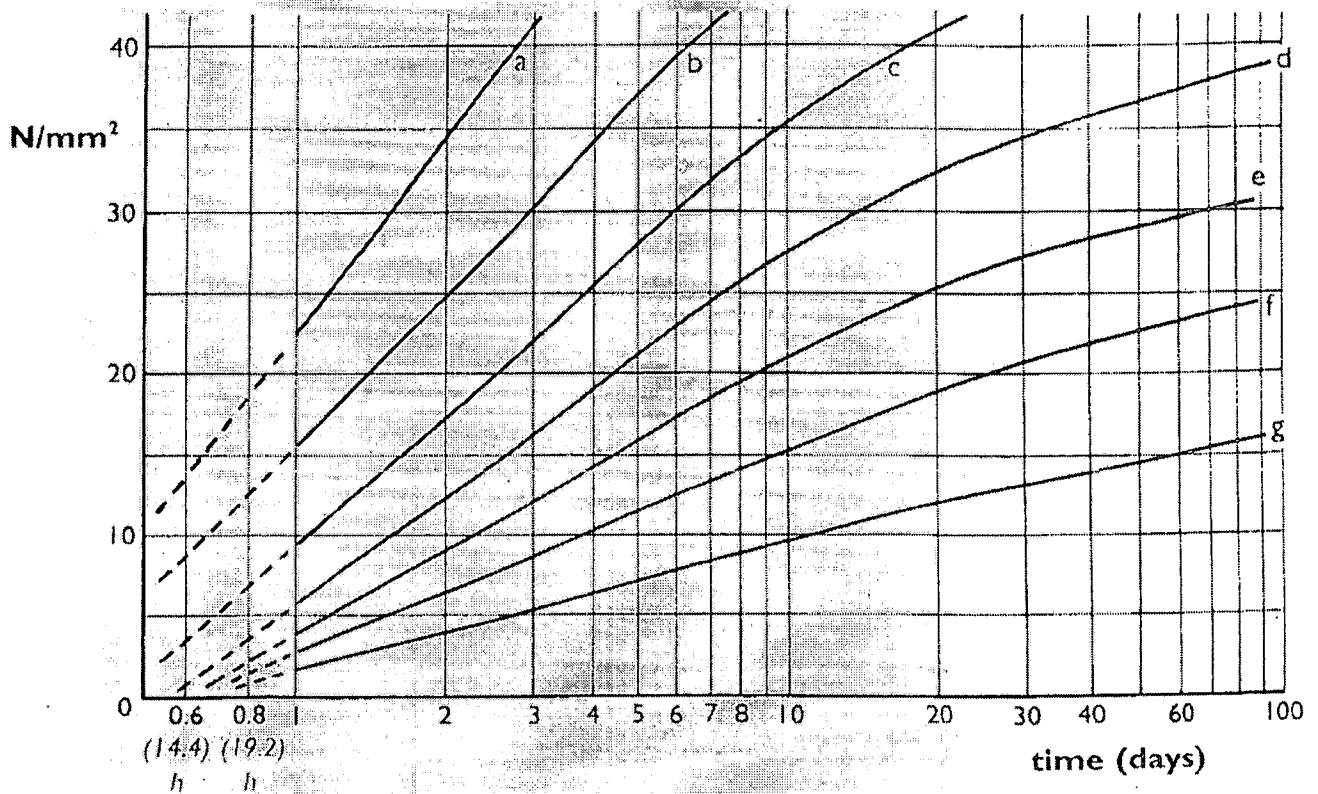
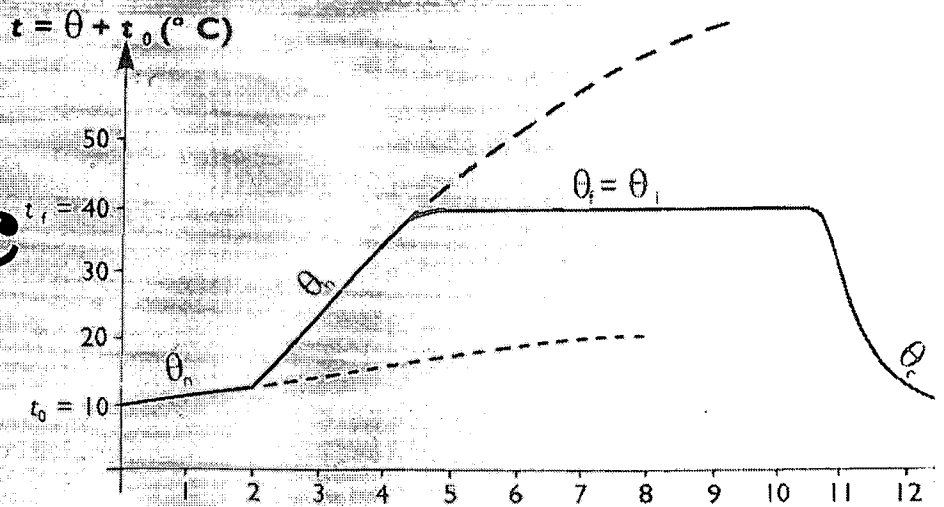


Direct Electric Curing of Concrete : Basic Design



I.D.Kafry

**Direct
Electric
Curing
of Concrete:
Basic Design**

To my sons, Adam and Yuval

Direct Electric Curing of Concrete: Basic Design

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Preface

Although the meteoric rise of concrete as a major constructional material began with the invention of the Portland Cement, its use dates back to Roman times. Those ancient master builders discovered that the volcanic ashes found around Pozzuoli (hence the name *pozzolanic*), when ground and mixed with water and sand, formed a strong and durable binding material, as found now in some instances withstanding the onslaught of the elements for over twenty centuries.

In our modern world, the study of the properties of the various cements, aggregates and their combinations with water i.e. the design of concrete mixes, became a science with fairly predictable results. However, one aspect with an important rôle in the quality of the end product remained an art, based on experience rather than exact knowledge: the curing process.

In the earlier days of the industry, when time was not yet money (at least not in today's sense) and natural curing was the order of the day, the problem may have been of lesser importance. With the advancement of accelerated curing, the situation has changed. Not only time, but energy expenditure became an important parameter.

The intention of this treatise is to bridge the gap, with emphasis on the newly developed Direct Electric Curing (DEC) method. This lends itself eminently to the quantitative establishment of the governing factors.

I gratefully acknowledge the help extended to me in my investigations by Mr A.S.Darroch, former managing director of Dow Mac Concrete Ltd., Stamford; Mr R.J.Wellman as quality control manager in the same company and Mr Miniovits, Ramat-Hen, Israel, consulting engineer to the Mediterranean - Dead Sea project.

My thanks are also due to Mr A.H.G.Jeffery, managing editor of *Precast Concrete*, subsequently *Concrete Plant and Production*, for his encouragement and publication of papers which form the basis of this book.

I.D.Kafry
Stamford

Errata

page 3, line 16	should read ...temperature <i>versus</i> loss
page 9, line 31	should read (section 2.2.2)
page 26, Fig. 10	insert T_n beneath the first dotted vertical line
page 27, line 14	should finish ...curing cycle in W, then
page 28, line 12	for (Fig. 14) read (Fig. 13)
page 30	interchange figure captions for Figs 16 and 17
page 38	interchange figure captions for Figs. 28 and 29
page 40, Fig. 32	for insulating leaf read insulating <i>seal</i>
pages 56 and 59	For calculations beginning with P_{c1a} etc, the p should be lower
page 56, line 13	for 37.7V read 37.3V
page 71 line 38 and page 72 line 5	for Q read Q_{hy}
page 75, line 13	for P_c read p_c
page 76, line 2	for 3 months read 4 months
page 78, lines 10 & 11	for 9 months and 1½ years read 1 and 2 years respectively

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List of symbols

T	time, h
t	temperature, °C
t_0	ambient temperature, °C
θ	temperature rise, °C
θ_m	maximum temperature rise, °C
θ_f	final temperature rise, °C
A	surface area, m ²
V	volume, m ³
e	base of natural logarithm (ln)
ρ	specific resistance, Ω cm
η	efficiency, %
F	cross-sectional area, m ²
τ	time constant, h
M	mass, kg
c	specific heat, Cal/kg °C
Q, E	energy, kWh
P	power, kW
k	thermal conductivity, kW/m °C
λ	coefficient of convection and radiation, kW/m ² °C
γ	surface modul, A/Vm ⁻¹
U	tension, V
I	current, A
R	resistance, Ω

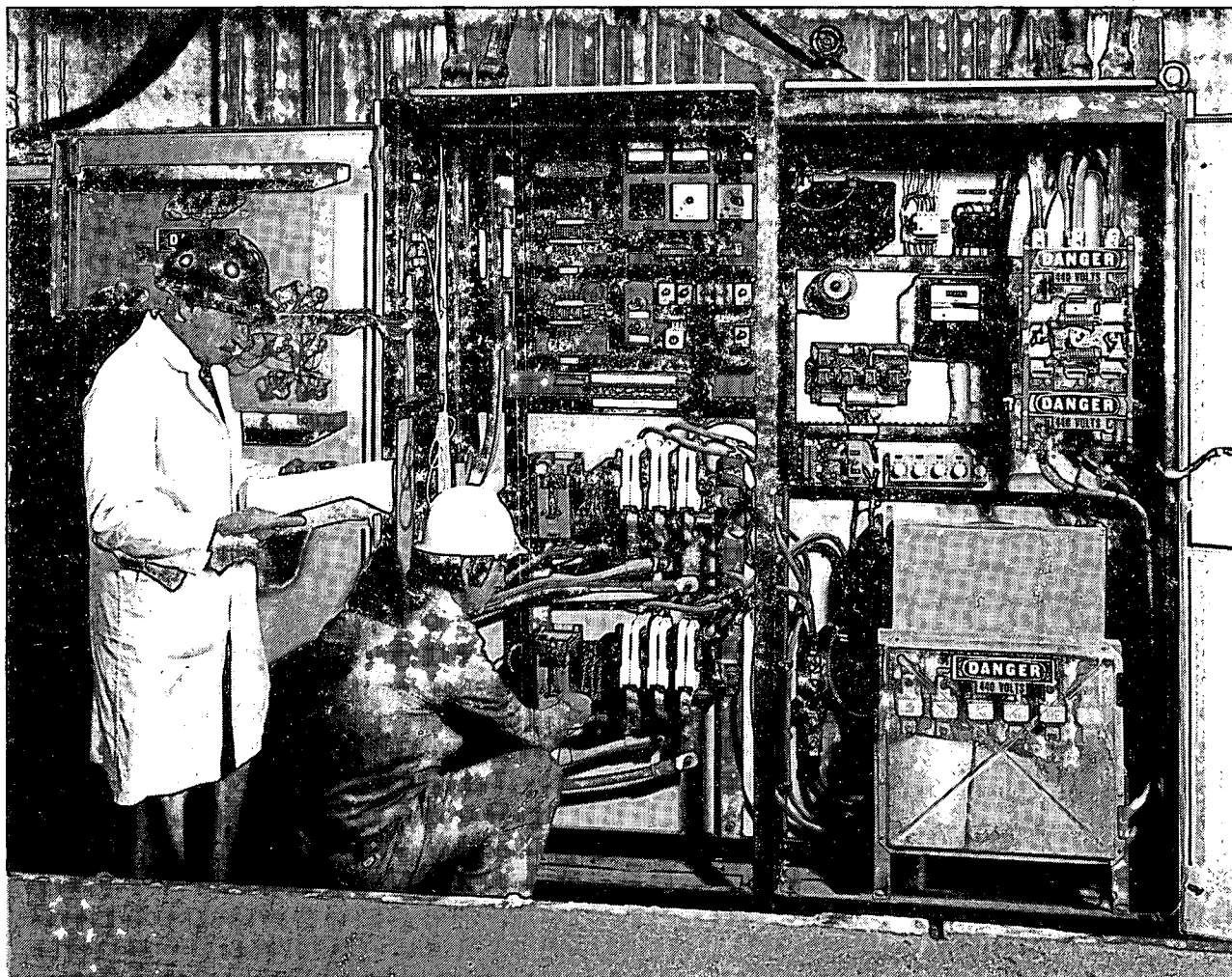


Plate 1 DEC M.V. board interior. Sleeper factory, Gloucester (Quedgeley)

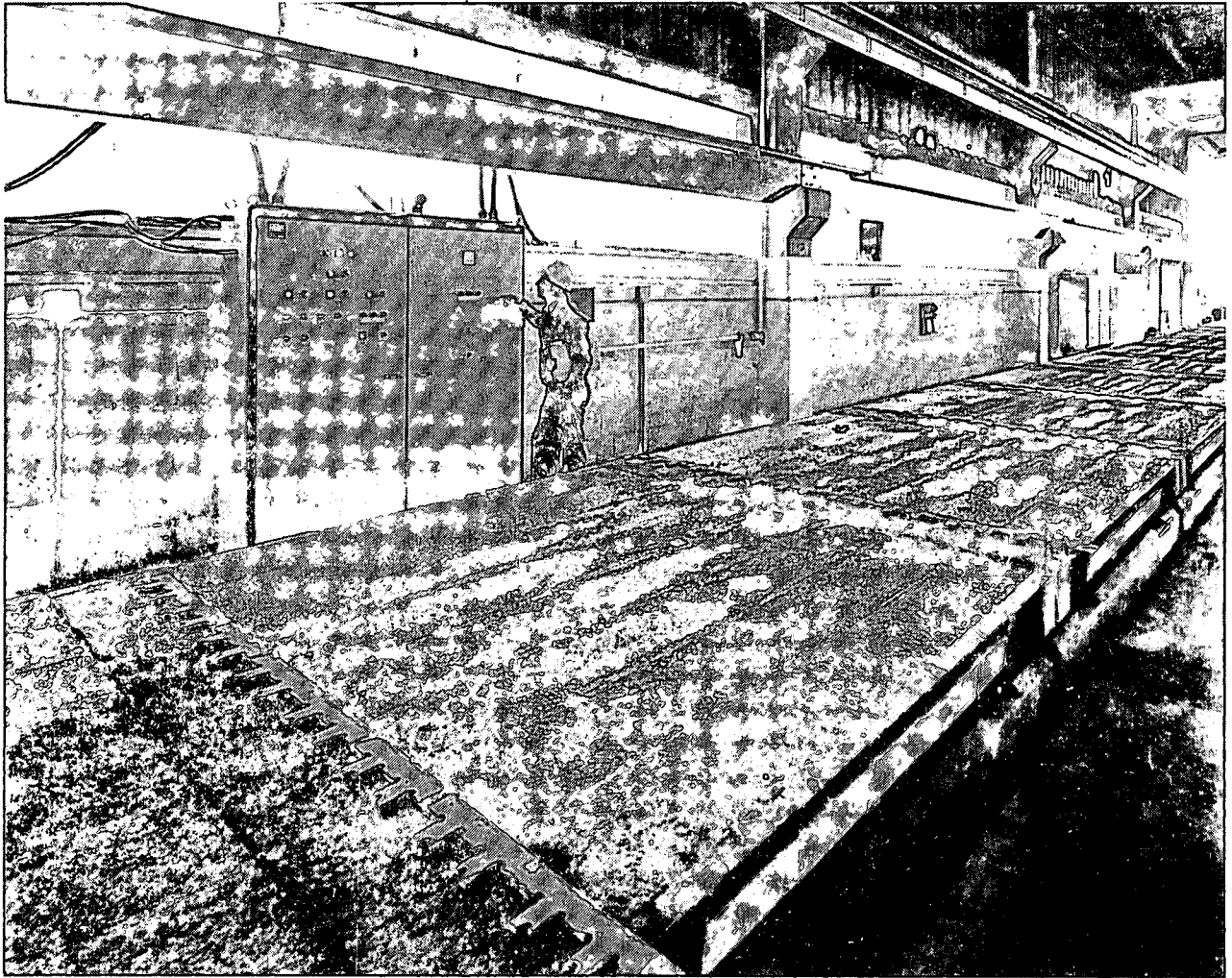


Plate 2 Sleeper casting bed with DEC boards in background (Quedgeley, Gloucester)

I Introduction

During the last 25 years, economic and technological changes have taken place in the concrete industry, greatly enhancing the popularity of accelerated curing. Its advantages and progress are most evident in the field of precast concrete production, but some forms of it have been employed successfully in on-site concreting as well.

