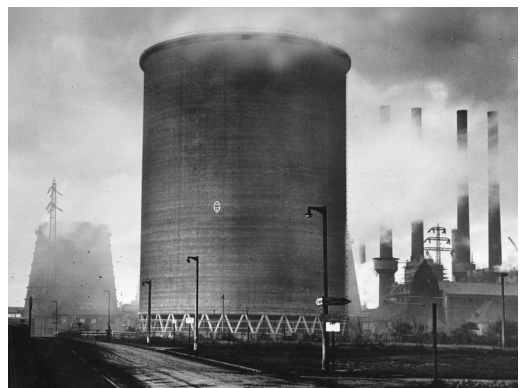


Figure 6. Concrete cylinder for chimney cooler, 1952.

as well as certain specified requirements. For example, the quality of the cooling water or the assumed wind velocity at the location or the topographic height of the construction site or the material/work cost ratio or specific requirements in respect of noise immissions of the cooling tower or of flue gas imissions in case of an integrated flue gas discharge can lead to completely different proportions of a chimney structure. By merely modifying the height of the chimney structure (HTOT) of a cooling tower designed for a certain output, to any height e.g. in the range of 140 m to 230 m and simultaneously adapting the parameters DSYS and DMIN, it is possible to construct a variety of different towers for practically the same overall cost, as illustrated in detail in [10].

Early constructions in the then still novel material, reinforced concrete using the familiar shapes from concrete constructions such as frames, domes and cylinders provide interesting examples of the variety of designs for chimney structures and natural draught cooling towers and also of the endeavors made to reach a low-cost solution for a cooling tower by toying with the aforementioned parameters, in particular the diameters DSYS and DMIN. These examples are taken from a classic of German reinforced concrete literature, namely the book “Der Eisenbetonbau, seine Theorie und Anwendung” (Reinforced concrete construction, theory and practical application) by Emil Moersch, 1926 [11]. Moersch, Emil, 1872–1950, is author of the theoretical part of the paper published in 1902 by the company Wayss & Freitag A.-G. under the title “Der Eisenbeton, seine Anwendung und Theorie” (Reinforced concrete, practical application and theory), and helped to lay the foundation for the scientific and technical discipline of reinforced concrete construction. In 1907, Mörsch is the sole publisher of the third edition of this book entitled

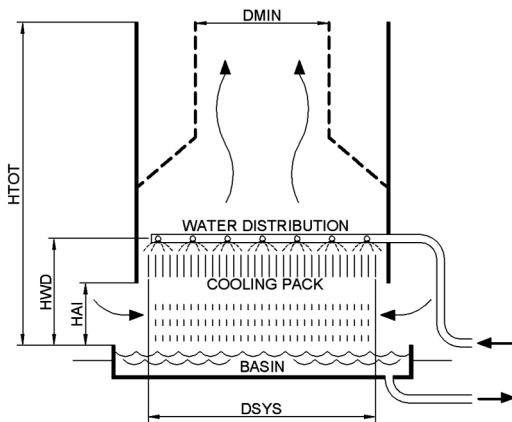


Figure 7. Cooling tower design parameter.

“Der Eisenbetonbau, seine Theorie und Anwendung” (Reinforced concrete, theory and practical application).

In the chapter headed “Cooling Towers” Moersch writes that Figure 8 “refers to the cooling tower built as early as 1904 at the steel works in Differdingen. This consists of a cylindrical substructure which stands on the outer wall of the collecting pond and which has air openings in its lower section. Above that is a dome which supports the slightly tapering shaft with a diameter of 7.5 m at the bottom and 7.0 m at the top resting on a compression ring. At the top outlet, the shaft is braced with two intersected transverse walls. The internal cooling fill support structure hardly extends into the dome; therefore the inherent weight and the wind pressure are the only loads acting on the reinforced concrete structure.” The 14 cm thick dome and the 15 to 12 cm thick shaft wall each have two layers of reinforcement. The building has an overall height of 35.5 m above ground level.

Figure 9 shows other examples of this astonishing structure in which both the five parameters of a natural draught cooling tower are handled excellently

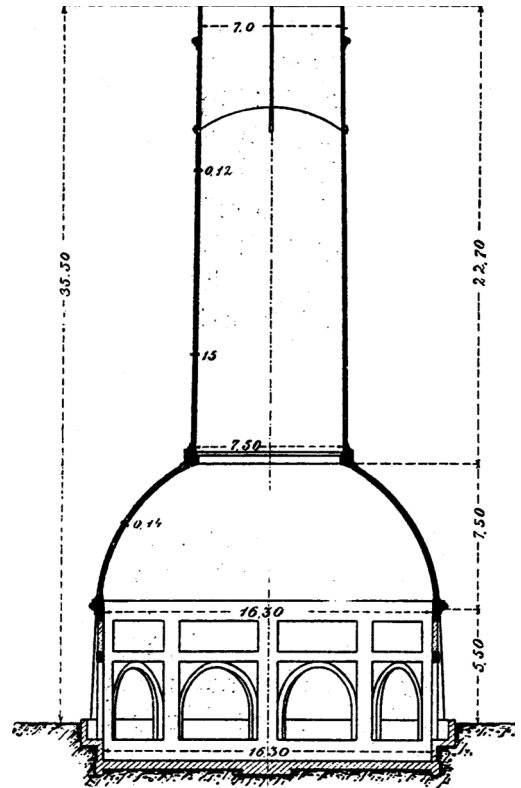


Figure 8. Cooling tower for the steelworks Differdingen, 1904.

and also handed-down or recently developed architectural and reinforced concrete construction elements are brought together somewhat unscrupulously to meet the terms of reference: the dome with the extended skylight or cylindrical shells on a multistorey reinforced concrete skeleton structure. Moersch also describes other structures for cooling tower chimneys in the chapter “Cooling Towers”, e.g. chimneys which are shaped like a 12-sided polygon to enhance the appearance and whose massive walls bear the wind loads in the manner of a folded plate system. Or a single-storey polygonal reinforced concrete framework or simply concrete columns merely fixed to the foundation on which prismatic or conical steel girders stand, these initially clad with timber and later with asbestos cement sheets (Fig. 10). Nothing is written about developments in the neighbouring country in which the abdicated German Emperor found refuge a few years earlier.

If one compares the described chimney structures which permitted the respective cooling towers to achieve their guaranteed performance, they all have one thing in common despite their various differences (with the exception of the cooling tower in Fig. 5): a design pattern is established which divides the building into a lower wet section with water distribution,

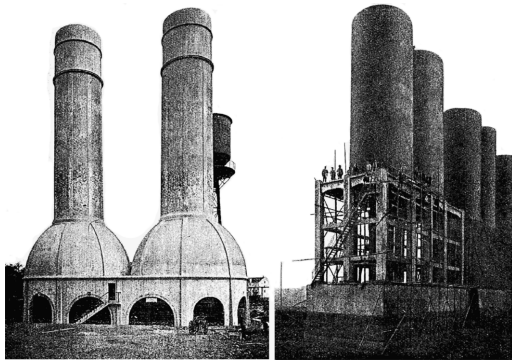


Figure 9. Cooling towers with cylindrical shafts [10].

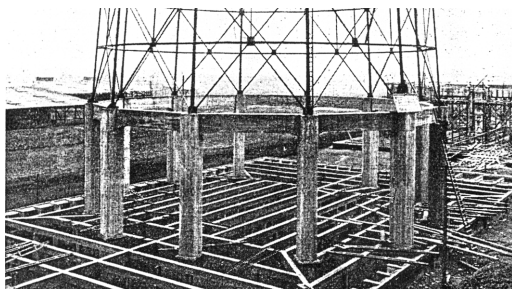


Figure 10. Steel girder chimney supported by concrete frame.

cooling pack and rain zone and the internal support structure and basin in reinforced concrete and an upper plume section with the chimney which constitutes the motive power of the gravity machine and which can, it seems, be built using materials such as steel and timber. For the time being, that is definitely a coherent design concept.

If we go on to consider the actual structures built completely of reinforced concrete such as the “cooling dome” dating from 1904 and the “cooling cylinder” from 1952, these certainly do not have the potential to adapt easily to the emerging requirements in the market for larger cooling units. Their future perspectives are limited. If the cooling cylinder’s claim, to be a cost-effective solution seems implausible, then the awe-inspiring cooling dome raises doubts as to whether the set task can be coherently resolved with the selected material, reinforced concrete. One could say that the design problem is clearly defined, many trials and solutions are available for analysis; even the development of steam-powered machines and steam turbines indicates clearly on the horizon the call for larger cooling units; the time seems right for a coherent design concept.

### 3 THE INVENTION

In the first decade of the 20th century, a very modern hard coal mining operation was started up by the Dutch government in the Dutch region of South Limburg following appropriate developments in the neighbouring mining areas of Belgium and Germany and the successful opening of a private mine. The “oppidum” of Heerlen became its centre and gave modernity a specific style. Exemplary buildings representing 20th century architecture sprang up in both the private and public sector with residential estates, administration buildings, cinemas and departmental stores. The mining companies also come forward with future-oriented visions. Monumental works of art illustrate progress in educational and ecclesiastical buildings.

For the civil engineers at the state-owned mine, building with reinforced concrete has top priority. The technology and the builders of the premises are teamed up with the commercial management and given equal status. Basic materials and talent are available in the mining district.

Events in world history such as the First World War give rise to a rapid and appropriate development of the mining operations along with their premises including the respective municipal infrastructure. The previously small place with a history reaching further back than the Roman period extends far beyond its boundaries and becomes the most modern town in the Netherlands.

The thirteen mining companies and private businesses in the rapidly growing Dutch mining district with its four state-owned mines and the only private mine proves a strong force of attraction for entrepreneurial talent of all kinds, whether it be workers without mining experience or those who have perhaps been trained for assignments in the colonies. A modern-style administration sector becomes established in the centre of the mining area. All in all, a selective pool of talent is building up which will be spoken of for generations to come.

One of the most outstanding personalities in the region at this time was undoubtedly Frederik van ITERSON who, on 1 January 1913, assumed the function of director at the Dutch State Mines at the age of 33 years. This enterprise was in the midst of an extensive development phase and offered the engineer in the civil service, responsible for the bank-head installations a wide scope of work.

Following the establishment of the Dutch State Mines in Limburg in 1902, the first two collieries, Wilhelmina and Emma, named after the then regent and her mother, started to produce coal in 1906 and 1911 respectively. Construction on the shafts for the Hendrik colliery, named after Queen Wilhelmina's husband, and the Maurits colliery (Prince Maurits 1567–1625, son of Willem van Oranje) got underway in 1911 and 1915 respectively with coal first being raised to the surface in 1918 and 1923. [12].

Frederik Karel Theodoor van Iterson was born on 12 March 1877 in Roermond, the son of Gerrit van Iterson, inspector, and Aghate Henriette van Woelderren. On 24 December 1910 he married Jennie Wouters Rotgans, with whom he had two daughters and a son [13].

His parents having moved to 's-Gravenhage in connection with work, he started school there and subsequently enrolled at the Polytechnic College in Delft. In 1899 he graduated as an engineer, having studied there successfully for four years.

Professional experience at an excavation works in Guadalquivir and as an engineer at the municipal gas works in 's-Gravenhage as well publication of his first article in *De Ingenieur* (in the period from 1900 to 1950 he penned 115 articles for domestic and international magazines) and also the way he had drawn attention to himself during his years of study contributed to his reputation as lecturer at the Polytechnic College. In his inaugural speech made on 3 November 1910: "De beteekenis van de leer der sterkteberekeningen bij het tot stand brengen van ijzerconstructies en haar waarde voor de vorming van de ingenieur" (The significance of stress calculations for steel structures and their value in the training and education of engineers) he expresses what was to remain the basis of his thinking.



Figure 11. F.K. Th. van Iterson 1877–1957, picture from 1935.

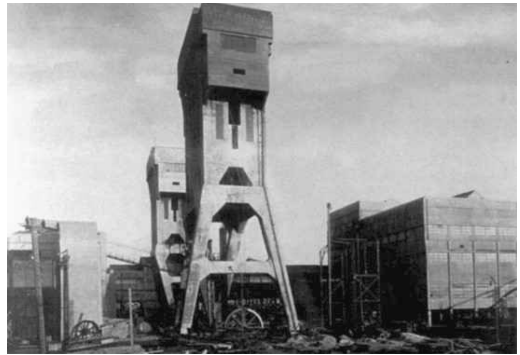


Figure 12. Concrete shaft towers for pit Maurits, 1915.

From the very beginning of his service at the Dutch State Mines, he was very involved in the efficient use of coke oven gas as well as the use of waste coal to generate electricity in boiler houses especially designed for the purpose. He exercised a marked influence on the planning work for the collieries then under construction by ensuring that for the first time reinforced concrete towers were designed and built instead of the conventional steel structure shaft-head towers. Whilst the hammer-head type tower built at the Hendrik colliery provided a completely new architectural profile in the mining landscape, the two

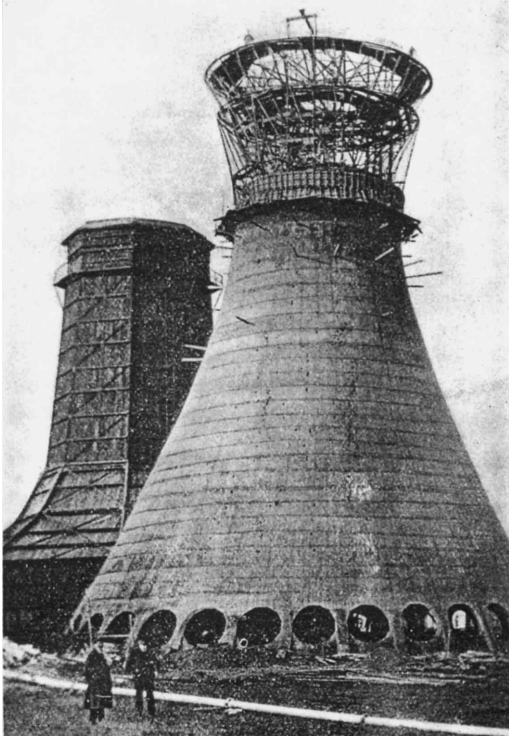


Figure 13. The first van Iterson Tower at pit Emma, 1918.

towers built at the Maurits colliery, their frame-type structures resting on three points, were excellent representatives of the new civil engineering techniques using reinforced concrete. An attitude definitely becomes apparent which pushes aside long established principles, replacing them with new ideas in a self-confident manner.

In February 1915, it was found that the octagonal cooling tower “I” constructed in steel structural work with timber sheathing could no longer meet the increased thermal load requirements at the Emma colliery (the left-hand tower in Fig. 13). The cooling tower had been supplied by the German company Louis Schwarz & Co A.G. from Dortmund-Brackel, which had developed this type of tower between 1911 and 1914 with a constricted chimney outlet and vertical supports in the air inlet section. Having obtained details for the construction of a second cooling tower, the possibility of also using concrete to construct cooling towers was raised at the Schlesische Elektrizitäts- und Gasaktiengesellschaft. It was then that van Iterson started his own project. On February 12, 1915, the management of the Dutch State Mines give their approval for a new cooling tower with a concrete chimney according to the ideas of their colleague van Iterson.

Emmen writes 1962 [14]: “On page 436 of Cement 13 (1961) No. 8 there is a photograph depicting a number of cooling towers, including the first two cooling towers made of reinforced concrete which were built as thin-walled shell constructions. They were designed and built in 1917–1918 by Bureau Kuypers under contract for the Dutch States Mines based on the van Iterson–Kuypers system.

I noticed that the text printed alongside the photograph indicated that these towers mark the introduction of the hyperbolic type structure, without this construction being referred to as a ‘shell’. At the time I was employed as an engineer at Bureau Kuypers and consequently involved in the design and construction of the two towers; I therefore remembered that the text sections in inverted commas could not correspond to the facts ... I recall as if it were yesterday that van Iterson attempted to investigate the possibility of building a cooling tower of reinforced concrete comprising a ‘thin concrete membrane’ based on the principle of an ‘eggshell’. In this attempt, he was guided by the reasoning that a cooling tower built of reinforced concrete must be more cost-effective than the conventional timber constructions which entail high maintenance costs due to the many damaging influences to which the timber is exposed. Van Iterson also stated that he had already sent the same proposal to two other companies, both of which claimed that it was impossible to build a cooling tower in this manner.

With his third attempt, van Iterson was successful; a cooling tower was designed and constructed in the form of a thin, shell-type rotational hyperboloid. Bureau Kuypers was responsible for the project and the execution. The hyperboloid shape is chosen partly because it is considered to have a beneficial effect on the supply and discharge of the air used to cool the water and partly because the reinforcement could be installed without bends ... because the main reinforcement is positioned parallel to the describing straight lines of the hyperboloid.

The towers were built during the First World War when both skilled labor and material were in short supply. In Heerlen, however, the circumstances were particularly favorable because the government regarded it to be of a national importance that plants connected with the Dutch State Mines should not be impeded in any way in order to ensure the coal supply, and consequently qualified personnel and the necessary material were available there; ...

To ensure the reliability of the hyperboloid shell, it is necessary to install single base bracing at the upper edge. Therefore the upper edge is shaped in such a way that deviations from the circular shape can be virtually excluded and the gradients of the meridians are guaranteed to be constant. Reference can be made to the drawings for more details” (Fig. 14).

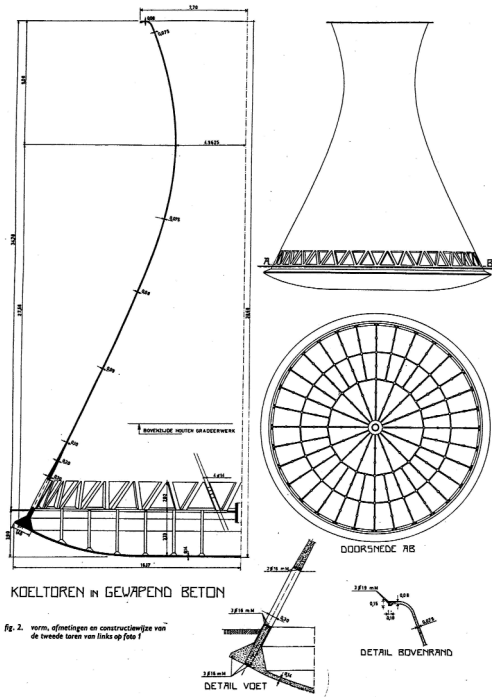


Figure 14. Sketch of the 2nd van Iterson Tower at pit Emma.