Accelerated curing is achieved by the following two and basically different methods:-

- 1) A chemical process, in which an accelerating agent (such as CaCl_2) is added to the concrete mix.
- 2) A physical process involving:-
 - a) the application of vacuum,
 - b) the application of heat.

Method 1, the practice of using admixtures, has suffered some setbacks, because of damage caused to some concrete structures following the corrosion of the steel reinforcement by the accelerator.

Method 2a, the use of a vacuum, has been employed mainly in on-site concreting, and its primary action is to reduce the water content of the concrete after it has been placed, thereby changing the mix to one with a lower water/cement ratio.

Method 2b, thermal curing, involves the application of heat as an accelerator and is the subject of this study. Heat imparted to the concrete may be:

1. supplied from an external heat source, or
2. generated within the concrete.

To the first group belong steam curing, steam injection (hot concrete), steam heating, oil heating, water heating, the use of hot air or other gases, infra-red heating, electric pads, etc. The second group, in which heat is generated within the concrete, may be sub-divided into semi-direct and direct electric curing.

a) Semi direct methods

In the semi-direct methods, either comparatively cheap electric heating elements are embedded in the concrete mass, or the ends of the reinforcement are connected to an electric power source and the reinforcement is used as a 'heating element'. In both cases, no heat is lost directly to the surroundings from the heat source. The limitations of these otherwise very efficient methods are:-

- i) When electric heating elements are used, they are lost in the concrete.
- ii) When the reinforcement carries the current, working voltages are very low except in the case of long, continuous casting beds.
- iii) The heat energy developed in the reinforcement is transferred to the concrete around the circumference of the wires, presenting a comparatively small transfer area per unit length.

Consequently, the power levels used must be kept low, in order to prevent over-heating in the vicinity of the wires.

The semi-direct method lends itself most readily to the curing of long, slender concrete units.

b) Direct electric curing

No such limitations exist with direct electric curing (DEC). This method is based on the phenomenon that fresh concrete is an electrical conductor, albeit of rather high resistivity: 500 to 1500 ohm cm, depending on its composition and temperature. It has a negative temperature co-efficient and behaves like an electrolyte; for that very same reason, only alternating current is suitable for DEC.

DIRECT ELECTRIC CURING OF CONCRETE

The process consists essentially of passing a current through the concrete, between two immersed electrodes. As a result, heat is generated within the concrete mass, which acts as the 'heating resistor'. With a suitable electrode configuration - which may comprise parts of the mould or the reinforcement - an evenly distributed temperature rise from within can be obtained in a short time.

It is a very economical way of curing both precast and *in-situ* concrete; and especially those elements with moderate or low surface modules, and hollow units (pipes, etc.).

2 Underlying Principles

2.1 Fundamentals

During the heating of a body, part of the energy supplied raises the body's temperature, the remainder is lost to the surroundings. The efficiency of a heating method - like that of any other energy conversion - is expressed as the ratio of the useful energy to the total input energy:

$$\eta = E_w / E_T \cdot 100\%$$

where $E_w = E_T - E_L$ and E_w = useful energy, E_L = losses, and E_T = total energy.

The temperature rise of the body is a function of the rate at which heat is imparted to or developed within it, its mass and readiness to accept heat (specific heat), and the rate at which the body loses heat to the surroundings. The rate of heat dissipation is affected by the amount of conduction, convection and radiation over its boundaries. When air - or any other gas - is the surrounding medium, the loss through conduction is negligible and can be disregarded. Convection losses are determined essentially by the size of the exposed area, the quantity of air passing over it per unit time and the temperature difference between the body and the cooling medium. Radiation losses are the function of surface area, texture, colour and temperature; the latter actually in proportion to the 4th power, (Stefan-Boltzmann Law ²⁷).

However, low temperatures within a very limited range, are encountered in concrete curing, and a linear temperature loss relationship is quite acceptable for practical purposes. Accordingly, the two loss factors, i.e. those for convection and radiation can be replaced by the single co-efficient λ .

The respective equation (ideally for a homogeneous body, with uniform heat development) expressing the temperature rise of a system is:-

$$\theta = \theta_m (1 - e^{-\frac{T}{\tau}})$$

θ_m , the maximum temperature rise a body can attain within a certain set of conditions, is determined solely by the rate of its heat gain dQ/dT , and rate of heat loss $A\lambda$. The former is actually the power P supplied to or developed within the body. Thus:-

$$\theta_m = \frac{P}{A\lambda} \text{ } ^\circ\text{C}$$

τ , the 'temperature-time' constant, denotes the time required for the body to reach 0.632 θ_m (Kostenko¹⁵) and is an expression for the relationship between the system's heat capacity and heat dissipation:-

$$\tau = \frac{cM}{A\lambda 860} \text{ h **}$$

(** 1 kWh = 860 Cal.)

For concrete, P is made up of 2 components: the power supplied from an external source - which in the case of DEC is the electricity network - and the power supplied by the process of hydration.

The latter varies with time and temperature. Thus, although the total hydration heat of the cement, over a period of time, can usually be ascertained from tables or determined experimentally, hydration power as used in calculations is an artificial average quantity:-

$$P_{hy} = \frac{Q_{hy}}{T_c}$$

where P_{hy} denotes hydration power, Q_{hy} hydration heat and T_c the actual curing time.

2.2 The curing process

The curing of concrete consists of two stages: the setting and hardening processes. During setting, the concrete loses its fluidity but gains very little strength. The breaking up of a set, or partially set concrete, say, by vibration, has no adverse effect on later strength development. Strength development takes place during the second stage; the hardening or maturing process. The rate of maturity gain of a concrete product is a function of both curing time and temperature. The relationship formulated by Sadgrove and Pink²¹ is:-

$$M = T \left(\frac{t+16}{36} \right)^2$$

where M = maturity and denotes the strength development related to a similar concrete mix cured at 20 °C. (Other research workers like Saul and Nurse, Mironov and Ganin, Nykänen, etc., arrived at somewhat differing formulae, but the above seems to have a good general validity for the range of accelerated curing temperatures used.)

For example, the natural curing curve (at 20 °C) of a particular mix shows a crushing strength of 30 N/mm² developed in 48 hours. Accordingly, the maturity of the product at 30 N/mm² is said to be:-

$$M = 48 \left(\frac{20+16}{36} \right)^2 = 48$$

If we want to obtain the same strength in, say, 15 hours by accelerated curing, the required curing temperature would be:-

$$M = 48 = 15 \left(\frac{t+16}{36} \right)^2$$

$$t = \left(\frac{48}{15} \right)^{\frac{1}{2}} \cdot 36 - 16 = 48.4^\circ C$$

In practice, the value M is usually made up of 2 to 4 components, obtained during the total curing cycle, which comprises the following periods:

- a) The pre-heat storage (natural curing) period.
- b) The heating up period.
- c) The constant heat (isothermal) period.
- d) The cooling period.

We shall examine these now in some detail.

2.2.1 The pre-heat storage period

With all the conventional heating methods - except steam injection - it has proven necessary to observe a substantial natural curing time before the application of heat. This is particularly so with high strength, prestressed units. The natural curing time allows the concrete to gain sufficient strength to withstand the disruptive forces created by the application of heat.

Fresh concrete is a heterogeneous mass containing, in addition to the aggregates, cement and water, a fair amount of surplus water, and entrapped air. The coefficients of thermal expansion for aggregates and cement are of the same order of magnitude, but for water it is roughly 15 times, and for air 200 times, higher. Once the heated concrete starts gaining strength but not yet enough strength to counter the forces of this differential expansion, permanent voids are being formed from within, resulting in reduced later strength.

With DEC, the concrete can actually be heated during the casting without unduly heating up the mould. This causes the differential expansion to take place predominantly during the fluid-plastic stage, allowing the entrapped air to escape without any residual effect, and driving the surplus water to the surface. However, with very dry mixes, the length of the casting time should be carefully considered. In addition, the delayed application of heat usually permits a better energy exploitation scheme, by deferring the heating power peaks to periods of low power demand in the factory.

Thus, whether the pre-heat storage period is to be omitted or not, should be considered on its merits for each case.

2.2.2 The heating-up period

This is, of course, an essential stage for any accelerated curing process. The heating-up time should be minimised to conserve energy and render the process more economical. This endeavour is, however, curbed by the following considerations:-

a. Admissible heating rate

For the reasons explained in section 2.2.1, once the hardening process has started, the heat flow administered must be kept to a level where the forces of expansion develop at a slower rate than the gain in strength. This is rather difficult to calculate and is based mainly on experience. It depends to a great extent on the heating method and thermal properties of the mix.

Where heat is brought to the surface of the mould and/or of the product, it propagates to the inner parts by conduction. An unduly high heating rate may create steep temperature gradients within the product, causing, in addition to porosity, an uneven structure development.

With internal heating, especially DEC, the heating is more even and temperature differences are smaller. However, the danger of void formation must be considered. Another factor affecting the permissible heating rate is the mould construction. Stiff, deep moulds with small casting openings are capable of withstanding the effect of higher heating rates more readily than weak, shallow and open moulds.

b. The size and cost of the curing equipment

The heat energy imparted to the concrete is the product of the heating power and the heating time. The shorter the latter, the larger must be the former. When choosing the right size of equipment, economic factors play a major rôle in addition to practical engineering considerations. The balance between the yearly capital and the energy costs must be considered.

c. Production requirements.

This aspect is closely related to (b) above. If the intended production schedule is a single

shift or single mould turnover operation, the curing equipment will be used for only a few hours in a 24-hour period. Accordingly, its yearly capital cost (per unit produced) will be higher than that of equipment used twice or three times daily. The energy saved by a shorter heating time would be greatly offset by the increased capital costs.

Another factor to be considered is that larger equipment requires more space and more ventilation.

2.2.3 The constant heat (isothermal) period

With conventional, indirect heating methods, the isothermal period was the longest and most essential curing stage. However, with DEC, it is really necessary only with products of low heat capacity and high dissipation rate: in short, products with high surface modul. Thin plates, lintels, fencing posts, heat up rapidly and lose heat just as readily. The maintenance of an optimum constant temperature is essential for satisfactory results. The heating power required at this stage should be just enough to cover the heat losses at the particular curing temperature.

This does not apply to massive configurations. During the longer heating up period, a considerable amount of heat energy is stored in the concrete. This is subsequently increased by the onset of hydration. The effect is a continued temperature rise after heating has been cut off, and a greatly reduced cooling rate. The cooling period actually replaces the iso-thermal stage.

2.2.4 The cooling period

With light products, the cooling period is short and has little practical effect on the maturity gain. With good thermal insulation - essential at any rate for energy conservation - its duration can be somewhat extended. Nevertheless, the cooling curve is fairly steep and follows closely the equation:-

$$\theta = \theta_f e^{-\frac{T}{\tau}}$$

θ_f being the product temperature above ambient at the end of the isothermal period.

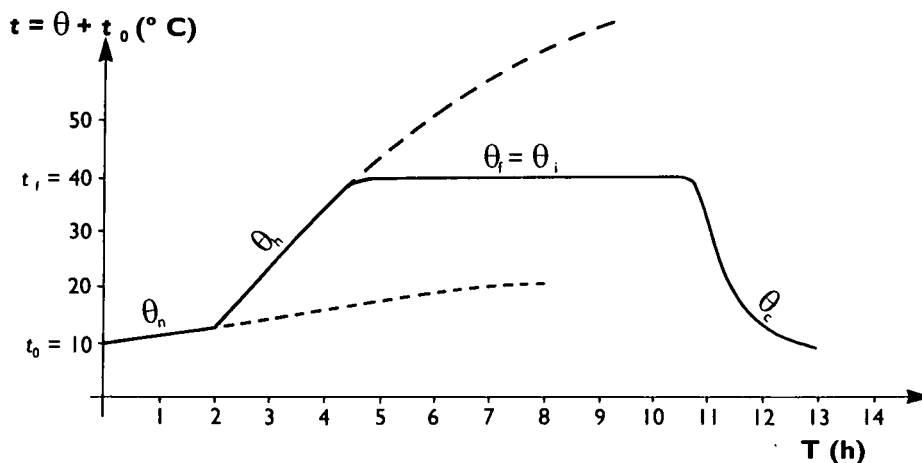


Figure 1 Heating and cooling curves

For Figure 1:

$$\theta_n = \theta_{mhy} (1 - \epsilon^{-\frac{-T_n}{\tau}}); \theta_h = \theta_m (1 - \epsilon^{-\frac{-T_h}{\tau}}); \theta_i = \text{constant}$$

$$\theta_c = \theta_f \epsilon^{-\frac{-T_c}{\tau}} + \theta_{mhy} (1 - \epsilon^{-\frac{-T_c}{\tau}})$$

In dealing with massive products, good practice involves prolonging the heating up period until the somewhat higher limiting temperature rise θ_f is reached. The heating is then stopped altogether. By this time, hydration has begun and the temperature rise continues for a while, due to the internal heat developed by chemical reaction, which continues to affect the cooling curve throughout most of its duration. Accordingly, the equation of the cooling process can be modified to:-

$$\theta = \theta_f \epsilon^{-\frac{-T}{\tau}} + \theta_{mhy} (1 - \epsilon^{-\frac{-T}{\tau}})$$

where $\theta_{mhy} = P_{hy} / A\lambda$, i.e. the maximum temperature rise the concrete can reach by hydration heat only. The respective heating-cooling curves are shown in Figure 1.

As stated in Chapter 1, P_{hy} and consequently θ_{mhy} are artificial average quantities, disregarding the fact that both are variables with time. Nevertheless, they are useful tools in maturity calculations and provide realistic results. Summarizing the foregoing, the total maturity gain of a product, using accelerated curing, can be represented by the general formula:-

$$M_t = M_n + M_h + M_{is} + M_c$$

where M_n is the maturity gain during the natural curing period,
 M_h is the maturity gain during the heating up period,
 M_{is} is the maturity gain during the isothermal period and
 M_c is the maturity gain during the cooling period.

Within a given length of total curing cycle, they are interdependent and the time span allotted for each (or omission of any) will be determined chiefly by the following factors:-

- a) Length of total curing cycle.
- b) Prevailing ambient temperature.
- c) Product surface modul.
- d) Demoulding strength requirement.
- e) Production procedure.
- f) Economic considerations.

These will be dealt with in Chapter 3.

3 Design Considerations

In the design of a DEC scheme, the following factors have to be considered:-

- 1) Product parameters.
- 2) Curing requirements.
- 3) Electric power supply.
- 4) Manufacturing conditions.

In the chapters to follow, these factors will be explored in some detail.

3.1 Product parameters

The more important parameters relevant to the design of a particular scheme include the product's mass and shape, the reinforcement configuration and the electrical and thermal properties of the concrete.

3.1.1 Mass of the product

This is the primary factor determining the energy and power requirements in a set of conditions. In general, when compared to surface heating methods, DEC is better suited to products with a large mass, within limits. The product $M \times c$ i.e. mass \times specific heat, is the measure of the body's heat capacity, the quantity of heat it can absorb and store at a certain temperature.

3.1.2 Shape of the product - surface modul

In this context 'shape', means the surface/volume ratio of the product, irrespective of whether it is a prism, slab, cylinder or any other configuration. By its very nature, an increase in size entails a reduction of that fraction denoted as surface modul. When the linear dimensions of a body change, its surface changes in proportion to the second, but its volume in proportion to the 3rd power. In consequence, the surface modul of a small product is high, that of a large one is low, regardless of its shape. For example, γ for a cube with sides 0.5m long is 12m^{-1} and for a cube with sides 1m long, 6m^{-1} .

On the other hand, with a given size determined by the mass, the shape is obviously of importance. A thin plate, for instance, will have a considerably higher surface modul than a cube of the same mass. The surface of a product - its boundary - determines primarily the rate of heat dissipation. First and foremost is the surface area A . To a lesser extent the texture and colour affect this quantity, but for closed and covered moulds texture and colour are of little practical significance.

3.1.3 Configuration of the reinforcement

The electrodes of a DEC set-up are either the mould or part thereof, the reinforcement or part thereof, or a combination of the two. The majority of cases fall into the latter category. The choice depends on the mould construction (section 3.2.2), and the relative positioning and cross section of the individual bars, strands or wires making up the reinforcement.

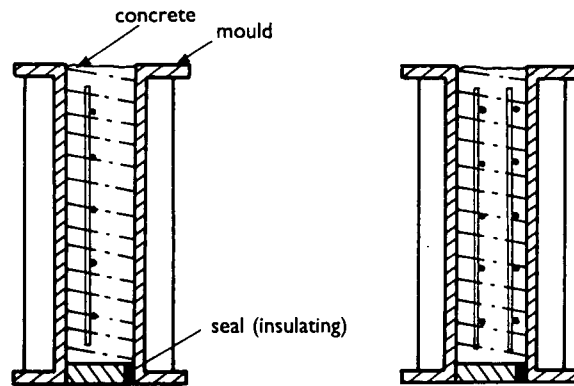
The following configurations are of particular interest:-

a. WIRE MESH, LAID IN PARALLEL WITH THE PRINCIPAL DIMENSIONS (SLAB)

If the reinforcement is in a single layer, it can be used either as one of the electrodes - the mould walls forming the other - or it can be disregarded and the mould divided up electrically into electrodes

of opposing polarity (Fig. 2).

Should the wire mesh be used as one of the electrodes, and the mould as the other, care should be taken that the distance, d_2 , at the edges of the mesh is greater than the distance d_1 between mesh and mould wall. The mesh, built up of steel bars, or wire, forms for all practical purposes an equipotential surface relative to the concrete. A reduction in d_2 would cause local over-heating at the edges.



Figures 2 and 3 Configurations of slab reinforcement (schematic)

b. TWO WIRE MESHES, IN PARALLEL WITH THE PRINCIPAL DIMENSIONS (Fig. 3).

Here we can differentiate between:-

- 1) the two meshes forming separate reinforcements and
- 2) two meshes tied together to create a single cage.

In the case of the former the options are to use the meshes as the two electrodes, or use the mould walls as the electrodes, disregarding the reinforcement, or to use a variety of possible combinations of the two. This is a very flexible system of reinforcement and easily adapted to other considerations of a DEC scheme.

The second case is much more rigid and the possible solutions are similar to the ones with a single layer mesh. However, it should be reiterated that the entire cage is to be considered as an equipotential surface.

c. PRESTRESSING WIRES OR STRANDS, IN PARALLEL WITH THE PRINCIPAL DIMENSIONS (BEAMS, POLES, SLEEPERS ETC.)

The tendons are usually anchored to a common end plate. It is cumbersome and costly to insulate them electrically from each other and the jack, due to the large forces involved. However, it is possible and the best practical way is to treat such reinforcement as a single conductor, with the envelope of the outer strands facing the mould as its equipotential surface, forming one electrode. The other electrode is the mould.

The active (current-carrying) part of the reinforcement is the strands making up that envelope. The electric field is set up between them and the mould walls (Fig. 4). There is, of course, a great variety of concrete products and respective shapes of reinforcement. However, they can all be placed in one of the three categories.

It is possible to cure non-reinforced concrete, such as building blocks, by this method, with the

mould (or parts of it) forming the electrodes. The decisive factor is the economic viability of the process.

3.1.4 Electrical and thermal properties of the concrete

With DEC, as explained previously, the concrete in the freshly-cast product acts as the heating resistor. The *electrical properties* of the mix are determined by those of its components and their proportions.

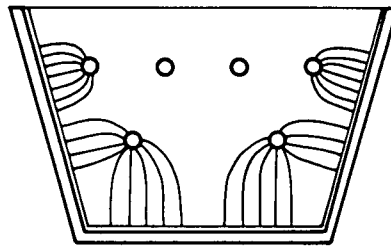


Figure 4 Electric field between prestressing strands and mould (for railway sleeper)

a. THE AGGREGATES

The aggregates normally used for concrete and making up the major part of it, have a negligible electrical conductivity in the dry state. Although this varies over a considerable range according to composition, they can be safely considered in this context as insulators.

b. CEMENT

When combined with water, cement forms an electrolyte. The electrical conductivity of this cement paste is influenced by the chemical composition of the cement. Conductivity variations in the ratio of 4:1 have been observed with Portland cements of different make (Malinin *et al*¹⁸). The generally-accepted theory (Malinin *et al*¹⁸, Gendin *et al*⁹) behind the phenomenon is that the electrical conductivity increases with the rise in the alkali concentration ($K_2O + Na_2O$) of the paste. Mixes containing cements of higher alkalinity are better electrical conductors.

c. WATER

Tapwater is itself a fairly good electrical conductor. However, a higher water/cement ratio actually decreases the conductivity of the electrolyte, due to a reduction in the alkali-ion concentration. On the other hand, surplus water increases the volume of the total conducting portion of the concrete relative to the non-conducting ingredients.

In summary: by increasing the total water content of a mix, the conductivity is increased. The effect is greatly enhanced by maintaining simultaneously a low W/C ratio; i.e. using an altogether richer mix. Lean, dry concretes have a higher electrical resistance.

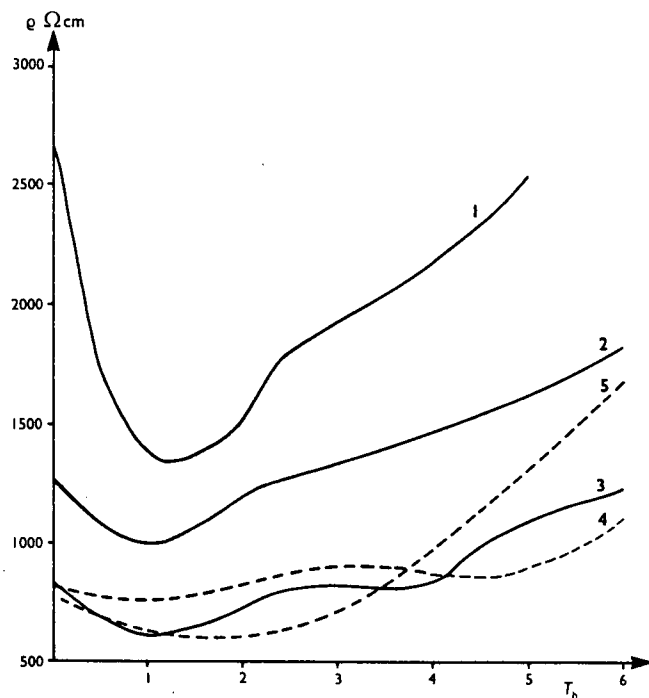
d. ENTRAPPED AIR

Like all gases at atmospheric pressure, air is a poor conductor. A well-compacted mix, with a low

proportion of air bubbles, is a better electrical conductor. The electrical properties of a concrete mix as a whole are further influenced by its temperature and rate of maturity gain.

With rising temperature, the ion movement in an electrolyte increases and the conductivity rises. As we have seen, the water-cement paste is electrically active and forms an electrolyte. Thus, while in the fluid-plastic stage, increasing temperature lowers the resistance. With the onset of hydration and the gradual transformation of the water-cement paste into a non-conducting crystalline structure, the tendency is reversed and resistance begins to rise (Fig. 5). The lower the initial water content, the steeper the increase.

With wet mixes and short curing cycles, these variations are moderate and heating can usually be completed at a constant voltage. With dry concretes and longer cycles, the curing equipment has to compensate for the increasing resistance.



- Curve 1:** Low grade OPC, 371 kg/m³, W/C 0.41; $t_o=19^\circ\text{C}$, $t_f=45^\circ\text{C}$, $T_n= \frac{1}{2}\text{h}$, $T_i= 4.5\text{h}$
- Curve 2:** Low grade OPC, 400 kg/m³, W/C 0.45; $t_o=13^\circ\text{C}$, $t_f=40^\circ\text{C}$, $T_n= 1\text{h}$, $T_i= 5\text{h}$
- Curve 3:** Low grade OPC, 540 kg/m³, W/C 0.4; $t_o=17^\circ\text{C}$, $t_f=40^\circ\text{C}$, $T_n= 1\text{h}$, $T_i= 5\text{h}$
- Curve 4:** Low grade OPC, 540 kg/m³, W/C 0.4; $t_o=19^\circ\text{C}$, $t_f=64^\circ\text{C}$, $T_n= 1\text{h}$, $T_i= 5\text{h}$
- Curve 5:** Good grade RHPC, 540 kg/m³, W/C 0.4; $t_o=19^\circ\text{C}$, $t_f=64^\circ\text{C}$, $T_n= 1\text{h}$, $T_i= 5\text{h}$

Note: The low grade OPC apparently had pozzolanic added.

Figure 5 Changes in resistivity of concrete during heating

In considering the *thermal properties* of a concrete mix, we have to differentiate between the two main aspects: specific heat and thermal conductivity. The former remains comparatively even, despite variations in the density and component materials of the concrete. However, a higher water content increases the overall value because water has a specific heat 4 to 5 times that of the aggregates. A wet mix absorbs more energy than a dry one for the same temperature rise.

Thermal conductivity depends largely on the aggregates. Its magnitude is of vital importance in the design of any curing scheme. A mix with good thermal conductivity requires a lower limiting curing temperature than a poor conductor. In the former, due to even heat distribution and smaller gradients, the heating up time can be shortened without detrimental effect and the overall energy consumption reduced. The final product is likely to be more uniform structurally.

At the lower end of the scale for heat conductivity are amorphous aggregates of volcanic origin (basalt, trachyte). Crystalline rocks e.g. granite, exhibit high heat conductivity, while limestone,

dolomite and sandstone occupy the middle range.

Water is a poor conductor, and its presence in excess tends to reduce the overall heat conductivity of the mix. It is often necessary in calculating such factors, to consider the mass of the steel mould - or part of it. The same applies to dense reinforcement of heavy cross section. The latter has a beneficial effect on the temperature distribution in the concrete, because mild steel has a much higher thermal conductivity than the aggregates.

3.2. Curing requirements

Within the context of curing requirements, three major factors are to be considered:-

- a) The total length of time allotted for the curing cycle.
- b) The demoulding or lifting strength to be obtained during that time span.
- c) The final quality of the product aimed at: later strength, surface finish, general appearance.

3.2.1 Length of the curing cycle

The type of product and the overall production procedure affect the design of a curing cycle. High quality products, especially prestressed units that require a high demoulding strength also need a longer curing time. In many respects, the same applies to an increase in size.

The objective of accelerated curing is obvious. However, in reaching the required maturity, energy is used more efficiently over a longer period of curing time. This applies in particular to DEC. This tendency, to prolong the curing cycle, is contrary to the aims of production, viz the manufacture of the maximum number of units with the minimum equipment in the shortest possible time.

With small products of high surface modul, the problem is less marked. The major part of the cycle is taken up by the isothermal period when heat energy is supplied constantly to maintain the product temperature. If, for reasons dictated by production, the curing time is to be shortened, the isothermal part of the cycle would be affected most. The time loss could be compensated for by elevating the curing temperature and the total energy expenditure would be hardly affected. Some increase in the power rating of the curing equipment would then be expected.

For larger products of low surface modul (less than 20m^{-1}), the energy is absorbed during the heating up period and stored for the greater portion of the cooling time, which is the most effective part of the cycle. The options for shortening the curing cycle in this case are limited, for the following reasons:

- a. By cutting down on the preheat storage time, the natural strength gain will be lower. Consequently the heating rate would have to be reduced and the length of heating time increased. No time economy would be effected.
- b. The heating up time could not be shortened. It would not be advisable to increase the heating rate for large products, the choice being dictated by an acceptable heating rate. In addition, the size of the curing equipment, which is designed to suit the accepted heating range for that particular product, would have to be increased. This in itself creates a limiting factor.
- c. Consequently, time may be saved only by shortening the cooling period. This would call for a higher average curing temperature, which could be obtained by raising the limiting heat-up temperature. The introduction of an isothermal stage would be self-defeating.

The reduced cooling time means that, for the demoulding strength, a portion of the stored heat energy is lost and is to be compensated for by an increased input, of which an even greater part will be wasted during the shortened cooling stage.