In his article, Emmen presents the second of the first two cooling towers (the one with diagonal supports in the air inlet section) as a “true copy of a former accurately revised drawing from my archive as far as geometry, dimensions and details are concerned.” According to Emmen’s sketch the dimensions of the cooling tower are:

- HAI ~2.0 m,
- HTOT ~34.8 m,
- DSYS ~27.4 m,
- DMIN ~10.0 m and DMAX = 32.34 m.

The basin depth is 3.2 m. The shell wall thickness starts at 30 cm and reduces gradually to a minimum thickness of 7.5 cm. The shell reinforcement consists of dia. 6 mm horizontal bars spaced at intervals of 20 cm at the shell bottom and gradually increasing to 50 cm at the shell top. The meridional reinforcement bars are placed both sides of the horizontal bars following the two straight generator lines of the hyperboloid.

“The construction is not based on a calculation. Dimensions and reinforcement are intuitive and based on constructive discretion determined as an estimate, taking especially into account the influence of wind.”

We assume this report to be an authentic eyewitness account, corroborating the fact that this revolutionary invention can be definitely attributed

to the inventor Van Iterson. It is therefore only logical not to omit the final paragraph of Emmen’s rectifying article in order to gain a picture of him as a design engineer and contemporary bystander:

“To state this (that no calculations were carried out for this construction, Author, pers. comm.) is in no way meant to imply that theoretical investigations and calculations are superfluous; in my opinion, it is on the contrary, to be regretted that more thought is not given to theory and calculations than is generally the case ...

If one were to be confronted with the same problem nowadays instead of in 1917, that is to build a shell-shaped cooling tower for the first time, then one would now be able to resolve the problem much more easily and with greater certainty than at that time, thanks to the many theoretical investigations carried out over the past few years; but to exactly determine the static status of the structure would, however, also today not be possible as it was not possible in 1917.”

van Iterson had visited Bureau Kuypers in the year 1915. On December 14, 1915, G. Kuypers offers the design and construction works for the new cooling tower to the Dutch State Mines and as a result of the discussions between van Iterson and the four years younger civil engineer G. Kuypers we find the British patent 108,863, the Convention Date (Holland) of which being August 16, 1916. The complete specification of the patent refers to the “Improved Construction of Cooling Towers of Reinforced Concrete”:

*“We, Frederik Karel Theodoor van Iterson, of Heerlen, in the province of Limburg, The Netherlands, Engineer, and Gerard Kuypers, of No. 1, Sleepersvest, Rotterdam, The Netherlands, Engineer, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:-*

*This invention relates to cooling towers of reinforced concrete. Cooling towers as hitherto constructed of wood alone or steel alone, have the drawback that they are not able to resist the action of moisture.*

*Existing cooling towers of concreted iron, that is to say, concrete reinforced with iron or steel bars or expanded metal or other such reinforcements, although able to resist the action of moisture, are however, very expensive to construct; for example, because their dead weight and the pressure of the wind in the case of storms, necessitate very costly preventive measures.*

*The object of the present invention is to provide an improved construction for cooling towers of reinforced concrete wherein, instead of supporting the dead weight and providing for resistance against the pressure of the wind by means of separate supports on the outside walls, or by beams, buttresses, ties or other reinforcements, the walls are constructed without any*

such reinforcements and are enabled to withstand pressure of the wind and support the dead weight of the structure.

The mere omission of all beams, buttresses, ties and so forth does not solve the problem of economically constructing a useful cooling tower of reinforced concrete, but is necessary to build the wall in such a manner that, in the first place, there are no points in the wall where the internal stresses either direct, in consequence of the construction of the walls at the points, or indirect in consequence of the construction at more distant points of the wall surface, are too great, and that, in the second place, there is no danger owing to the shape of the wall, of the occurrence of direct or indirect unequal expansions of the structure caused by hardening, temperature and moisture. This would endanger the whole structure.

The present invention consists in a cooling tower of reinforced concrete, characterised by the feature that the wall, for its entire height or the greatest part thereof is not provided with any separate support or reinforcement such as by means of buttresses and so forth, and that the wall surface for its entire height or the greatest part thereof is of double curvature in form and that the thickness of the wall varies gradually, and that the wall is of a flowing shape or form in outline.

The wall may be reinforced at any necessary openings therein, that is to say, the upper and lower edges of such openings may be made thicker or provided with a strengthening border or edge or the metal reinforcement may be of stronger iron or steel bars in order that they may withstand extra strains at these places. In this way, the wall will consequently obtain greater rigidity and strength so that the strains or stresses which the cooling tower has to withstand will not result in fracture or cracking.

In the same manner as an egg-shell the form of wall according to the invention is of unexpected rigidity and strength, although built with a minimum use of material with the result that the construction is extremely economical.

The invention is illustrated in the accompanying drawings in which Figures 1 and 2 are vertical sections of two different forms of cooling tower constructed according to the invention.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to be performed, we declare that what we claim is:-

1. A cooling tower of reinforced concrete characterised by the feature that the wall for its entire height or for the greatest part thereof is not provided with any separate support or reinforcement such as by means of buttresses and so forth, and that the wall surface for its entire height or the greatest part thereof is of double curvature in form

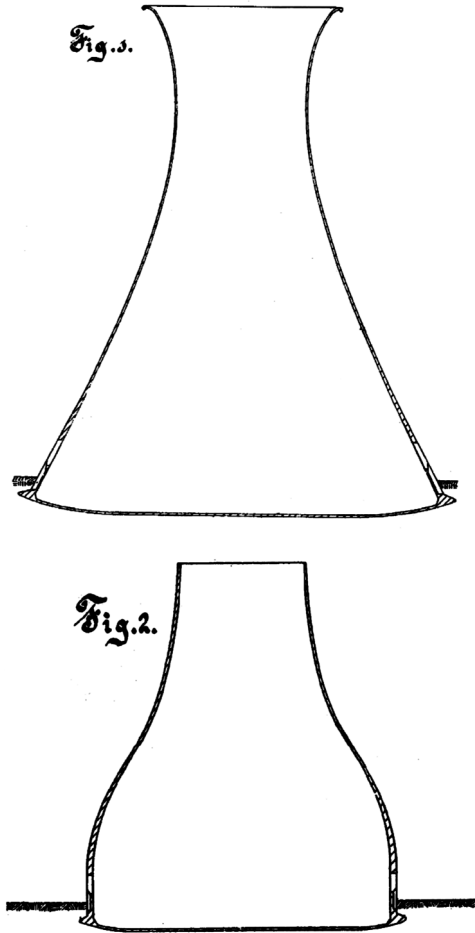


Figure 15. Illustrations from Patent van Iterson/Kuypers.

and that the thickness of the wall varies gradually and that the wall is of a flowing shape or form in outline.

2. The improved construction and form of cooling towers of reinforced concrete substantially as hereinbefore described and as illustrated in the accompanying drawings.

Dated this 9th day of August, 1917.  
Marks & Clerk”

“That the wall is of a flowing shape or form in outline” and that the DSYS/DMIN ratio of the cooling tower shapes depicted in the patent specification, a ratio which corresponds to that of the steel/timber cooling tower illustrated in Figure 13, reveals the work of a cooling tower expert which van Iterson proves himself to be, for example in an article published in THE ELECTRICIAN, 1920 [15], from

which both Figure 13 and the reference to the patent specification quoted in full above were taken.

And as principal, he reveals his identity by the fact that, in using the shape depicted in *Figure 2* of the patent specification, he ensures that there is enough space for a cooling tower with a large DSYS on a small plot of land. And it is indeed possible to identify early on such bell-shaped towers on aerial pictures of the collieries in the region; for example at sites where the area designated for the cooling units is restricted at one point by railway line previously in existence. However, with this contour he also traces that of the steel formwork tower whose supports in the air inlet section simulate a cylinder.

It should be added that the scale attached to the figures in the patent specification records that the hyperbolic tower has a height of approx. 38 m and an area of approx. 33 m.

It is obvious from the more or less truncated cone-shaped base of the depicted tower and the curvature which gradually increases as the tower rises that the tower contour can best be described as a hyperbola. In fact it must have been an exciting process when – perhaps during design discussions at Bureau Kuypers – the tower was given the hyperbola contour and the choice of rotational diameter produced a single-sheet hyperboloid in which reinforcement rods then represented the materialization of the two opposite groups of straight generator lines. The form was given a formula. A caricature drawn based on reports of eye-witnesses and showing van Iterson demonstrating these features of his invention using woolen threads illustrates how fascinated van Iterson himself was by the actual application of a conic section which had only existed in theory up to then. We do not wish to deprive any well disposed readers of this illustration of the sensation of pleasure experienced by an inventor (Fig. 16).