With normal reinforced concrete products of moderate strength, the natural curing period often can be omitted, as stated previously. In such a case, the heating should start simultaneously with the beginning of the casting operation and can be carried out at a fairly high rate, especially if the mix

is well vibrated. Intensive vibration in the plastic-fluid stage liberates the entrapped air, drives out surplus water and gives a good heat distribution within the mould due to the mechanical stirring action.

The outcome is a compacted 'hot concrete' mix produced on site. Once the casting is completed, it is advisable to reduce the heating rate, before the onset of the hardening process. Ideally, the latter should take place predominantly during the cooling stage.

Typical time values for normal reinforced concrete are: 1 to 3 hours for heating up time and 3 to 5 hours for the total curing time measured from the *beginning* of the casting. The curing cycle of such products can also be prolonged, creating energy savings of up to 30 - 40% due to the lower limiting temperature required.

Typical time values for prestressed products are: 2½ to 5 hours for heating up and 13 to 18 for the total curing time. For products of high surface modul, the heating up time is largely replaced by the isothermal stage.

3.2.2 *The demoulding strength*

One of the main reasons for the accelerated curing of precast concrete products is the enhanced exploitation of production equipment and available space, i.e. a shortened mould-turnover time. This time period is the sum of the working and curing cycles. The latter is determined by the minimum demoulding or lifting strength required i.e. the length of time necessary to obtain the required strength. As stated previously (section 2.2), the strength gain of a product is a function of both time and temperature. If the time is to be shortened then the temperature will have to be increased. The possibility of increasing the curing temperature, however, is limited. The maximum temperature of the product should never reach 100°C and, preferably, be kept below 90°C. This means an upper range for the heat cut-off point (the "final" temperature) of 70° - 80°C. Economic considerations would seldom justify a higher peak temperature.

Accelerating additives are possible sources of corrosion and are therefore not used. However, rapid hardening Portland cement may be used to gain early strength. It is well adapted to DEC and produces no side-effects, differing from the ordinary Portland cement only by its grain fineness.

Two groups may be defined when considering strength requirement - prestressed products and normal reinforced concrete. With prestressed units, demoulding and lifting strengths are identical. The strength is that required for the concrete to grip the prestressing members (wires, strand or bar) sufficiently to withstand the compressive forces created on release of the tension. It may vary considerably from product to product, ranging between 25 - 40 N/mm² for stiff, low W/C ratio mixes.

Due to their relatively low water content, mixes for prestressed concrete have a higher electrical resistance and better heat conductivity. The former property permits the use of higher voltages (for the same power) reducing the capital outlay for the curing equipment. The improved heat conductivity allows a shorter heating up time with reduced energy consumption. Because of the high initial strength required, it has been found more economical - if ambient temperature conditions permit - to make use of the primary strength gain during the natural curing period and proceed with a gradual increase in the heating rate, conforming to the progress of maturity gain. Again, good use should be made of the cooling period.

With normal reinforced concrete, the required initial strength depends in part on the size of the product and the mould construction. Small units (for example, a purlin) are more often cast in moulds made in a single piece. These products can safely be demoulded and handled at 4 - 5 N/mm². The moulds for larger products are usually made up of several parts consisting of a base and side walls. The side walls can be removed without adverse effects at 3 - 5 N/mm² and the product lifted off at 6 - 10 N/mm², depending on weight and shape. This assumes the product is sheeted down to prevent heat and moisture loss.

3.2.3 Product quality

Concrete products and structures are usually designed for the strength developed in 28 days. Beyond that period a further maturity gain is to be expected, though at a gradually decreasing rate. With accelerated curing care should be taken that despite the rapid initial strength gain, the later maturing process is not disturbed. It is important that undue moisture loss is prevented during curing, especially with dry mixes. This applies to DEC, and any other dry heating method. A mix with insufficient water for the hydration has practically the same effect as if the cement content were reduced. The final product will be of a lower strength.

Moisture loss can be prevented by sheeting down the product with an impervious material (such as polythene, rubber, etc.) immediately after casting, or by spraying the exposed concrete surfaces with a water-sealing compound. The other principal cause for later strength deficiency could be the use of an excessive heating rate. Although with DEC a temperature rise of 35°C/h in the fluid-plastic stage is quite acceptable, it should be kept below 20°C/h during the first hour of the setting-hardening period. With the advance of maturing, the heating rate can be increased gradually again.

The surface finish of a product depends largely on the mix. However, even with a rich mix, sufficient time at an elevated temperature must be allowed for fine particles to migrate to the product-mould interface.

The colouring of the product will be lighter at a higher surface temperature, due to the free lime concentration. Concretes cured by DEC tend to show a darker colour even at advanced maturities which is similar to products cured naturally. This is due to the inverted temperature gradient from the centre to the surface. For the same reason, DEC is less likely to cause thermal cracks than surface heating methods. With the latter, the product surface undergoes the greatest temperature changes, reaching the maximum and minimum temperature of the product (Fig. 6). Consequently, on cooling, the greatest contraction stress appears in this surface layer. With DEC, the product surface *always* has the lowest temperature; accordingly, for the same average product temperature the volumetric changes in that vulnerable layer are smaller.

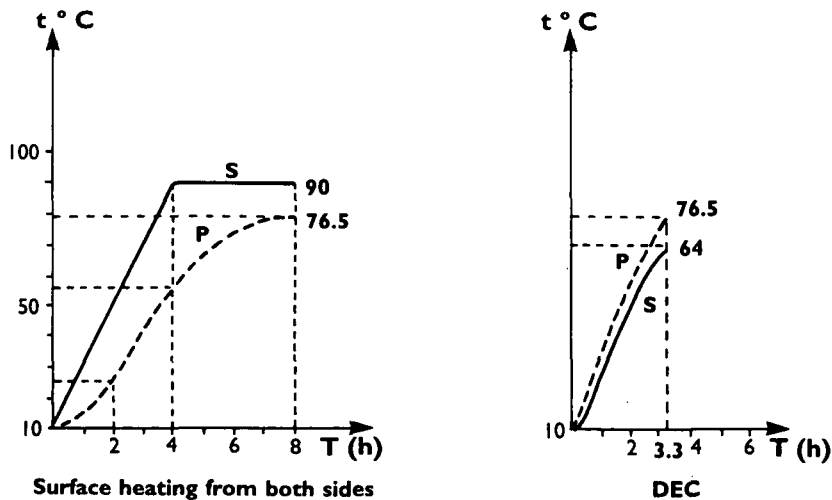


Figure 6 Changes of surface vs. average product temperature in a slab. Rate of temperature rise, 20°C/h. S - surface; P - product

Irrespective of the smaller surface temperature changes with DEC, products of a more intricate shape, where differential contraction can occur, may develop cracks. In such cases, the best solution is to prolong the cooling cycle, possibly with the gradual opening of the mould.

3.3. Electric power supply

By its very nature, the prerequisite of a successful DEC scheme is the availability of a reliable and comparatively cheap power supply. Although private generation may be a viable proposition for a very large installation - especially if some form of low-cost fuel is available on site - this will be the exception. In general, we have to consider energy bought from a supply company.

3.3.1 Technical aspects

a. The magnitude of the existing sub-station. If the sub-station has sufficient spare capacity to accommodate the foreseeable maximum heating load, there is no problem. If not, we have to examine:

b. Will the heating load coincide with the normal factory load, or can it be accommodated in off-peak hours? If so, will the existing sub-station capacity then be sufficient? Very often, the answer will be 'yes' depending, to a great extent, on the largest mass of concrete to be cured at one time.

DEC is a very flexible method for the production of large quantities of small or medium sized articles (200 - 500 kgs). Due to the short heating time, several groups of production lines can be cured consecutively, thereby obtaining a high diversity and an even load factor. However, should the heating be needed during normal production time or cumulatively exceed the available supply, the next question will be:

c. What is the load capacity of the existing H.T. line feeding the factory? Does it allow for an extension of the existing sub-station? With very few exceptions, this will be possible, unless the existing network is a very old one and the factory happens to be at its terminal. In such a case, the costs for increasing the line capacity could be quite substantial. Negotiation with the supply authority may lead, however, to some sort of compromise, the expenses being split among present and future consumers.

Of course, if DEC is incorporated into a newly erected factory, the heating load - forecast in accordance with the previous deliberations - will simply have to be added to the expected maximum factory demand, allowing for a reasonable spare capacity.

d. Harmonics. The backbone of the DEC regulating equipment is quite often thyristors, working on the wave-chopping principle (see section 4.4.2). Thyristors generate harmonic voltages and currents, which are fed back to the supplying network. In most countries guidelines are laid down, regulating the maximum permissible values of harmonics fed to their network. It is advisable to obtain information from the equipment manufacturers about the magnitude of the harmonics to be expected and consult the supply authority at an early stage. This will prevent problems arising during operation.

3.3.2 Economic considerations

Electricity tariffs vary considerably. Even in different supply areas of the same country, tariffs differ. However, they all consist of two basic elements: a charge related to the capital cost of generating equipment, sub-stations and network of the supply authority, tied up with the particular customer; and a charge for the running costs of the generation and distribution of electrical energy.

The former is reflected either in the payment for the connection of the load specified by the customer, or a maximum demand charge according to the peak load supplied at any time, or both. The running costs are expressed as the unit charge. This may vary for different times of the day, in accordance with the network loading conditions of the area. Some countries have three unit charges;

peak, normal and low, while others have just two. As a rule, there is a substantial price reduction for units consumed during the night hours. When designing a DEC scheme, the following points should be considered:

- a. Is it feasible to stagger the load, i.e. to switch on the heating of the various production lines at different times? A better distribution in time will result in a lower maximum demand charge (and a better utilization of the heating equipment).
- b. Can the switch-on time be postponed until after the normal working hours of the factory? (assuming a single shift production regime). If the switch-on occurs in the late evening, the bulk of the heating will take place at the night tariff. This would reduce both the maximum demand and unit charges.

Maximum demand charges often vary throughout the year in countries with cold or temperate climate being higher during the winter months. The curing regime should have some inbuilt flexibility to allow for this constraint.

3.4 Manufacturing conditions

The topics to be examined in this chapter are:

- a) The production site
- b) Range and nature of the products
- c) Production method and requirements.

3.4.1 *The production site*

a. CLIMATIC CONDITIONS

The ambient temperature and its daily and seasonal variations greatly influence the choice of equipment and thus the final decision. In general, the lowest ambient temperature at which production is required is taken as the basis for calculations. However, if it occurs only during short periods, either daily (by night) or throughout the year, allowances can be made.

In countries with very severe winter conditions, precautions should be taken to prevent freezing of the concrete. Ice does not react with the cement and in partially set or hardened concrete, it will disrupt the homogeneity of the product. Under such conditions some form of pre-heating should be considered. During off peak periods the mixing water can be pre-heated in insulated storage tanks and the same applies to the concrete in the dispensing buckets (which can be heated by DEC), prior to casting. A 12-15°C pouring temperature for the concrete is usually adequate. The natural curing phase under such circumstances is of course dispensed with.

Countries with a hot climate have different problems. Whether tropical or arid with dust and sand storms, the equipment has to be designed to meet the adverse conditions. If the humidity is very low and long lines are to be cast, it may be necessary to cover those moulds already filled while casting is in progress, in order to prevent the concrete from drying out. Accelerated curing is usually required only through part of the year, unless multi-turnover production is being envisaged. In all climates, it is economical to regulate the curing regime in accordance with the seasonal ambient temperature changes.

b. PREMISES

Production can take place either in an open courtyard, or in a building. A courtyard, although it needs a good concrete floor and often a colonnade supporting the beams to carry a gantry crane, is likely to be the cheaper solution when considering capital investment.

However, if we consider production lost due to adverse weather conditions, discomfort to the labour force, faster depreciation of the equipment exposed to the elements and greatly enhanced curing energy expenditure, precast manufacturing in a building will probably prove to be the more economical solution in most cases.

A building gives protection from rain, snow and sun, but above all, in view of the curing costs and resultant efficiency, from wind. The advantage of a production hall with well-closing doors and windows is quite apparent from the following figures. The convection (heat) loss of a dark grey body such as concrete in still air is around $8\text{W/m}^2\text{ }^\circ\text{C}$, while in an air stream of 10 m.p.h. (which would correspond to a light breeze) it becomes $30\text{W/m}^2\text{ }^\circ\text{C}$, according to the formula for convection losses:

$$\lambda' = \lambda_{\text{conv}} (1 + \text{Ca}\sqrt{v})$$

where λ' = coefficient of convection from a ventilated surface

λ_{conv} = coefficient of natural convection

Ca = empirical coefficient for uniform airstream, ≈ 1.3

v = velocity of airstream, m/sec

3.4.2 Range and nature of the products

a. SIZE AND SHAPE

The viability of a DEC scheme when compared to other methods of accelerated curing, depends to a great extent on the surface modul of a product, as defined by the size and shape of it. (see section 3.1.2). For small pieces, with a surface modul of 40 or higher, DEC is unlikely to be competitive, even in mass production. With very large compact units, with a surface modul of less than 3, the technical solution may become cumbersome, although any other accelerated curing method will be much less efficient. On the other hand, with such a product, the maturing process will take care of itself once hydration has begun. DEC is ideal for products with a surface modul between 5 and 30.

b. QUANTITIES

DEC is particularly suited to mass production. Although the equipment is versatile, setting up may become too time-consuming and the necessary skilled labour too expensive for widely differing one-off units. However, it is a useful and economic proposition for on-site production of repetitive elements.

c. REINFORCEMENT

The method suits reinforced and prestressed concrete equally well. The only criteria to be satisfied are:

- adequate cross section and electrical continuity in the current-carrying parts of the reinforcement.
- prevention of accidental contact between the electrodes - predominantly reinforcement and mould - during the heating process.

● proper electrical connections to the current-carrying elements, in particular to the reinforcement. With repetitive work - usually the case - the lugs of the supply cables should be cleaned from concrete spillage before each application. The mould seldom presents a problem.

3.4.3 Production method and requirements

a. The PRODUCTION METHOD can vary from the casting of a single or a few individual moulds during a shift, to the forming of a large number of units on a long continuous bed, or several beds. The latter is typical of prestressed concrete.

A precast concrete factory usually has more than one production line and different products are manufactured simultaneously. With steam curing, heating is usually turned on by the end of the day for the whole factory and kept running until the morning hours. This is not the case with DEC.

Although night curing is still advantageous for tariff considerations, the switch-on time should be staggered for the various lines, as far as possible. The result will be a better exploitation of the heating equipment, reduced maximum demand and a better load factor. As the heating of a line automatically stops at the cut-off temperature, further lines can be switched on consecutively, using the same heating equipment or part of it. In multi-shift operation, this advantage is lost, but the increased output (two or three times) with the same plant facilities is ample compensation.

It is quite feasible to make two casts with the same mould in an 8 hour shift, using DEC. High power is switched on at the beginning of the casting and maintained until casting is completed. Then the mould is thoroughly re-vibrated to remove entrapped air and excess water liberated during the rapid heating up. The product is then sheeted down and the power switched to a low level, until the final heating temperature of around 60°C is reached. The product can usually be lifted off within 5 hours of the beginning of casting, using rapid hardening portland cement.

For the second cast, when a much longer cooling period is available, the cut-off temperature can be reduced to around 35-40°C.

b. DEMAND

It is necessary to differentiate between long contracts, often running for years and between medium and short ones, lasting for months or weeks. For a large contract, a more accurate evaluation and design for optimum performance is justified. Connections to the electrodes should be more permanent, as far as possible, and temperature control consistent with the actual requirements, should reflect ambient variations. Power control should be continuous and automatic. The latter is achieved usually with the help of thyristors, which perform at their best with prestressed products.

With medium and short-term production programmes, the considerations differ. In these cases, versatility and the capital cost of the installation weigh more heavily. The equipment has to be designed for a wider range of products. Connections to the electrodes will probably not be permanent. The power control will not necessarily be fully automatic and continuous, but hand operated, step by step. Primary tapped heating transformers with off-load tap changer, are less expensive than power thyristor regulators (see section 4.4.1).

The same is valid for operations with two or three shifts. For high turnover, primarily of RC products, the heating times are shorter (see section 3.2.1) and the site is attended, because most of the curing is done during normal factory hours. As the setting and the hardening in multi-shift operation takes place predominantly during the cooling period, little use would be made of the favourable - but costly - regulating characteristics of the thyristor. On the other hand, step by step control, unless motorized, will not be automatic and it might require some skill from the operator.

c. QUALITY

Much depends on the desired quality of the concrete. Relevant factors include the demoulding strength required and the ultimate use and design strength of the product (see section 3.2.2)

Prestressed units need high demoulding strength to withstand the prestressing forces. The mix has to be fairly rich with a low water/cement ratio, at minimum workability, enhanced by the addition of a plasticizer. RHPC is widely used. The end product should have a high density and particular care is required during the heating up period to prevent void formation. Close power control is essential.

The curing conditions for normal reinforced concrete are less onerous because the demoulding strength is lower. However, an appropriate curing regime will ensure a better end product.

4 Design procedure

The design can now proceed, based upon the guidelines and information presented in previous chapters. The basic data requirement is as follows:

- a. Quantity of concrete to be cured in an 8 hour shift
- b. Number of shifts in 24 hours
- c. Number of production lines envisaged and general layout of the production site
- d. Demoulding strength required
- e. Quality of cement and aggregates, W/C ratio, mix proportions, and use of plasticizer if any
- f. Product parameters
- g. Reinforcement data and drawings
- h. Mould drawings
- i. Production procedure envisaged
- j. Site conditions: general, climatic, annual average temperature, daily and yearly maximum and minimum
- k. Nature of premises
- l. Electric power supply. Availability and distance from production site

The actual design procedure consists of:

1. Calculating the power
2. Calculating the working voltages and respective currents
3. Designing the curing scheme
4. Designing the control scheme
5. Specifying the equipment

4.1 Calculating the power

The most convenient approach is to refer to a unit length of product, say 1 metre. As stated in section 2.1, the temperature rise of a homogeneous body follows the equation:

$$\theta = \theta_m (1 - \epsilon^{-\frac{t}{\tau}}) \quad \text{and} \quad \theta_m = \frac{P}{A\lambda}$$

i.e. the power supplied to and developed within the body, divided by the heat lost over its boundary. For heavy moulds, the heat capacity of the steel per unit length should also be considered thus the theoretical formula modifies to:

$$\tau = \frac{c_1 M_1 + c_2 M_2}{A\lambda 860} \text{ h}$$

where c_1 is the specific heat of concrete, ≈ 0.22 Cal/kg
and c_2 is the specific heat of mild steel, ≈ 0.11 Cal/kg
 M_1 is the mass of concrete per unit length, kg and M_2 is the mass of the mould per unit length, kg.

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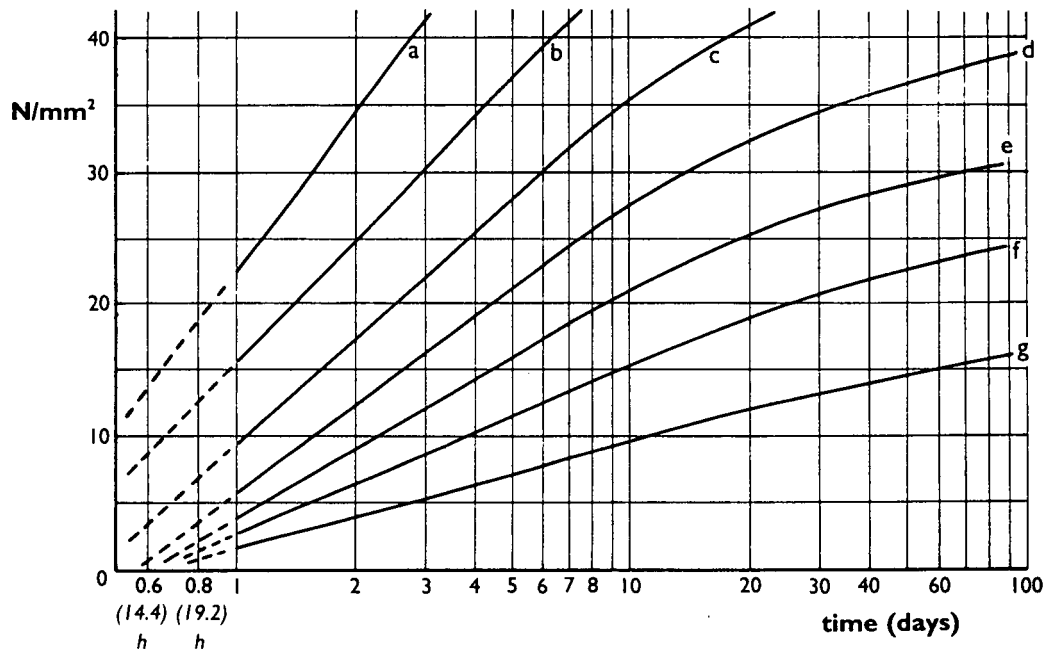


Figure 7 Cube strength development of various concrete mixes at 20°C. Redrawn from *Design of Concrete Mixes* (Road Research Laboratory, 1950, 1969)

In practice, M_2 is considered to be the mass of steel in intimate contact with the concrete. Steel is a comparatively poor conductor of heat and therefore the supporting structure of the actual mould can be ignored in this calculation. The final temperature rise is the final curing temperature less the ambient temperature:

$$\theta_f = t_f - t_0$$

and is determined by:

- a. the maturity requirement,
- b. the total length of curing time available,
- c. the product parameters and expected heat losses,
- d. the minimum ambient temperature to be reckoned with.

It is advisable to start with the lowest yearly ambient temperature. However, if this prevails for very short periods only, allowances can be made, especially with single shift operations. From the required demoulding strength and the length of the curing cycle, t_c , the average curing temperature can be calculated. Ideally, it can be obtained from the natural cure (at 20°C) time-strength development curve of the particular mix or by using the data of a similar one, if available. Alternatively, a few 150mm test cubes should be prepared; cured isothermally at 20° C and strength-tested at the following time intervals: 12, 24, 36, and 48 hours, 3, 4, 7, 14 and 28 days. The tests can be either non-destructive, using a Schmidt Hammer, or for more accurate results, the cubes should be crush-tested in a calibrated test rig.

After drawing the curve on a logarithmic scale, (Fig. 7.) the following steps are taken:

1. Find the demoulding strength aimed at, on the vertical axis (ordinate).
2. Draw a horizontal line, to intersect the curve.
3. From the point of intersection, drop down to the time axis (abscissa).

The result will be the time required to gain the specified strength at the curing temperature of 20°C. The maturity is then reflected in the formula

$$M = T_{20} \left(\frac{t+16}{36} \right)^2 \quad \text{with } t=20, M=T_{20}$$

Replacing T_{20} by the specified curing time T_t , the average curing temperature would be

$$t_t = \left(\frac{M}{T_t} \right)^{\frac{1}{2}} \cdot 36 - 16 = 36 \left(\frac{T_{20}}{T_t} \right)^{\frac{1}{2}} - 16$$

However, as discussed in section 2.2, the maturity is made up of several components, obtained during the total curing time. In the interpretation and further use of t_t , it is necessary to differentiate between products of various surface moduls.

CASE STUDY 1

To simplify matters, we shall firstly consider products with a surface modul (γ) in the range of 12-20, cured at an ambient temperature of $t_0 \leq 5^\circ\text{C}$. This will reduce the curing cycle to 2 stages, heating up and cooling (Fig. 8). At the low ambient, the natural cure strength gain M_n is negligible, and due to the favourable surface modul, the isothermal stage can usually be dispensed with.

Accordingly, T_t will be made up of T_h the heating time and T_c the cooling time. Correspondingly, $M_t = M_h + M_c$. The idea behind the two stage curing is that the energy imparted during the heating up will be retained in the concrete (and mould) for a considerable part of the cooling time. The longer the cooling time, the better the energy is used. On the other hand, this results in a shorter T_h and for the same maturity necessitates a higher final temperature t_f and thus more power. The maturities gained during the two stages will be:

$$M_h = T_h \left(\frac{t_{\text{hav}} + 16}{36} \right)^2 ; M_c = T_c \left(\frac{t_{\text{cav}} + 16}{36} \right)^2 ; \text{ where}$$

$$t_{\text{hav}} = t_0 + \frac{1}{T_h} \int_0^{T_h} \theta dT = t_0 + \frac{1}{T_h} \int_0^{T_h} \theta_m (1 - \varepsilon^{-\frac{T}{\tau}}) dT = t_0 + \frac{1}{T_h} \theta_m \left[T_h + \tau (\varepsilon^{-\frac{T_h}{\tau}} - 1) \right]$$

$$t_{\text{cav}} = t_0 + \frac{1}{T_c} \int_0^{T_c} (\theta_f \varepsilon^{-\frac{T}{\tau}} + \theta_{\text{hy}}) dT = t_0 + \frac{1}{T_c} \left(\tau \theta_f (1 - \varepsilon^{-\frac{T_c}{\tau}}) + \theta_{\text{mhy}} \left[T_c + \tau (\varepsilon^{-\frac{T_c}{\tau}} - 1) \right] \right)$$

So as we see, the allocation for $M_h(T_h)$ and $M_c(T_c)$ out of $M_t(T_t)$ is a matter of judgement and

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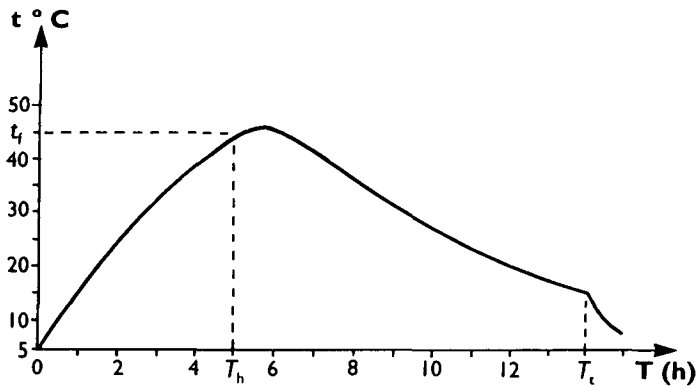


Figure 8 Two stage DEC of prestressed product, $\gamma = 19$

experience, rather than exact calculation. However, some indication is given by the allowable rate of temperature rise, θ_r/T_h . For high quality prestressed concretes, 10-15 °C/h is acceptable. For lower quality RC products the temperature rise may reach 35 °C/h, without detrimental effects, depending upon the manufacturing method. In chapter 5 worked examples will shed more light on this subject.

Once the decision is taken, often after several trials, the rest follows.

$$\theta_m = \frac{\theta_f}{1 - \varepsilon} = \frac{P}{A\lambda};$$

$$P = \frac{\theta_f A \lambda}{1 - \varepsilon}$$

This is the power required to raise the temperature of a 1 metre length of concrete and mould from t_0 to t_f in T_h time, and cover the heat losses during this stage. In the above formula the factor λ , the sum of convection and radiation losses, is introduced. For a well-sheeted down product in a closed production hall $\lambda=7-9 \cdot 10^{-3}$ kW/°Cm², and in an open courtyard 12-16 $\cdot 10^{-3}$ kW/°Cm², depending upon the weather conditions.

The equation for the average cooling temperature contains a member with the coefficient θ_{mhy} . This is the maximum temperature rise due to hydration heat only. As stated previously, hydration heat can be quite considerable. Its magnitude depends upon the heat content of the cement used and its quantity per unit product. For practical purposes a useful reference point is the heat released by the sample in a 0.4 W/C ratio cement paste during three days of hydration at 20°C.

APPROXIMATE VALUES OF HEAT OF HYDRATION FOR VARIOUS CEMENTS	
Rapid hardening portland cement (RHPC)	70-80 cal/g
Ordinary portland cement (OPC)	50-60 cal/g
Low heat (pozzolanic cement)	30-40 cal/g

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The three day hydration heat will be

$$Q_{hy} = \frac{q 10^3 w V}{860} \text{ kWh}$$

where q is the heat content of the cement (cal/g), w is the cement content of the mix (Kg/m³) and V is the volume of the product per unit length (m³).
and the average hydration power

$$P_{hy} = \frac{q 10^3 w V \eta}{860 T_t} \text{ kW} \quad \text{and} \quad \theta_{mhy} = \frac{P_{hy}}{A \lambda}$$

η is the estimated ratio of the hydration heat released during T_t and the total three day heat content. It is again an empirical figure.

$$\begin{aligned} \text{For } T_t = 10 \text{ hours,} & \quad \eta \approx 0.6 \\ \text{and } T_t = 16 \text{ hours,} & \quad \eta \approx 0.75 \\ \text{and } T_t = 20 \text{ hours,} & \quad \eta \approx 0.8 \end{aligned}$$

Accordingly, as stated in section 2.1, the power to raise the temperature of the concrete is derived from two sources. The internal source is from hydration and the electricity network forms the external supply. The latter is therefore the difference between the total power requirement and the hydration power,

$$P_{\text{electrical}} = P_t - P_{hy}$$

CASE STUDY 2

For products with γ higher than 20, the isothermal stage is also considered. Its importance grows with increasing surface modul. If natural curing is again neglected, and with the effect of M_n diminishing anyway due to the greater losses, three curing stages must now be considered: heating up, maintaining the final temperature and cooling.

$$M_t = M_h + M_i + M_c \text{ and } T_t = T_h + T_i + T_c$$

For surface moduls in the range 21 to 25, generally $T_i \approx T_t / 3$ and $M_i \approx M_t / 2$, t_i being equal to t_f . T_c is shortened and restricted, as far as is practicable, to the steeper part of the cooling curve. When γ is above 25, the isothermal stage becomes preponderant (see Fig. 9). Both heating and cooling times are cut to a minimum and the maturity gain takes place primarily in the isothermal stage. Then the calculation can be based upon

$$M_t \approx M_i; t_{av} \approx t_i = t_f; t_{hav} \approx t_{cav} \approx t_f / 2$$

M_h and M_c are often only minor additions to M_i and can usually be ignored. However, the power calculation remains the same as in case study 1. The energy expenditure increases in direct proportion to γ .