Comments on his invention by van Iterson himself can be found in an early publication dating from 1919 [16] and in a paper from 1946 [17].

In the article dating from 1919 which is based on examples from steel vessel construction, we read “experiments were made with a model constructed of thin sheet iron. The crumpling load obtained was remarkably high, greatly exceeding all expectations.” In theoretical derivations of the structural conditions of the cooling tower shell, he uses the Eiffel Tower as an example and in a diagram (Fig. 7 of the article) he illustrates the pattern of membrane stresses in a horizontal section under horizontal wind loads. In this diagram shown in Figure 17, the understanding or misunderstanding of these structural conditions becomes obvious because the membrane shell under wind load does not react like a beam in a state of bending. It was, however, already made clear in the first chapter, that it had been possible to carry out appropriate stress analyses for the Ferrybridge towers.



Figure 16. v. I. demonstrating the straight generator lines.

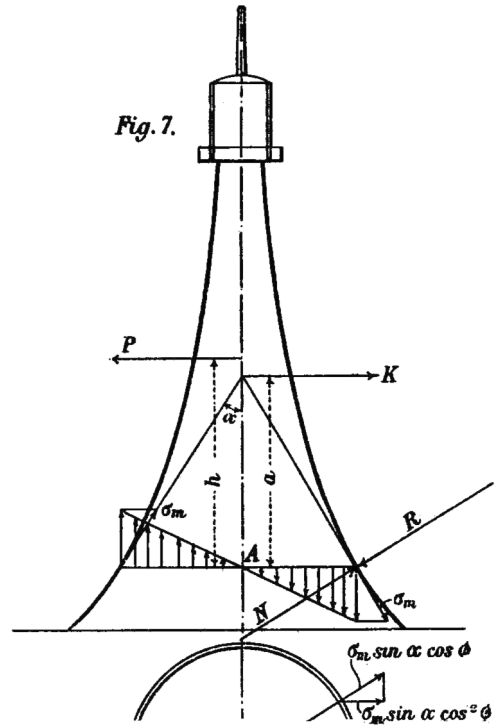


Figure 17. Stresses due to wind loading by v. I.

In a paper from 1946 it is stated: “We shall now deal with the incentives which led to the construction of the unifoil concrete cooling towers, which in the first place were invented on behalf of the exigencies prevailing at the Dutch State Mines, where the building site is subjected to subsidences. ... From experience and theoretical investigations on gasholder frames and other three dimensional frame-work we were aware that mantle-like frames open at the top may follow uneven subsidences of their foundation and we soon were conscious that the same freedom of coactions exists in thin walled unifoil structures open at the top, as we had long ago demonstrated with gasholder tanks. We experimented with paper and tin-plate models and found our prediction confirmed. ... That our assumptions were justified has been proved in a remarkable manner. Figure 3 (of v. Iterson’s article, Author pers. comm.) shows a cooling tower at mine Emma severely deformed by soil subsidence. ... As the reinforcement of the concrete can freely bend and is not subjected to pull or compression in the sense of the shell surface, the concrete is only cracked but the structure presents no danger and still resists the strongest gales.” In Figure 18, this tower is depicted from a perspective from which it is easy to surmise the substantial twist of the shell from the curvature at the outlet level.

The paper goes on to once again discuss in detail the derivation of membrane stresses under wind load but does not contain any important new findings. “The main outline of our construction was conceived after a study of EIFFEL’s famous lecture in the French Institution des Ingénieurs Civils on his tower of 300 meters. We also applied the underlying principle in a project of masts 300 m high proposed during the First World War to be built as thin walled steel shells of circular section intended for wire-less communication with the Dutch East Indies ...”

In connection with the construction of the concrete shaft for the Maurits colliery, van Iterson had already demonstrated that the foundation conditions in areas where there is underground mining have to be taken into account in the design planning. Van Iterson presented his paper in 1946. In 1953 Rabich wrote in an article entitled “Die Membrantheorie der einschalig



Figure 18. Strain-less deformation of a van Iterson Tower.

hyperbolischen Rotationsschalen” (The membrane theory of single-sheet hyperbolic rotational shells): “Hyperbolic rotational shells have already been frequently applied in cooling tower construction. In the relevant literature, there is however still neither a complete description of the statics nor the dynamics of such structures, neither for the membrane theory nor for the bending theory ...” [18]. In the beginning was the deed.

In 1930, van Iterson was endowed with an honorary doctorate for technical sciences by the TU Delft (Polytechnic College). In the laudatio given at the endowment ceremony, it was stated that his versatility in technical fields was almost proverbial. And at that very time, the foundation was being laid for a completely new field of activity at the Dutch States Mines, namely nitrogen chemistry.

The fight against rock pressure had fascinated van Iterson for a long time. When he was relieved of his function by the German occupation force in 1941, just prior to his retirement, he became deeply involved with the problem. Lectures on this topic, given at the University in Liege, were incorporated in one of his few more extensive publications entitled: “Traité de plasticité pour l’ingénieur” (1944) (Study of plasticity for the engineer) a pioneering work which was translated into several languages. And this was in Limburg during the final months of the war. In an interview, one of his daughters told how he used to cycle from Heerlen to Liege and back to give the lectures because the public transport system was in ruins. Van Iterson died on 11.12.1957 in ’s-Gravenhage.

In 1954, the Dutch State Mines start to construct a fifth colliery which is given the name Beatrix after

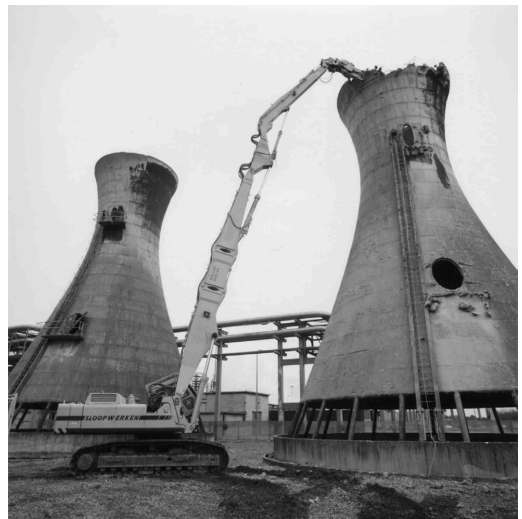


Figure 19. Demolition of van Iterson Towers, 2000.

the then crown princess of the Netherlands but the work was stopped in 1962 and never re-started. As a result of coke and coke gas production, activity in the chemical sector increases and a large chemical production complex springs up in Geleen next to the Maurits colliery. Production of chemicals rises from 1960 onwards and becomes the main business of the Dutch State Mines (DSM). In the early 1970s coal mining at the Dutch State Mines ceases completely.

Coal mining is dependent on the underground coal reserves; when these are exhausted or when it is no longer worthwhile extracting them, then the buildings no longer required soon become memorials.

The first hyperbolic reinforced concrete tower was classified as national heritage at the end of the 1970s. Despite this, it was demolished on 26 June 1985. Once the artefact had disappeared, not only was the appearance lost but also the opportunity to find the answers to present day questions from the object itself. In its day, it was a product of rational reasoning, in its construction, however, a sign of intuition and imperturbable confidence in reinforced concrete as a building material.

#### 4 THE SPREAD

In his paper of 1946, van Iterson continues: “When the idea of constructing these simple shells free to contract and to deform in case of subsidence was first presented for execution, the prominent contractors of reinforced concrete works refused to tender. They lacked confidence in the righteousness in our contrivance for meeting shrinkage and setting stresses totally differing from their concepts. An enterprising and very competent friend of ours, the civil engineer G. Kuypers without hesitation built the first 1918 and took an active part in the development of design, shuttering, scaffolding and other details of execution. ... Kuypers in later years was worried by the patent law cases fought in England against infringement on of our patents under an absurd and costly system of procedure. In that country it was the firm L.G. Mouchel and Partners, who in the early stage of their application have shown full confidence in the exactness of our assertions. They enjoyed the benefit of their enterprise and built not only the many hyperboloids which are characteristic of the English inland power stations, but in our days they charm us by pictures of large scale application of our invention in France, Belgium, India, Germany, Egypt, Manchuria, Iran, Italy, Morocco, Rumania, South Africa and by the proofs of their lasting friendship.”

If we follow this up, then we find for example in “Beton und Eisen”, 1936, the article “Hyperbolische Kühltürme bei Hams Hall in England” (Hams Hall “A” Birmingham, Author pers. comm.). T.J. Guerritte,

senior engineer at Mouchel & Partners, Ltd., London, reports here in great detail on the design and construction of natural draught cooling towers as developed by the engineers van Iterson and Kuypers from Holland. The towers have a diameter at the height of the basin sump of 55 m and a height above the basin sump of approx. 68 m and the shell wall thickness is 13 cm over a wide area [19].

And indeed, it is the name L. G. Mouchel, which is connected with the international spread of van Iterson cooling towers. It is not the person Mouchel – Mouchel himself, born in 1852 in Cherbourg, died at the age of 56 years in 1908 – but the company, which still bears his name today and which in the meantime has attained the status of a Group. If, however, one takes the history of this company from the book “100 – Mouchel Centenary 1897–1997” [20], then it is once again Mouchel himself whose deeds become apparent in the actions of his successors.