CASE STUDY 3

With massive structural elements the situation is different. In case studies 1 and 2, the natural curing phase *does* contribute to the maturity gain at higher ambient temperatures, but to a limited extent.

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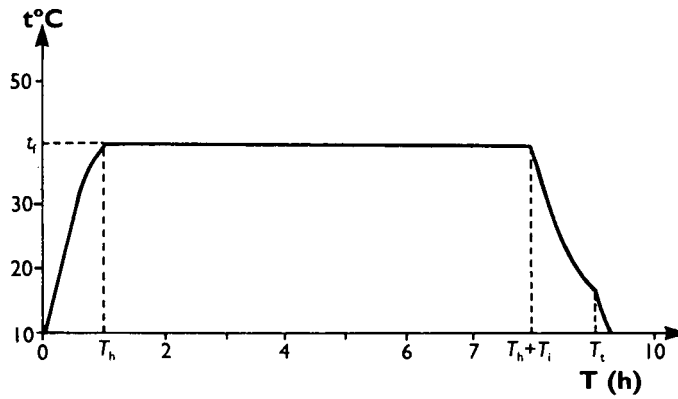


Figure 9 Three stage DEC of an RC product, with isothermal stage; $\gamma = 28$

Chapter 5 shows that at surface moduli below 12 its contribution becomes quite substantial (see Fig. 10).

$$M_t = M_n + M_h + M_c$$

At $t_0 \geq 10$ °C, it is often worthwhile considering a longer natural cure period, say up to 3 - 4 hours, providing this is feasible within the total curing time available. By the end of T_n , the temperature of the product will have risen to $t_0 + \theta_n$ where

$$\theta_n = \theta_{mhy} (1 - e^{-\frac{T_n}{\tau}})$$

and θ_f is reduced to $t_f - (t_0 + \theta_n)$. As a result, the power input required could be less. However, under these circumstances it is good practice to raise t_f , leaving θ_f as if the starting point were at t_0 and then to exploit the cooling period to a greater extent. The energy expenditure will thus be considerably lower. It should be remembered when calculating the average cooling temperature that the starting temperature difference will be $\theta_f + \theta_n$ (instead of θ_f), because the ambient temperature remains unaltered

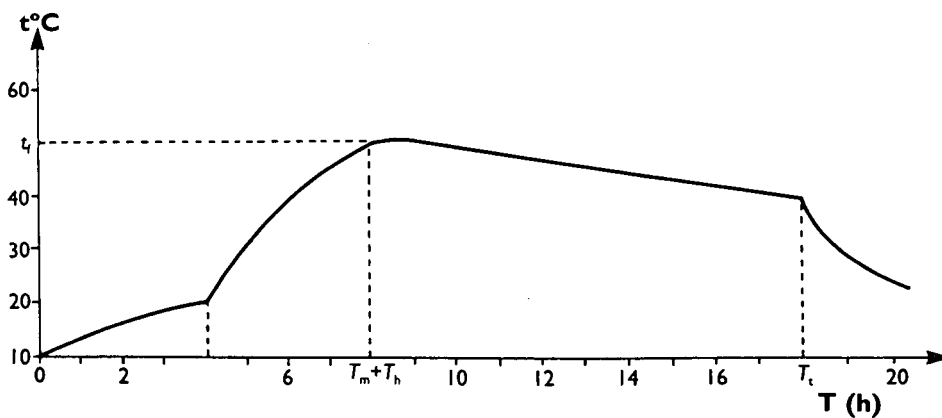


Figure 10 Three stage DEC of prestressed and RC product, with prolonged natural cure, $\gamma = 7.5$

4.2 Calculating the working voltages and respective currents

According to Ohms' Law, $I = U^*/R$, $P = IU = U^2/R$. In order to calculate the tension necessary to obtain the required power, we must first know the load resistance. (* see list of symbols, page ix)

$$p = \frac{U^2}{r}; \quad U = (pr)^{\frac{1}{2}}$$

where p = unit power, U = tension, r = unit resistance

The calculations can be simplified by selecting 1 cm^2 as the average cross section of concrete between the electrodes. The method of calculation varies greatly according to the shape, size and relative position of the electrodes. We shall deal with this aspect in some detail.

CASE 1 The simplest configuration is the case of two parallel, equidistant plate electrodes of identical dimensions, as in a battery casting machine (the ideal application of DEC). In this case, the electric field is uniform. The current flow and the resulting heat distribution are also uniform, assuming no part of the reinforcement is perpendicular to the leaves, which conforms to general practice (Fig. 11).

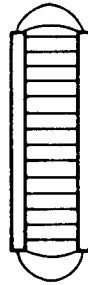


Figure 11 Electric field between parallel equidistant plates

If F is the area of a plate in cm^2 , d the distance between the electrodes in cm and P_e the total calculated electric power for the specific curing cycle in w . Then

$p = P_e / F$ = the power dissipated in 1 cm^2 cross section of concrete, parallel to the electrodes

$r = \rho d$ = resistance of 1 cm^2 cross section as above ($\Omega\text{ cm}^2$)

ρ = specific resistance, referred to 1 cm^3 concrete ($\Omega\text{ cm}$)

i = unit current = U/r ; I = total current = Fi

The resistivity ρ of freshly poured concrete varies, depending upon the composition of the mix (see section b in Chapter 1), its age and temperature. For best results, ρ should be measured on a representative sample of the mix, between parallel plate electrodes at various curing points. A DEC test cube mould fitted with a temperature sensor, fed through a Variac, is well suited for the purpose. (Fig. 12) The procedure is as follows.

- a. Establish the power requirement of the cube, in order to obtain a temperature rise similar to that of the product, in the same heating time. The power will not be proportional to the respective masses, because the cube has a much higher surface modul and consequently smaller time constant. However, using the same θ_f and T_h (the intersection of the two heating curves) gives the right result.

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- b. Regulate the input voltage to produce a current, when the product of the two will roughly equal the required power. (The power factor will approach 1.) Note pressure, current and temperature.
- c. Adjusting the pressure, to maintain approximately the same current, take repeated readings after 1, 2, ... T_h hours. The resistivities will be given by

$$\rho = \frac{U}{I} \cdot \frac{F}{d} \quad \Omega \text{ cm}$$

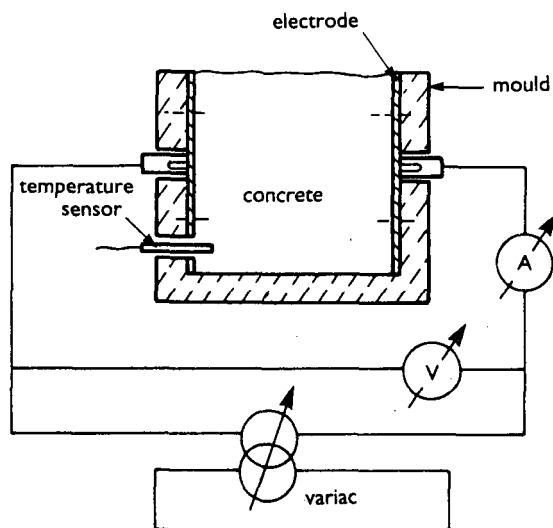


Figure 12 Cube test rig for measuring ρ

- d. Draw the time/resistivity curve (see Fig. 5). Take the arithmetical average for ρ as measured at equal time intervals and from the respective formulæ calculate r , U and i .
For example, in a mix with 360kg/m^3 RHPC and 0.38 W/C ratio, heated from 10°C to 40°C in 3 hours, a good approximation for ρ_{av} would be $850 \Omega\text{cm}$. With the heating time increased to 5 hours, it will be nearer to $1000 \Omega\text{cm}$.

CASE 2 The computation becomes more intricate when the mould and reinforcement constitute the electrodes. In its simplest form, the reinforcement consists of equidistant rods or prestressing strands forming a plane, running parallel to the sides of the mould (Fig. 14). Here the electric field is no longer uniform, nor is the current flow. However, if $r_0 \ll h$ and $r_0 \ll a$, there is an algebraic solution to the problem:

$$R_{\text{sub}} = 2\rho \frac{(0.01h)}{a} \cdot \frac{\ln[\sin(\pi r_0/a) / \sinh(\pi h/a)]}{\ln[\sinh(\pi 0.99h/a) / \sinh(\pi h/a)]}$$

= resistance of a quadrant, and $R_u = (R_{\text{sub}} / 4N) \cdot 100$
 = the total resistance of 1cm^2 of slab, between mould plates and reinforcement.
 N is the number of rods per metre length.

If the reinforcement is not symmetrically located within the mould, (Fig. 14) the calculation can be modified so that the resistance of two quadrants is calculated in relation to h_1 and h_2 . Then the resulting

total resistance will be

$$R_u = \frac{R_{sub1} R_{sub2}}{2N(R_{sub1} + R_{sub2})} 100$$

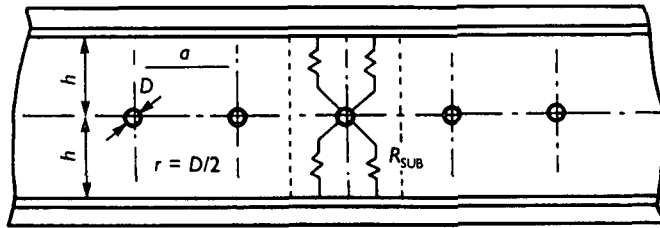


Figure 13 Resistance between centrally located reinforcement rods and parallel mould plates

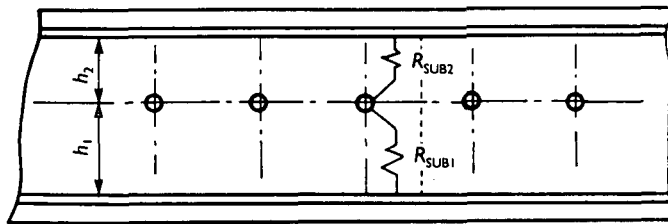


Figure 14 Resistance between asymmetrically placed reinforcement rods and parallel mould plates

When the reinforcement consists of a mesh instead of rods, two calculations are needed, one for the vertical and one for the horizontal rods. The two are then superimposed, i.e. put in parallel. The actual resistance will be slightly higher than calculated, due to the increased electric flux density at the intersections. For instance with a square mesh, the approximate resistance will be

$$R_{usq} = 0.5 R_u \rightarrow 0.6 R_u \text{ with decreasing mesh size}$$

The algebraic solution can also be used for reinforcing rods or strands distributed symmetrically in space (Fig. 15). For the configuration shown, the resistances of the strands to the nearest mould side are calculated and added up in parallel. The algebraic solution is valid only for cases, where $h > a/2$.

The resistance between reinforcement and mould, with a near-concentric section (Fig. 16) is given as:

$$R_{uc} = \frac{\rho}{2\pi} \ln \frac{r_2}{r_1} \text{ per cm length}$$

or in the case of a semicircular configuration, twice the above value. With certain reinforcement-product shapes, a combination of R_{sub} and R_{uc} calculations can give a useful numerical solution.

CASE 3 Many reinforcement-mould parameters and shapes do not satisfy the constraints indicated. Although some can be resolved into planar components to make use of the algebraic method, this does not apply to all cases (Fig. 17). Such problems have no exact mathematical solution and the best approximation can be obtained by either

- a) Experimental field mapping, or
- b) The iteration method

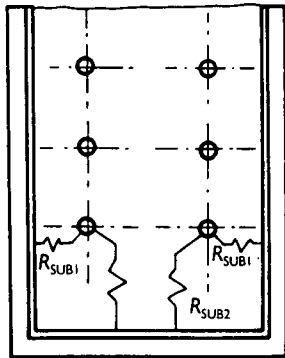


Figure 15 Reinforcing strands distributed in space symmetrically

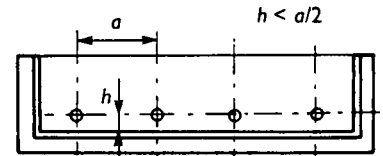
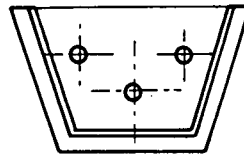


Figure 16 Reinforcement and mould approaching the shape of two concentric circles

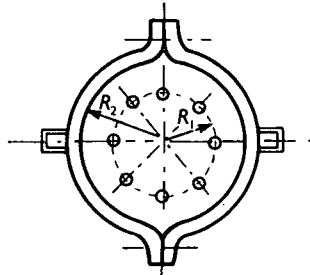


Figure 17 Reinforcement-mould configurations, with no algebraic method to calculate the resistance

$$\text{For Figure 15: } \frac{1}{R_u} = \frac{1}{R_1} + \frac{1}{R_2}; R_1 = \frac{R_{\text{sub1}}}{12}; R_2 = \frac{R_{\text{sub2}}}{2}; R_u = \frac{R_{\text{sub1}} R_{\text{sub2}}}{12R_{\text{sub2}} + 2R_{\text{sub1}}} \text{ /cm}$$

a) *Field mapping*, although requiring some graphic skill and experience, is a very convenient means of solving practically *any* problem encountered in dealing with precast and building elements. The accuracy of the method is sufficient for practical purposes. The underlying principle is the fact that the resistance of a square - for example, cut out of a sheet of conducting paper - is invariably ρ , irrespective of its size. Namely, the resistance of a conductor $R = \rho (\ell/A)$, where ℓ = length and A = cross section. If, for unit thickness $A = \ell \times 1$, $R = \rho (\ell/(\ell \times 1)) = \rho$. The same is valid for a square faced prism (measured across the square), 1 cm deep. Accordingly, the method is suitable for configurations of a constant cross section, which reduces the problem to one of two dimensions.

If there is a pressure difference between two electrodes, an electric field is created. The potential distribution in this field can be conveniently represented by equipotential lines (Fig. 18). The strength of the field is indicated by the density of the electric flux lines, commencing at one electrode and terminating at the other (In DEC we deal only with two electrode systems) (Fig. 19). The flux lines are perpendicular to the electrode contours and the equipotential lines.

To establish a "field map", the electrodes should be drawn to scale and the equipotential lines, which divide the field into equal pressure zones, entered with reasonable accuracy. Next, the flux lines are marked in, creating curvilinear squares with the equipotential lines. Thus a "map" emerges, made up of

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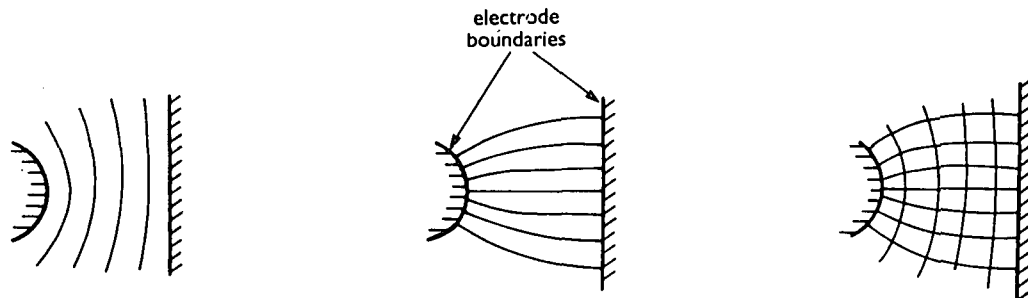


Figure 18 Equipotentials in an electric field Figure 19 Electric "flux" lines Figure 20 Field map

(near) squares. The resistance between the electrodes - for unit depth - will then be represented by

$$R = \frac{\text{Number of squares lengthwise}}{\text{Number of squares crosswise}} \rho$$

"lengthwise" meaning along the path leading from one electrode to the other, "crosswise", perpendicular to it (Fig. 20). A recurring problem in DEC is the calculation of the resistance between a reinforcing rod - or bunch of rods - and the sides of a mould (Fig. 21). For this drawing:

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} = \frac{1}{1} + \frac{1}{2} + \frac{1}{1} = \frac{2+1+2}{2} = \frac{5}{2}$$

$$R = \frac{2}{5} \rho \text{ ohm/unit mould length}$$

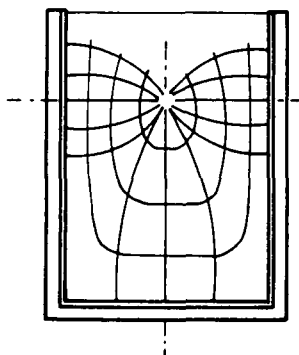


Figure 21 Field map solution for resistance problem between reinforcing rod and mould sides

b) With some rarely-occurring configurations however, the potential distribution and consequent position of the equipotentials is not obvious, not even approximately. In such cases the *iteration method* is helpful. It works as follows.

The section to be investigated is divided into a network of squares. The junctions are the potentials to be found. It can be shown (from Laplace's equation in two dimensions: $\nabla^2 V = 0$) that the potential at a junction is one quarter of the sum of the potentials at the four adjacent junctions, i.e. $V_0 = \frac{1}{4} (V_1 + V_2 + V_3 + V_4)$. Now let us consider the cross section with the boundary potentials marked in Figure 22. Applying the formula for V_0 , the potential at the centre of the square will be: $\frac{1}{4} (100 + 0 + 0 + 0) = 25V$ (Hayt W.H. Jr.: *Engineering Electromagnetics*, McGraw-Hill, 1958)

The region has been divided arbitrarily into 16 squares, and some estimate of the potential must now

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be made at every corner, before applying the iterative method. The better the estimate, the shorter the calculation. However, the final result will be independent of the initial estimate.

The potentials at the centres of the four double-sized squares will be estimated by taking the average of the potentials at the four corners, applying the formula this time, along a diagonal set of axes. The "diagonal average" is used only for initial estimates. By estimating a potential of 50V for the gap - the average of 0 and 100 - the potential at the centre of the two upper double squares will be $\frac{1}{4} (50 + 100 + 25 + 0) = 43.8V$. For the lower ones = $\frac{1}{4} (0 + 25 + 0 + 0) = 6.2$. The potentials at the remaining four points may now be obtained, by applying the formula directly.

Now we have a set of *estimated* values shown in Figure 22. In order to obtain *exact* values, we have to make corrections. To do so, a traverse is made, beginning in the upper left hand corner with the 43.8 value, working across the row to the right and then dropping down to the second row, proceeding again from left to right. Thus the 43.8 value changes to $\frac{1}{4} (100 + 53.2 + 18.8 + 0) = 43.0$. Using always the last (best) data, because of the obvious symmetry, 53.2 changes to $\frac{1}{4} (100 + 43.0 + 25.0 + 43.0) = 52.8$. Dropping down to the next line, the 18.8 value becomes $\frac{1}{4} (43.0 + 25.0 + 6.2 + 0) = 18.6$, the traverse continuing in this manner. The values at the end of this traverse are shown as the top numbers in each column of Figure 23.

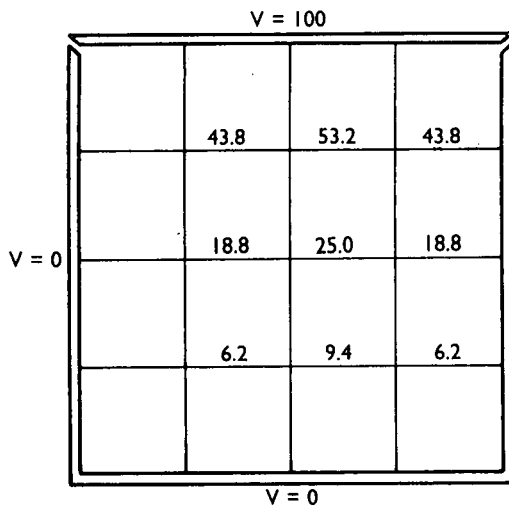


Figure 22 Iteration-Preliminary estimated values

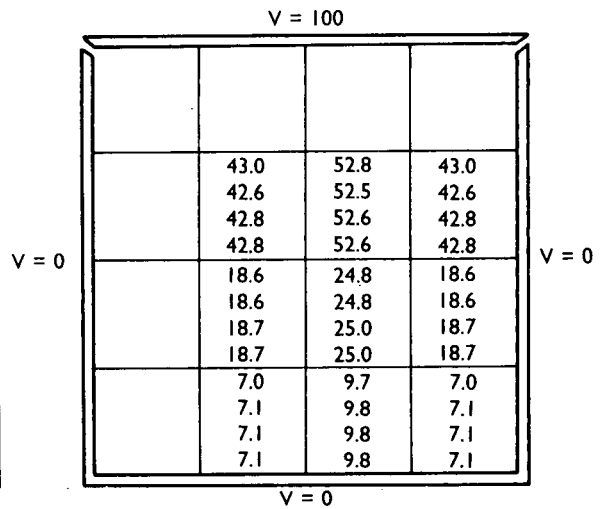


Figure 23 Iteration-Subsequent traverses and final values

Additional traverses should follow, until the figures at each junction do not change any more. The values of the successive traverses are entered below each other in column form, the final one shown at the bottom of the columns. In our case, only four traverses are required to obtain the final values, as shown in Figure 23. For greater accuracy a denser grid should be used, such as subdividing each square into four smaller ones. This will entail more work, but will make it easier to draw the field map.

Iteration is a laborious, time-consuming process. However, it lends itself readily to computer programming, rendering it an efficient, powerful tool (See: Fenner R.T. *Computing for Engineers*, McMillan 1974).

Having established the resistance of the product between the electrodes per cm^2 or cm length, the tension and current is readily calculated, as shown on page 27. Although in the final heating stage the load is near resistive, during the earlier stages of the curing, the power factor may be rather low if the regulating equipment works on the wave-chopping principle. In such a case, it is advisable to assume a $\cos \phi$ (power factor) of 0.85-0.90 in calculating the rating of the heating equipment (as an average value).

4.3 Designing the curing scheme

When all the calculations have been made (pp 24, 27), the design of a DEC scheme differs little from that of any other industrial electric heating system. The design has to include the medium voltage power supply from a substation, a feeder line to the production site and its protection, a switchboard housing the protection, control, metering and alarm equipment, the heating transformers with their medium and low voltage cable networks, and the heat sensors with their control lines. A typical single line diagram of such an installation is shown in Figure 24.

The only basic difference between a DEC and any other resistance heating scheme is of course, that the heating element is the product itself, the wet concrete. During its transition from low to medium, and ultimately high resistivity, some form of power, voltage or current control is necessary, in keeping with these changes.

Considering the nature of the maturing process, i.e. the setting and the gradual hardening phase, the best approach involves applying a gradually-increasing voltage, while maintaining a constant current. In this way, the power fed to the product is directly related to the gain in its strength. The elegance of the solution lies in the self-regulation of the system. The increasing resistivity of the concrete - irrespective of time or temperature - is matched by an increase in the applied voltage and consequently the power input, until the full secondary pressure of the supplying heating transformer is reached. Beyond that "cut off" point, obviously the current tapers off with any further increase of the load resistance, thus limiting the power input.

Allowance should be made for pressure drops in the cable network, particularly in the secondary lines, when calculating the size of the heating transformer(s). Voltage drops can be quite substantial due to the use of high currents at low voltages. This is especially so during the initial heating period, when the system can have a rather low power factor. With increasing resistivity the $\cos \phi$ also improves, reaching nearly 1 at the "cut off" point. However, the ohmic resistance of the cables in itself can result in a pressure drop of 10 - 12%, if the cables are kept within reasonable size limits.

One way to prevent excessive voltage drops is to keep the length of the secondary cables to a minimum. The production line for many precast elements is long. It thus becomes economical to use two or sometimes even three heating transformers alongside the line and as near to it as operational constraints permit, instead of one large centrally-located unit. If several parallel lines are to be cured, the heating times should be consecutive, as far as practicable. If overlapping is unavoidable, it should be kept to a minimum. A carefully planned curing régime will give a favourable load factor and a better exploitation of the substation capacity.

With small installations, say up to 120 kVA, a single heating transformer will usually be adequate and a single phase supply admissible. The out-of-balance load (when the three phases of the electric supply system are unevenly loaded) should not be too onerous, even for a medium size factory. In such cases, the quantity of concrete to be cured is comparatively small (4 to 5m³) and the casting time short. Accordingly, with due precaution, the heating usually can be switched on after the first load of concrete has been distributed (to keep the reinforcement in place). As pointed out previously (Section 3.2.1), the initial heating rate will be high until casting is completed. The mould is then thoroughly revibrated (taking care not to cause segregation), removing the entrapped air and surplus moisture. Finally, the product is floated off and the mould covered.

At this stage, there should be a well-compacted, semi-fluid mass of warm concrete, at a temperature of 40 - 45°C, depending on the ambient temperature. If the product is of a medium or low surface modul and the available cooling time is long enough, the power can be switched off. With a higher γ , the heating should be prolonged, but at a reduced power. For a higher production rate, for example, two mould turn overs in an 8 hour shift, the overall curing time available is shorter, especially for the first cast. The cut-off temperature should be raised accordingly to 50 - 55°C for the first cast, but can be lowered for the second.

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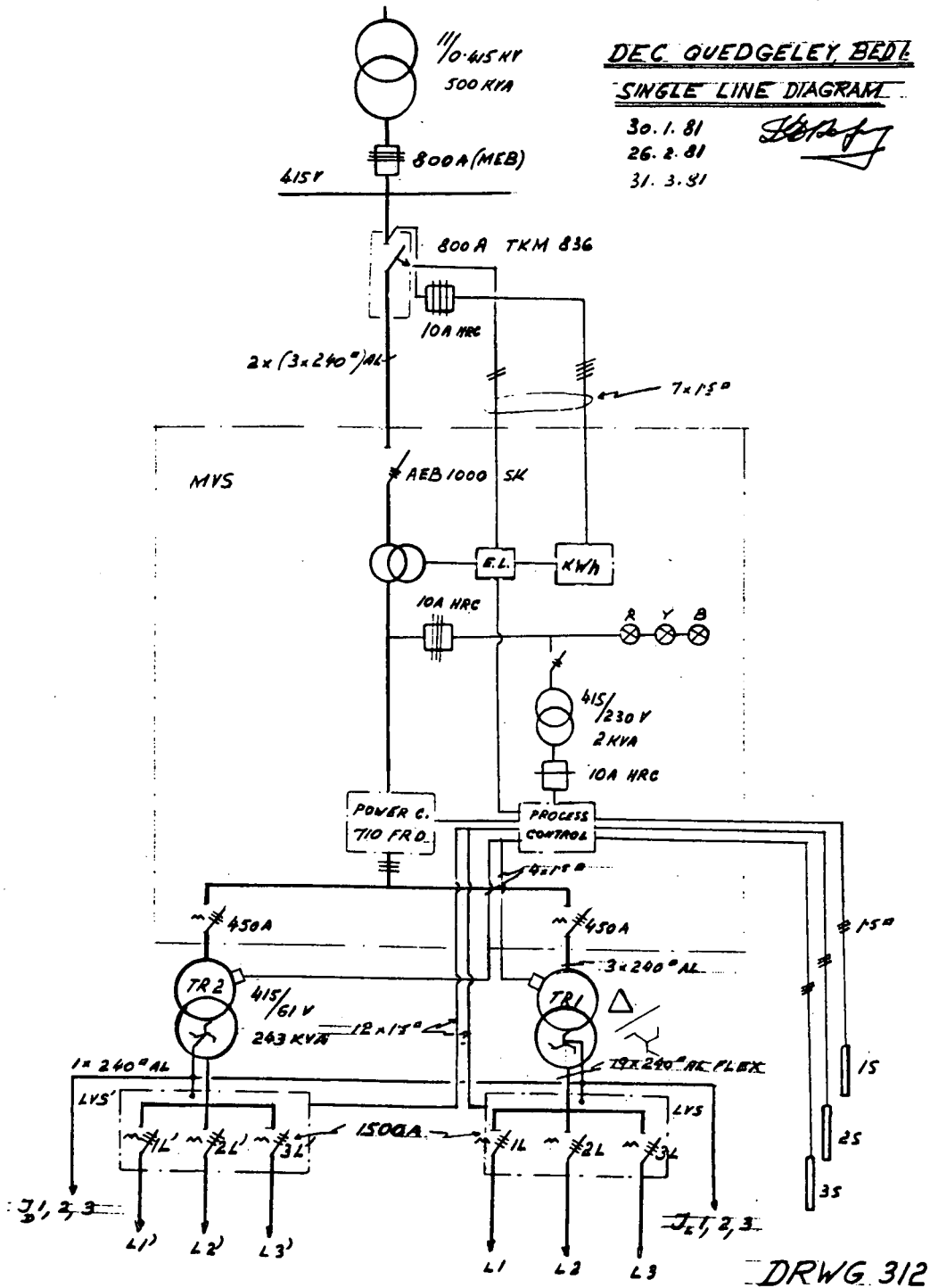