Mouchel left France in 1875 and established himself as a successful businessman in England. A business meeting with Hennebique, the protagonist of “beton armé” in France turned Mouchel into a protagonist of “ferro concrete” in the UK. In 1897 Mouchel becomes a licensee of Hennebique and, by applying his entrepreneurial energy, soon makes ferro concrete an acceptable structural material in the British Isles. Hennebique’s ferro concrete piles are used to build retaining banks for the railway, foundations for buildings of all types, quays etc. Engineering and construction of reinforced concrete buildings, bridges and quays followed and the licence agreement is revised to reflect Mouchel’s growing independence. In 1900, at the instigation of Hennebique, T.J. Guerritte joined Mouchel; he was later to become the longest serving director of the company (41 years). We have already become acquainted with Guerritte from his publication quoted above. Even after the death of Mouchel, the particular achievements in the field of reinforced concrete construction remain the distinctive mark of the company Mouchel. Concrete boats during the First World War and floating pontoons for the Mulberry Harbours in the winter 1943/1944 in preparation for the invasion in the Second World War deserve special mention.

Many patents are concerned with the application of reinforced concrete and there are inevitably patent disputes, e.g. with Coignet or, as reported above, with van Iterson and Kuypers.

“In 1924 a development of very great importance to the firm took place. T.J. Guerritte approached the City Electrical Engineer of Liverpool with proposals for a new type of concrete cooling tower to replace the timber towers used at power stations up to that time. The Dutch State Mines at Harlem (Heerlen, Authors per. comm.) had developed a circular concrete tower narrowing to the top with holes at the

ground level to allow the passage of air. The walls were built to a hyperbolic curve which also allowed the sloping reinforcing bars to be straight.

With the knowledge of the success of these towers in Holland, Guerritte persuaded the City Engineer to appoint Mouchel to design twelve ferro-concrete cooling towers for the Lister Drive Power Station, Liverpool. These Towers were 14 1/2 inches thick at the base, reducing progressively to 6 1/2 inches at the top. They were 130 feet high, and 100 feet in diameter at the base. (And they were still in use 40 years later, as already mentioned in chapter 1, Authors pers. comm.) Large as these were at the time, they were small compared to later cooling towers to be designed by Mouchel which rose to 500 feet in height, and 400 feet diameter at the base.

Mouchel therefore pioneered the design and introduction of ferro-concrete cooling towers in the United Kingdom, and maintained a commanding hold on this area of construction for the next 40 years, both in this country and overseas.

Over the next 40 years Mouchel would go on to receive 366 commissions for over 600 cooling towers. Of these commissions, 157 would come from UK, 78 from South Africa, 50 from India, 26 from Italy, 22 from France, 8 from Belgium, 4 from Germany, 4 from Egypt, 3 from Romania, two each from Luxembourg, Southern Rhodesia and China, and one each from Poland, Hungary, Algeria and Morocco.”

Limburg in The Netherlands was the first cooling tower land, i.e. a landscape with the hyperbolic shape marking the skyline of an industrial area. Now, with Mouchel’s help a global landscape appears with van Iterson towers as the symbol for power generation in particular or for industry in general.

The history of the spread of the van Iterson towers, based on the example of the company Mouchel, takes us right up to the Ferrybridge period. We do not wish to elaborate on this history and are therefore obliged to omit describing many significant developments, e.g. that of scaffolds and shutter systems or naming numerous outstanding persons and companies in many countries. That would exceed the bounds of this paper.

A comparison of the number of completed cooling towers which are included in this report, for example the 241 towers built in England and mentioned in the Report of the Committee, with the figure of 157 indicated in the Mouchel brochure or of the figure of approx. 130 towers which we estimated based on data given by Bosman in [4] with the number of 78 also indicated in the Mouchel brochure, shows that in the meantime international competition existed both in respect of services in this field and also in respect of ideas, for example, if one takes account of the fact that the Ferrybridge towers built by the company then known as FCT (Film Cooling Towers (Concrete) Ltd. [2: 8] only differed slightly from the van Iterson

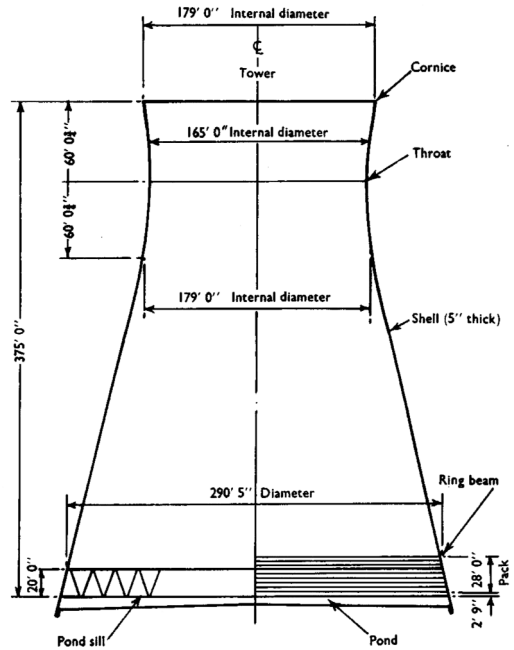


Figure 20. Geometry of the Ferrybridge cooling towers.

concept in respect of their geometry, although somewhat more as far as their static characteristics were concerned (Fig. 20). At the Ferrybridge Symposium it was therefore ascertained “that cone-toroids are more sensitive than hyperboloids to changes in pressure distribution” [1,2: 1.57].

These non-hyperbolic cooling towers of the conical/toroid type, such as those also built in South Africa based on Bosman’s data [4], were according to the company FCT [2: 35]- given their geometry “for constructional simplicity”. We are rather of the opinion that this was merely a case of evading the patents of van Iterson and Kuypers.

No, instead of delving more deeply into the history of the spread of the van Iterson towers, we would like to consider a remark made by Volker Hahn, former member of the management board at Züblin, which is quoted in the book “Züblin, 100 Jahre Bautechnik 1898–1998” [21] (100 Years of Civil Engineering).

We have not yet identified the 4 cooling towers which the company Mouchel claim to have supplied to Germany. In a report in the magazine “Beton- und Stahlbetonbau” 1950 [22] it is, however mentioned, that hyperbolic concrete cooling towers were introduced in Germany in 1938 by the company Wayss & Freitag working together with Maschinenbau-Aktiengesellschaft Balcke, Bochum and that by the

end of the war (1945), 21 hyperbolic cooling towers had been built in central Germany. As can be seen from the illustration given in this paper, the widening in the upper sections of these towers is only minimal and they have a distinct stiffening ring on the outside. The report mentions that the shell which is 10 cm thick in the upper section has a reinforcing network of horizontal and vertical bars both inside and outside. We are familiar with the details of the Ferrybridge towers built 20 years later.

And here we would now like to quote Hahn in [21] who, when comparing the pioneers of reinforced concrete construction, Hennebique and Monier, says: "Different as were the assumptions made by Monier and Hennebique, and different as were the paths they took, these were nevertheless pursued in a similar manner. Monier encountered important men such as Gustav Adolf Wayss, Mathias Koenen and Emil Moersch. Hennebique met Prof. Wilhelm Ritter and engineers like Eduard Züblin in Strasbourg (and here we must now add L.G. Mouchel in London, Authors pers. comm.). ... When Züblin came into contact with ferro concrete in the 1890s, there were two systems in Europe, the Hennebique construction method used in France, Belgium, Italy, England and Switzerland and the Monier construction method found in a belt extending from Germany through Austria to Hungary."

It was certainly not a conscious oversight in Hahn's presentation, of a smaller European country but rather a lack of knowledge or the difficulty of classifying what had happened in the field of reinforced concrete construction during the building of the bank-head installations for the Dutch State Mines in Limburg, the Netherlands. After all that was said at the Ferrybridge Symposium, thoughts increasingly focus on the fact that van Iterson's invention of the hyperbolic concrete tower, because of its peculiarities inevitably led to the linking of the two reinforced concrete hemispheres described by Hahn.

When analysing the spread of the hyperbolic reinforced concrete cooling tower, we notice its reserved introduction in Hahn's Monier hemisphere. One can assume that the development of a very successful cooling tower with an induced draught fan whose casing also comprised a reinforced concrete rotational shell with a very distinct DSYS/DMIN ratio (cylinder-conoid-conoid), can be attributed to this. However, the block output of this cooling tower was restricted by the fan diameter; this is not so in the case of the natural draught cooling tower thanks to the adaptability of the hyperbolic concrete shell.

Also the fact, that the natural draught hyperbolic cooling towers enter the USA at a relatively late date compared to other countries is due to fan assisted cooling towers being very successful in this country.

## 5 FERRYBRIDGE AND AFTER

It is certainly not poor engineering practice to repeatedly question issues which do not belong in generally recognised categories; for example in the case of the hyperbolic concrete tower, whether it is the right sort of structure. And that is how the comment made by the President of the Institution of Structural Engineers at the close of the first cooling tower symposium should be understood; this also applies to the following comments which briefly describe some development steps of the hyperbolic concrete tower since "Ferrybridge".

It was not long after the Ferrybridge collapse that the question of very much larger cooling towers was raised in connection with the steam turbines for nuclear power stations in view of the lower steam temperatures or, to an even greater extreme, when dry cooling is used for such plants. A size limit for hyperbolic reinforced concrete towers was seriously established and this led to a hyperbolic chimney structure based on a cable net construction being designed and built for a nuclear power station with dry cooling. When the nuclear power station was decommissioned, there was a discussion as to whether this novel construction should be preserved. The first cable net cooling tower was, however, demolished but one of the original knots is still in the possession of its creator, being an important detail. After this episode, the question of a size limit for hyperbolic concrete towers was for the present out of discussion.

Subsequently there was a call to reinforce or to dynamically adjust these large shells in a better manner using horizontal stiffening rings in addition to the top ring in the chimney outlet for chimney constructions of more than 165 m in height, also for nuclear power stations, and this call was heeded. Research work carried out on horizontal and vertical stiffening which is no doubt of value. This has been proved time and again when it comes to reinforcing dilapidated shells. As already said, the overall cost is in the end the decisive factor and consequently shells with larger diameters and/or heights were built without stiffening rings, even for significantly higher wind loads.

All further developments were only possible because in the years since "Ferrybridge", all the faults detected there have been and are still being systematically reconsidered. And had it not been for the rapid development of electronic calculation techniques and the development of efficient elements and theories to model the structures or for the results obtained in in-situ or in wind tunnel testing, it would under no circumstances have been possible to take such construction decisions.

When reading current publications: "Observed damage effects for RC cooling towers can be validated numerically by (a) nonlinear strategy. Hereby,

unloading and reloading, constrained forces and moisture gradients are taken into account. Subsequently, models can be derived where the actual load bearing behaviour is considered ..." [23], then we are reminded of the question posed at the first one-day symposium on natural draught cooling towers: "The influence of loss of stiffness and increase of deformation on stress must be studied." [2,3: 11].

Or if we read another recent publication: "It can be stated that the best possible load-bearing behaviour can be achieved when the curvature of the meridian increases continuously from the base lintel to the throat, and continues above the throat without any drastic change." [24], then we are reminded of the wording in the van Iterson/Kuypers patent specification: "and that the thickness of the wall varies gradually and that the wall is of a flowing shape or form in outline."

Overall these examples show that this particular structure constantly brings many people very close together in their thinking over a very long period and that the time is approaching when the following wish could be fulfilled: "If it were possible to design cooling towers on the basis of collapse, the collapse wind speed could be used directly in design" [2,2: 19] and that it is not necessary "to draw the maximum value from (an) incident by regarding it as full-scale experiment" [1: 1.1–6].

If hyperbolic concrete towers today appear in a bright light in the skies of engineering structures, then this is certainly not through their own power nor through the creative power of their inventor but because many engineers and scientists from various fields are constantly generating energy for this light.

Nevertheless it would be appropriate and correct from a historical point of view to have these engineering structures designated "van Iterson Tower" (as is normal practice in some countries), even detaching them from their link with the cooling apparatus. One would then have a definite designation for a concrete tower which not only covers the contour of the original, but also other bell-shaped structures built and alluded to in the patent document. There would then be van Iterson towers with a pure hyperbola as a contour or with a contour composed of hyperbola sections (there are many of these) or with an abnormal or cone/toroid contour etc. It would also permit a more precise differentiation in the technical and scientific discussion as to whether the features of the concrete tower or those of the cooling apparatus are to be discussed. In this way the door should be opened to make the investigations previously carried out on this structure available for applications other than cooling towers.

This designation could also express the commitment of all those who are interested in participating in the preservation of the brilliance of this object.

## 6 CONCLUSION

The hyperbolic concrete tower was invented in the year 1915 as a chimney structure for a natural draught cooling tower by the engineer F.K. Th. van Iterson and built for the first time as a one-sheet hyperbola on the premises of the state-owned colliery Emma near Heerlen, Province of Limburg, in the Netherlands in 1917/18 with van Iterson as the principal and Kuypers as the contractor.

A patent application filed in 1916 by van Iterson and Kuypers describes the invention as a reinforced concrete rotational shell in most cases with a double curvature with both completely negative and also partially positive Gaussian curvature in the lower shell section.

The collapse of such towers in Ferrybridge, Yorkshire, UK, in the year 1965 during a storm which was not particularly severe not only reveal the lack of knowledge about the effects of wind on building structures but also a fundamental weakness of a design based on a global safety factor.

The analysis of the spread of these cooling towers not only shows up two hemispheres in the development of reinforced concrete which can be linked to the two protagonists of this method of construction, Hennebique and Monier but also the competition between the civil engineering based natural draught cooling tower and a special mechanical engineering based ventilator cooler.

The authors are of the opinion that the engineer van Iterson deserves a place of honour amongst the protagonists of reinforced concrete construction for the introduction of a new body in the architectural and civil engineering field.

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## Heitkamp: 40 years' experience in cooling-tower construction

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**ABSTRACT:** Since the beginnings in 1964 with the dry cooling-tower in Ibbenbueren, the building company Heitkamp, with nearly 90 cooling-towers, has influenced the planning and building of these impressive shell structures considerably. The largest cooling-tower of the world in Niederaussem with a height of 200 m can be found in our reference list as well.

### 1 COOLING-TOWER CONSTRUCTION BY HEITKAMP

Reinforced concrete natural-draught cooling-towers shaped like a hyperboloid of revolution are celebrating their 90th birthday.

The type of natural-draught cooling-tower still in use today owes its technical development to the Dutch engineers Iterson and Kuyper. It was these two engineers who designed the very first hyperbolic natural-draught cooling-towers, built in 1914 with a height of 35 m.

We can now look back on 40 years of successful cooling-tower construction.

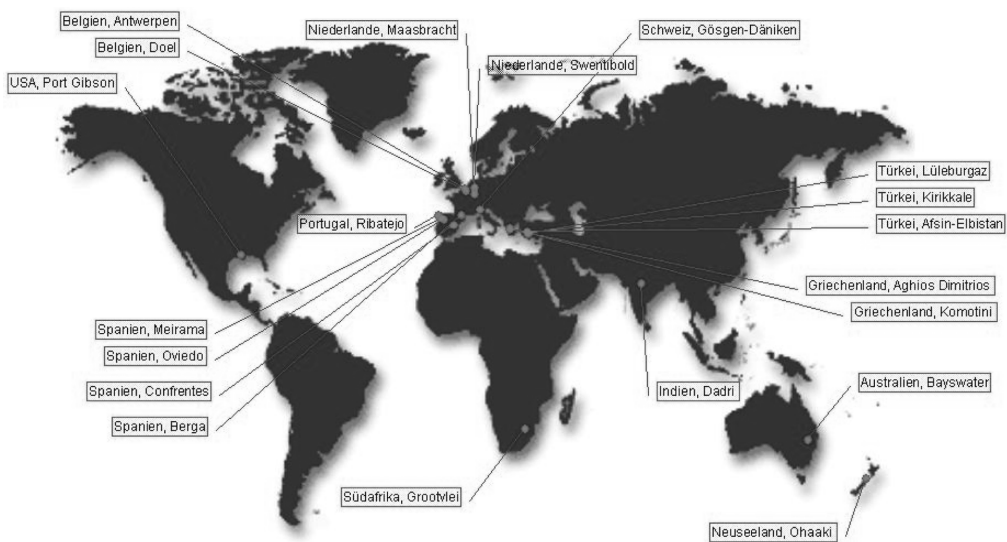
In 1964 Heitkamp built the first, almost 100 m high, natural-draught cooling-tower, breaking new ground

in Germany in the calculation, design and execution of such a structure.

Today, Ibbenbueren cooling-tower is the first of 89 cooling-tower projects on our reference list. 52 of them are located in Germany and 37 in twelve other countries worldwide.

Here in Turkey alone we were involved in the construction of 11 cooling-towers. Increasing power plant capacities led to an increasing demand for cooling water, presenting new challenges to natural-draught cooling-tower construction. The development that started was to take an even more dynamic course than the experts themselves had predicted.

By the mid-1970s, reinforced concrete natural-draught cooling-towers soaring to a height of 150 m had been built by Heitkamp.



20 years ago, we recorded our career in cooling-tower construction in an illustrated volume entitled “The way to new dimensions”. The completion of the cooling-tower for the Isar II nuclear power plant with a height of 165.50 m and a base diameter of 152.20 m meant that we had successfully completed one stage along this way in 1986.

At that time the 200 m limit was still seen as a visionary step in the development process. This step took concrete form with the construction of the natural-draught cooling-tower for the new 950 MW power plant in Niederaussem.

Last but not least, we take pride in having built this cooling-tower, currently the highest in the world with a height of 200 m, a base diameter of 143.45 m and a cooling-water flow rate of 91,000 m<sup>3</sup>/h.

This structure, which is located in the Cologne area, moreover secured for us an entry in the Guinness Book of Records.

Since the early days of large-scale cooling-tower construction, Heitkamp has been involved in working on, initiating and following up the necessary developments in terms of theory, design and process technology. Many of the structures built by us gave us the opportunity to put the latest findings into practice almost before they had left the drawing board.



Figure 1. Natural-draught wet cooling-tower with cleaned gas intake system.

The good reputation of cooling-tower construction by German companies is the outcome of outstanding cooperation between scientists, owners, thermal engineering companies and construction companies.

The individual components of natural-draught cooling-towers are basically the same for wet and dry cooling systems – except for the cooling system elements and the water supply and distribution system.

The natural-draught wet cooling-tower consists of the following components:

- foundation
- column framework
- cooling-tower shell
- water basin
- supporting structure for the cooling system elements
- water supply and distribution system.

## 2 FOUNDATION

A foundation is always meant to transfer the forces exerted at the bottom end of the column framework to the supporting soil with minimum and above all uniform settlement.

The decision on the most suitable foundation concept has to take account of these preconditions. Experience has shown that single-base foundations offer the most economically efficient solution, subject to normally admissible soil bearing capacities immediately

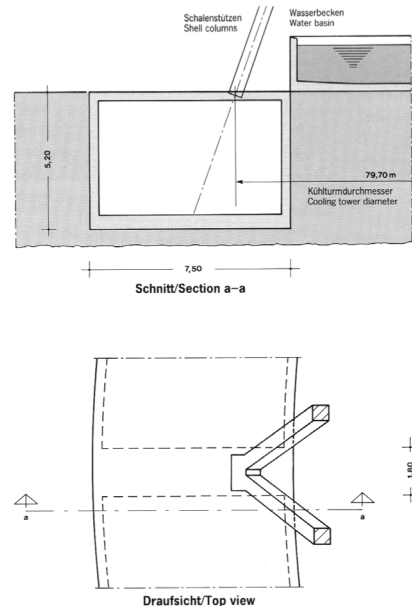


Figure 2. Floating foundation.

below the structure and consistent stiffness conditions along the circumference. Reliable proof of the safety of the ground against shear failure together with a minimum of displacement is absolutely essential for this purpose. In the event of insufficient safety against shear failure and/or excessive soil displacements, preference is to be given to the ring foundation.

If the bearing soil is encountered only at greater depths, the above-stated foundation options require additional measures such as:

- ground stabilization
- exchange of soil material
- deep-soil compaction
- gravel or ballast piles
- driven or bore piles
- floating foundation.

The “floating foundation” was selected in 1977 for the foundation of the four cooling-towers at Afsin-Elbistan.

The extremely unfavorable foundation soil conditions at the construction site permitted a shallow foundation only for lightweight, secondary structures. The bearing soil required for a pile foundation was encountered only at a depth that was no longer economically viable. The only solution for the required deformation-free transfer of the cooling-tower loads to the building ground was therefore a foundation type that would not disturb the state of equilibrium and thus the degree of consolidation of the deeper soil layers which are responsible for settlement. This demand could be met only by a floating foundation. A ring of hollow bodies with a rectangular cross section and a load-bearing transverse wall inside them was selected, with its volume multiplied by the weight of the soil corresponding to the dead weight of the entire structure.

### 3 COLUMN FRAMEWORK

The column framework must be designed in such a way that the air can flow as freely as possible into the cooling-tower and the forces exerted by the shell can be safely transmitted into the foundation. The arrangement and the number of shell-supporting columns are determined primarily by the height of the air intake openings (depending in turn on the respective thermal design criteria) and the load-bearing capacity of the foundation soil. Until the early 1990s, we placed the columns in a V- or A-arrangement for natural-draught wet cooling-towers. Today we prefer meridional columns for practical reasons. For large air intake openings, e.g. in natural-draught dry cooling-towers, column frameworks in X-arrangement have a good track record in the reduction of buckling lengths.

### 4 COOLING-TOWER SHELL

The reinforced concrete cooling-tower shell is simultaneously an enclosing and a supporting element. By keeping off the atmospheric influences the shell enables the vertical airflow to be regulated and thus a natural draught to be generated. Its main dimensions, such as height, diameter at air intake, etc. are determined on the basis of thermodynamics and fluid mechanics. Its definitive shape, i.e. the geometry of the shell’s center surface, the wall thickness curve and the dimensions of the ring beam, is specified by the structural design engineer, with factors relating to stress analysis, dynamics and structural design being taken into account.

In structural terms the cooling-tower shell consists of three sections:

- lower ring beam
- cooling-tower shell
- upper ring beam.

The first meter of the lower ring beam is mounted on the column framework as a semi-finished component and with pre-installed transfer formwork including the suspension structure and the platforms for erection of the scaffolding of the lower edge of the shell. The first four 1-m shell strips are produced from this scaffolding.

Once work on the lower ring beam has been completed and the working platforms have been dismantled, our company’s own climbing scaffolds are installed for the construction of the cooling-tower shell.

The climbing scaffold consists of climbing towers attached in pairs with three bolts to the inner and outer faces of the shell with working platforms located between them on two levels. The upper platform is used for placing the reinforcement and the formwork and for concreting, whereas the lower one is used for stripping and for curing the fresh concrete. To adapt to the constantly changing diameter of the shell, the platforms are of telescopic design.

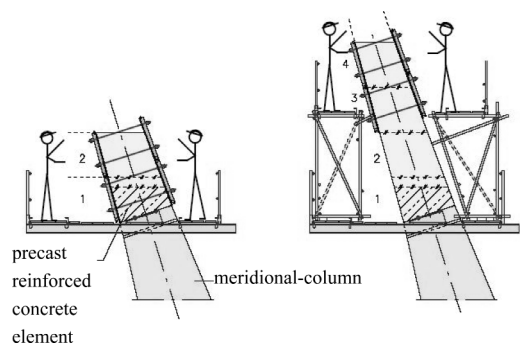


Figure 3. Lower ring beam with working platforms.

The hydraulic lifting gear of a climbing tower consists essentially of hydraulic cylinder, idler sheave and the necessary hydraulic lines.

Each step in the climbing process is controlled with an internal and an externally operated hydraulic unit.

For the actual climbing, the two top screws are slackened sufficiently to allow the tower to “travel” 1 m higher. The lower bolt is removed and is inserted as the top bolt once the specified height is reached. This procedure is repeated until the nominal height of the cooling-tower shell is reached. Attention must be paid to the system- and load-dependent cycle: tower 1 up, tower 3 up, tower 2 up, tower 5 up, tower 4 up, etc.

To allow vibration-free curing of the fresh concrete, the climbing scaffold works completely independently of the transfer formwork. The formwork consists of

two sets of forms with a height of 1 m each, the single elements of which are 50 cm or 25 cm wide plywood boards consisting of 11-ply plastic-coated panels.

As the radius changes, so does the circumferential length of the shell. In order to reduce or increase it without cutting the plywood panels, steel plates which are overlapped with the formwork panels to offset the differences are installed at the ribs.

The top ring beam is generally designed as an internal walkway. For its production, brackets are attached to anchor sleeves concreted into the shell. The brackets are used to support the working platform, which is simultaneously used as ground formwork for the walkway. The rising walls can be built with the transfer formwork elements.

The philosophy underlying this Heitkamp-specific system is one that has stood the test. It is the philosophy

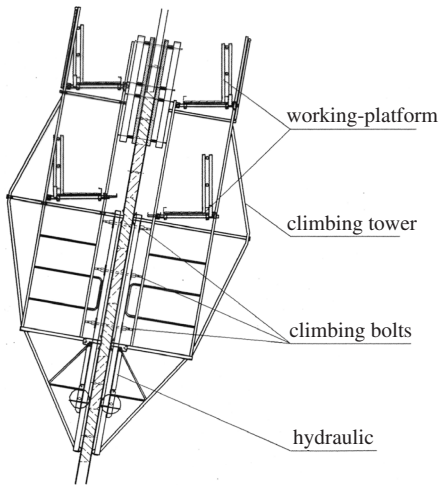


Figure 4. Inner and outer climbing tower.

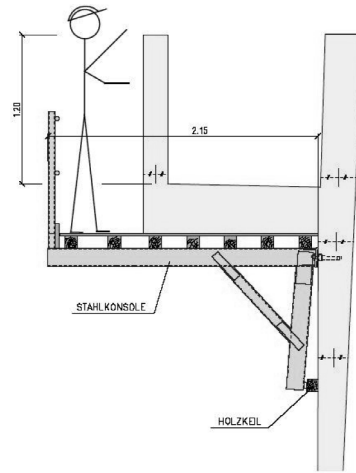


Figure 6. Upper ring beam.

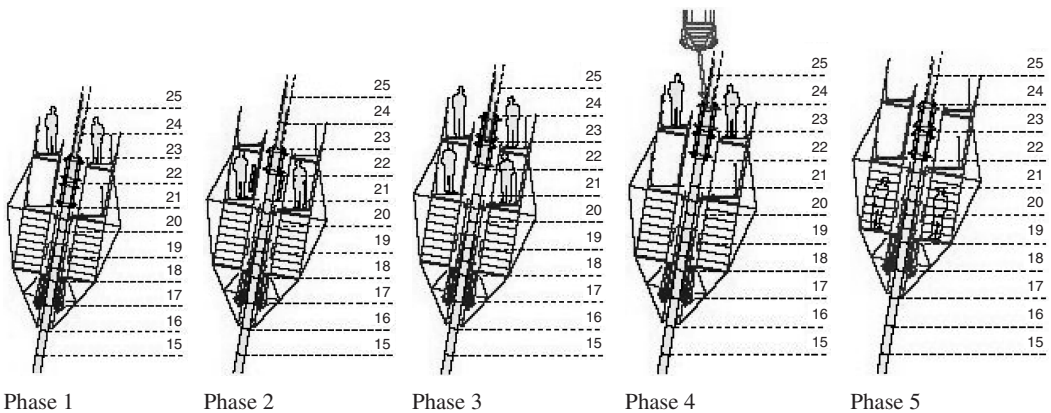


Figure 5. Climbing process.

of “small steps”, which allow individual alignment and adjustment to ensure that the objective of a top-quality structure is achieved.

The surveying work required for adherence to the shell geometry is carried out daily, immediately after concreting, and is recorded in measuring protocols. Precision surveying of the supporting structure of the shell, which is so susceptible to imperfections, remains a precondition for the construction of stable structures. Until the mid-90s, cooling-towers were surveyed one-dimensionally using an instrument plumb set up over the respective measuring mark.

Today, the cooling-tower shell is surveyed three-dimensionally, using a new measuring technique based on the alternating application of relative and absolute measurements.

The formwork is aligned to the specified inclination on the basis of relative measurements performed with an inclination spirit level, whereas a geodetic surveying network is required for absolute surveying of the shell geometry. This network consists of a number of fixed points, benchmarks, located on the column framework. Using this network, the measuring equipment – an electronic, compensator-controlled computer tachymeter – can be orientated to a free, appropriate observation point. From there, polar dimensions to the target on the cooling-tower shell are measured and stored. The target is a variable base-prism rod that enables visual obstacles to be overcome. In the case of compensator-controlled equipment, horizontal directions, zenith distances and inclined distances corrected for vertical and tilting axis errors are measured. These parameters can be used to calculate actual-value coordinates of the cooling-tower shell, from which the deviations in radius, height and lateral ribs are later computed and recorded. The measurements are performed at each 1-meter strip. The nominal inclination of the respectively following 1-m shell strip can be derived from the results.

This ensures that any necessary corrections can be executed in very small increments. At specific heights, reflex marks are also attached as reference points on the inner side. This enables the deformation of the cooling-tower shell induced by external influences to be determined if necessary once the zero points have been measured and to be taken into account if necessary in the analysis of the measuring results of the shell survey.

## 5 WATER BASIN

The water basin is required as a collecting and buffer basin for the water trickling down from the cooling system. Depending on the local ground conditions, it may be necessary to provide for an anti-capillary frost protection layer below the base of the basin.

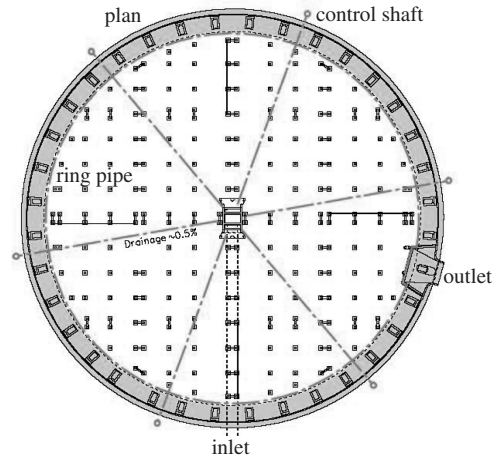


Figure 7. Area drainage system.

An area drainage system located below the base of the basin is connected segment-wise to control shafts to allow the basin to be checked for leakages.

An approach ramp is provided to permit cleaning vehicles to be driven into the basin. A fold-up construction is located in front of the discharge structure to intercept sludge. Removable precast concrete elements in the fold-up construction allow the basin to be completely emptied.

## 6 SUPPORTING STRUCTURE FOR THE COOLING SYSTEM ELEMENTS

The supporting structure for the cooling system elements consists essentially of precast reinforced concrete components joined in such a way that low-constraint individual systems result.

The supporting structure is stiffened or stabilized with supporting frames or framework systems. In individual cases, e.g. in regions prone to earthquakes, further stiffening elements may be necessary. The columns and framework stand on single-base foundations positioned in a specified arrangement on the base of the basin. The columns are designed as socketed stanchions. Horizontal loads resulting from inclinations and eccentric loads are transmitted by the beams to the framework and the riser shaft.

## 7 WATER SUPPLY AND DISTRIBUTION SYSTEM

The water to be cooled is fed to the system via the warm-water supply channels and the riser shafts, with the channels being located either on or below the base of the basin. Fiberglass supply channels, which are

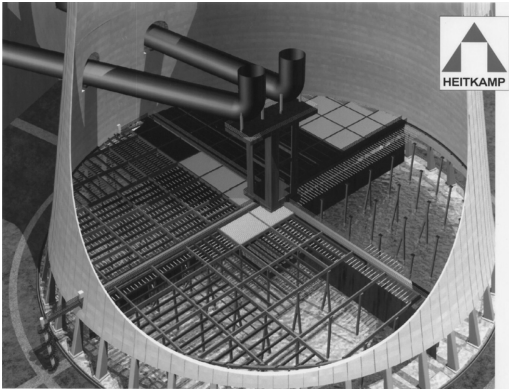


Figure 8. Supporting structure: water supply and distribution system.

located above the water level of the basin on account of the inadequate safety against foundation water pressure, have also been used. The warm-water supply channels, likewise precast reinforced concrete components, are mounted on the supporting structure. The individual precast components are joined by means of joint tape, screwed connections and sealing mortar and are connected to the cast-in-place concrete riser shaft.

## 8 COOLING-TOWERS WITH CLEANED-GAS INTAKE SYSTEM

Even in the early 1980s, Voelklingen natural-draught cooling-tower was serving the purpose of evacuating cleaned flue gases in addition to its normal function. The desulphurization system inside the cooling-tower made it necessary to install the cooling system elements in an annex structure in front of the cooling-tower, resulting in practical terms in a cooling-tower of the cross-current type.

The sulphurous cleaned flue gases in combination with the cooling-tower vapors proved to be chemically aggressive, so that an additional concrete protective layer was absolutely essential, at least for the inner face of the shell. As engineering experience relating to the resistance of concrete surfaces to specific aggression was lacking at that time, and no suitable theoretical computation-based models were available, trials were carried out with test specimens. The analysis of the test results, experience gained in stack construction, and a number of other engineering studies gave rise to the coating process still in standard use.

In today's coal-fired power stations, the cleaned flue gases are normally discharged parallel with the cooling water vapors. Intake is through cleaned-gas pipes running from the flue-gas desulphurization system

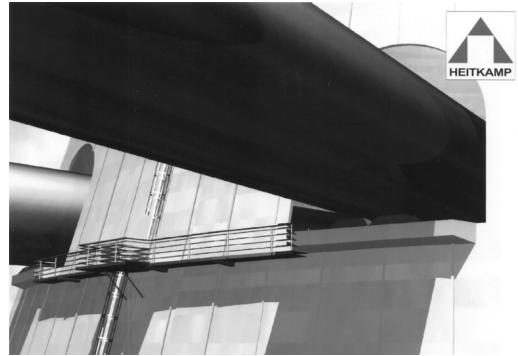


Figure 9. Cleaned-gas pipes through the shell.

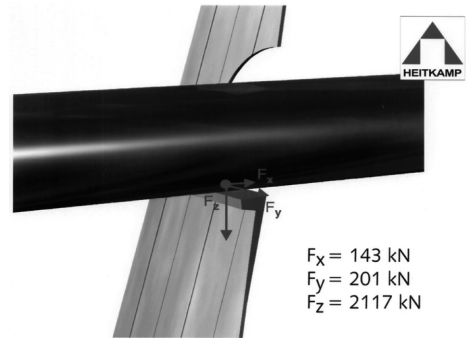


Figure 10. Fixed point at the shell.

through the cooling-tower shell to the center of the cooling-tower.

The cleaned-gas pipes are fixed to the cooling-tower shell, which absorbs the vertical and horizontal forces occurring. This makes higher cleaned-gas intake pipes, which provide for more efficient mixing of the cleaned flue gases with the rising water vapor, economically viable. Support is provided in the cooling-tower by increasing the height of the central riser shaft and equipping it with a platform for displaceable pipe support.

In the following years, concretes of strength class B 35 with subsequent epoxy resin coating to protect the concrete shell developed into the state of the art in cooling-tower construction with cleaned-gas intake.

However, the complex, technically demanding coating systems were cost-intensive in terms of the building of the structure, maintenance during the service life of the cooling-tower, and later dismantling.

In the mid-1990s, a start was made on finding alternatives to the coating, and consideration was given to the use of heavy-duty concretes. In the late 1990s this idea was put into practice in the construction