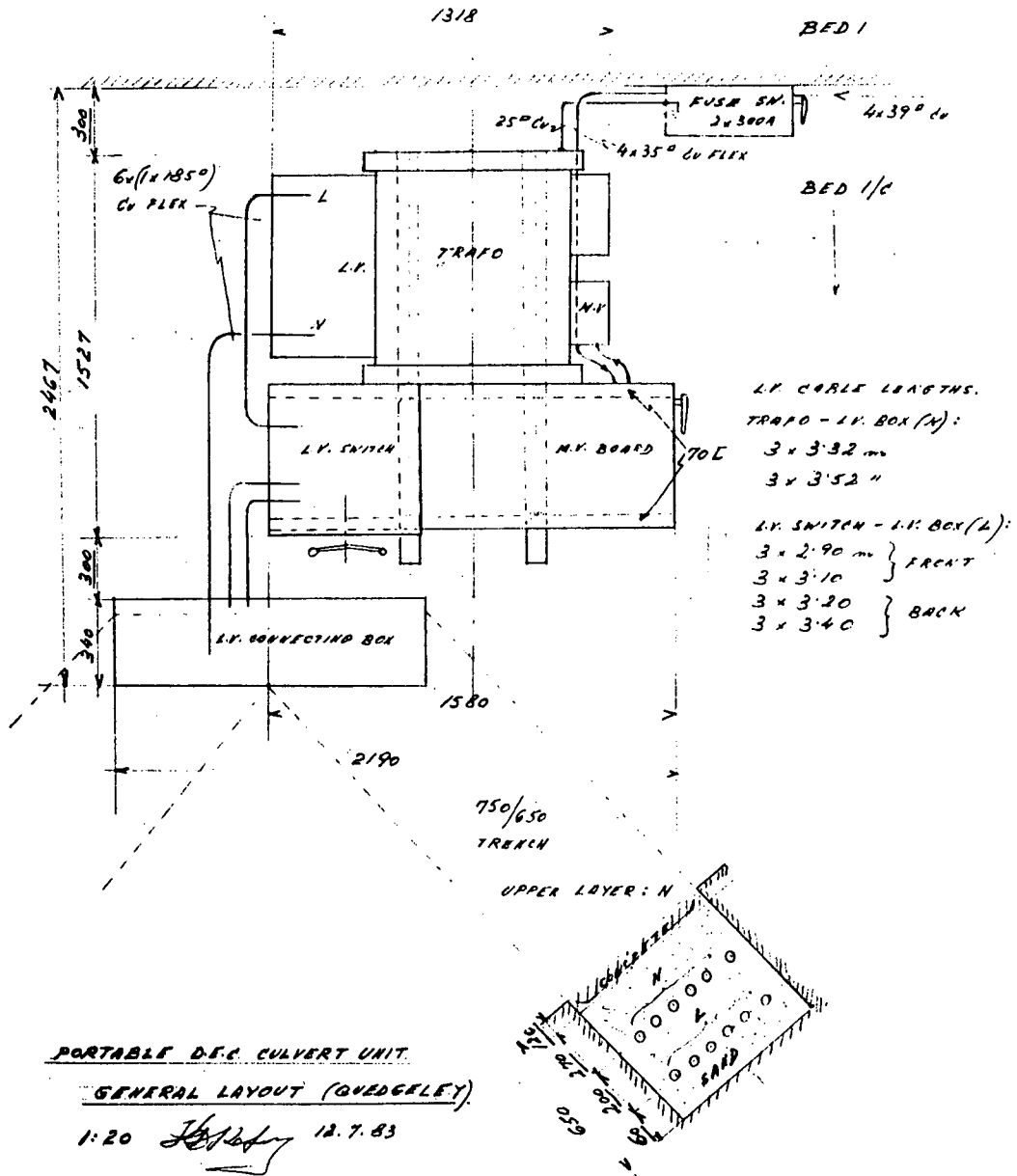
Figure 24 Single line diagram of a typical DEC installation

In such an installation, hardening takes place predominantly, or exclusively, during the cooling stage. A primary tapped heating transformer with off-load switching facility provides an adequate

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prestressed product. By necessity, the terminations fixed to the prestressing jacks are in air, cooled only by convection so their temperature can become much higher than that of the strand portions embedded in the concrete.

The generally-accepted alternative is the creation of a balanced three-phase load, as far as possible, on each production line. This is accomplished by dividing the mouldage of the line into 3, 6 or 9 discreet sections, connected consecutively to the three phases. The (electrically) continuous reinforcement will then serve as the neutral of the system. It will carry *within* the product the full load



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Figure 26 Portable DEC culvert unit. General layout.

current of that section at the boundary of two adjacent phase groups. However in the end portions, there is supposed to be only a small residual out-of-balance current.

In practice, the cost of equipment necessary to produce a perfectly-balanced three-phase load may prove prohibitively expensive. Consequently, up to 30% of the full load current should be allowed for in the end portions of the neutral and the cable connecting it to the heating transformer star point terminal. Figure 27 shows a workable layout for a factory with three production lines. The daily output is 84m³ of prestressed concrete in an 8 hour shift with each line divided into two 3 phase sections. There is more than a single L.V. line provided for each phase section, to ensure an even current and heat distribution in the product.

There are several methods to supply a multi-line production site. The most widely used solutions are:

- a. Each line or line section has its own heating transformer fed from its own power controller. In such a case, the on/off switching of the power is also performed by the controller, from the transformer primary side ("block switching"). No breaker or contactor is required, only an isolating switch in each branch (Fig. 28).
- b. One power controller feeding 2 or 3 line section heating transformers by way of a set of bus-bars, connected to the transformer primaries via contactors. Each line has its power controller and heating transformers (Fig. 29).
- c. Similar to the above, but a single power controller and 2 or 3 heating transformers supplying a whole multi-line installation. In this case, the trafo secondaries are connected to L.V. bus-bars, distributing the energy via L.V. contactors to the first, second, etc. production line in turn (Fig. 30).
- d. A single power controller, supplying all the heating transformers switched from the primary side, with the secondaries solidly connected to individual line sections of a multi-line system (Fig. 31).

The choice will ultimately depend on economic considerations when the decision is taken.

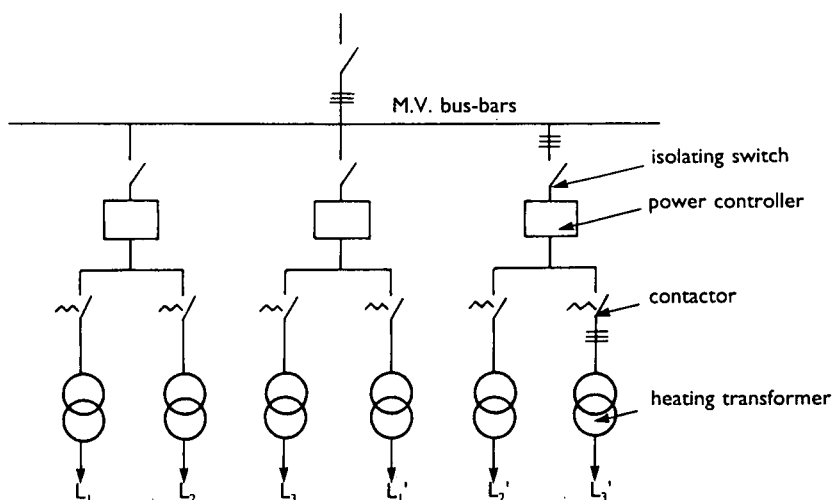


Figure 28 Each line section with its own power controller and heating transformer

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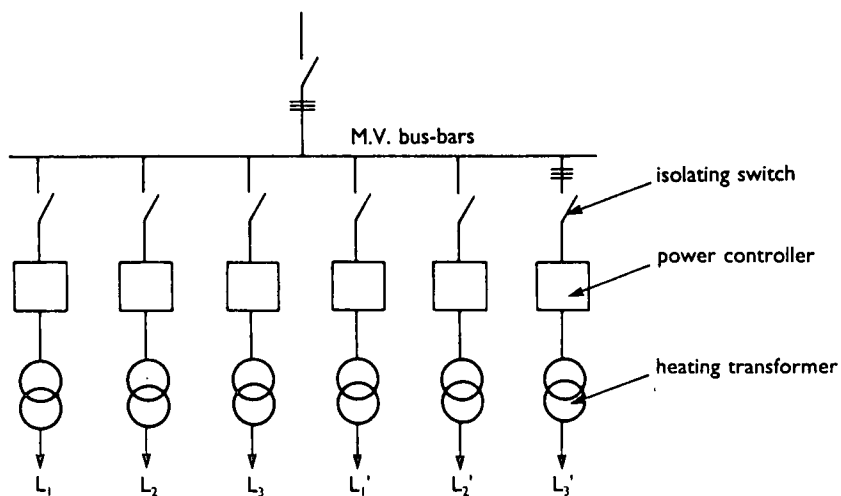


Figure 29 Each line with its own power controller and separate heating transformers for line sections

Battery Casting Machines deserve separate treatment. This is a popular method for the mass production of precast building elements, notably floor slabs and partition walls. It is also well suited to the casting of certain types of tunnel lining segments.

Batteries are compact and take up comparatively little space. They lend themselves eminently to DEC if purpose built for this curing system. The constructional criterion for such equipment would be that the individual "leaves" should be electrically insulated from each other - which is not too difficult to achieve. In order to achieve a well balanced load, such a battery should be made up of $3N - 1$ intermediate, plus two end support leaves (N being an integer, usually 1-3). Although larger

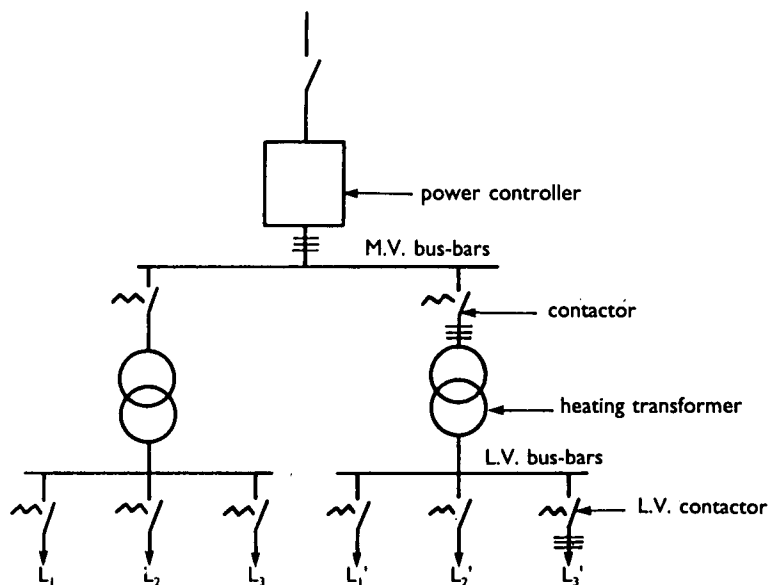


Figure 30 One power controller feeding two heating transformers, supplying all the line sections

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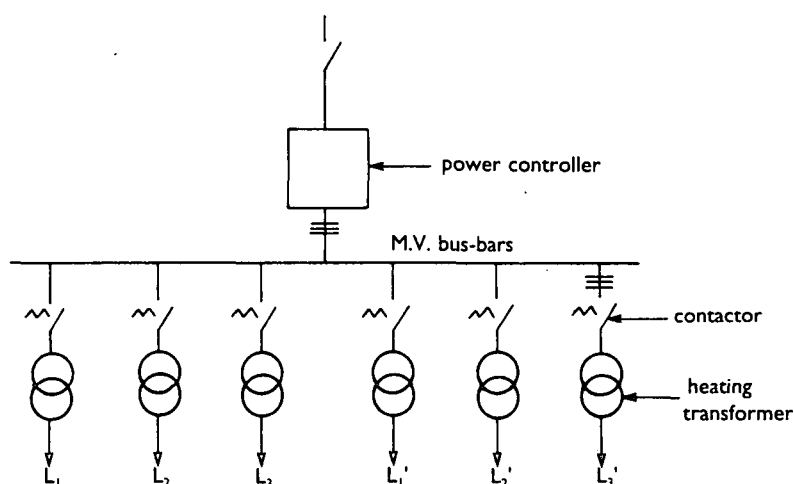


Figure 31 One power controller feeding individual transformers for each line section

batteries are conceivable, the setting up and casting time could become unduly long, the latter at the expense of product uniformity.

The curing power is fed from a single 3-phase transformer, the leaves connected consecutively to the three phases (Fig. 32). The secondary neutral is earthed, thus conforming to the statutory safety regulation which specifies less than 50V (50 cycle A.C.) equipment to earth potential. Depending on the size of the battery and the corresponding casting time, the heating rate can be controlled either by a primary tapchanger on the transformer, or the more expensive but more accurate power controller. The rather short secondary cables are connected by flexible terminations to the movable leaves.

With batteries casting up to 6 elements at a time and a good concrete supply system, two casts can be achieved in 24 hours without difficulty, at an ambient temperature of 10°C. With simple, standard reinforcement, i.e. short setting-up time, an even bigger turnover is feasible.

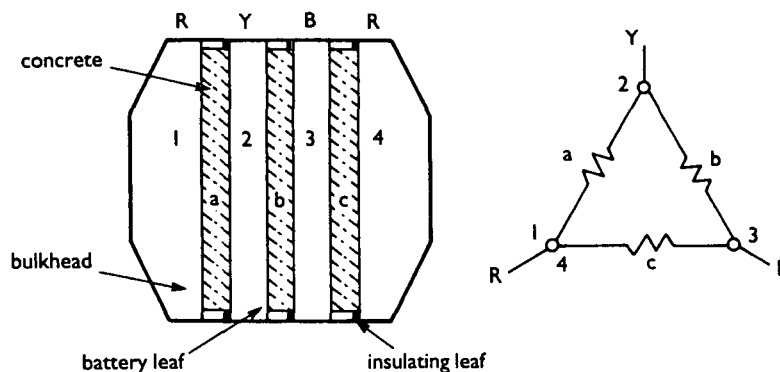


Figure 32 Battery casting machine for 3 elements-plan, schematic

The design of a curing scheme for the on-site application of DEC differs little from the ones for precast manufacturing factories, except for the greater flexibility required. If applied to the structural elements such as pillars, beams, solid cast floors of a high rise building, the position of the heating transformers will have to be changed, in step with the progress of the building. Although the main switchboard will be situated at ground level, some of the controls can be housed in a secondary board,

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mounted on the individual heating transformer. All the cables have to be flexible, and each M.V. line provided with earth leakage protection. The size of the transformers will be limited by the weight handling capacity of the building cranes. In order that the units be mobile, the transformer wheels will have to be rubber tyred (probably solid) and larger than standard.

For most applications the shuttering must be metallic. In the case of low-rise, widespread housing estates, the main switchboard should be portable, and the main feeder, possibly in the form of a ring main, should have several outlets. If public power supply is not available at the time of construction, portable diesel alternators can be used. Such power is more expensive, but probably still cheaper than steam.

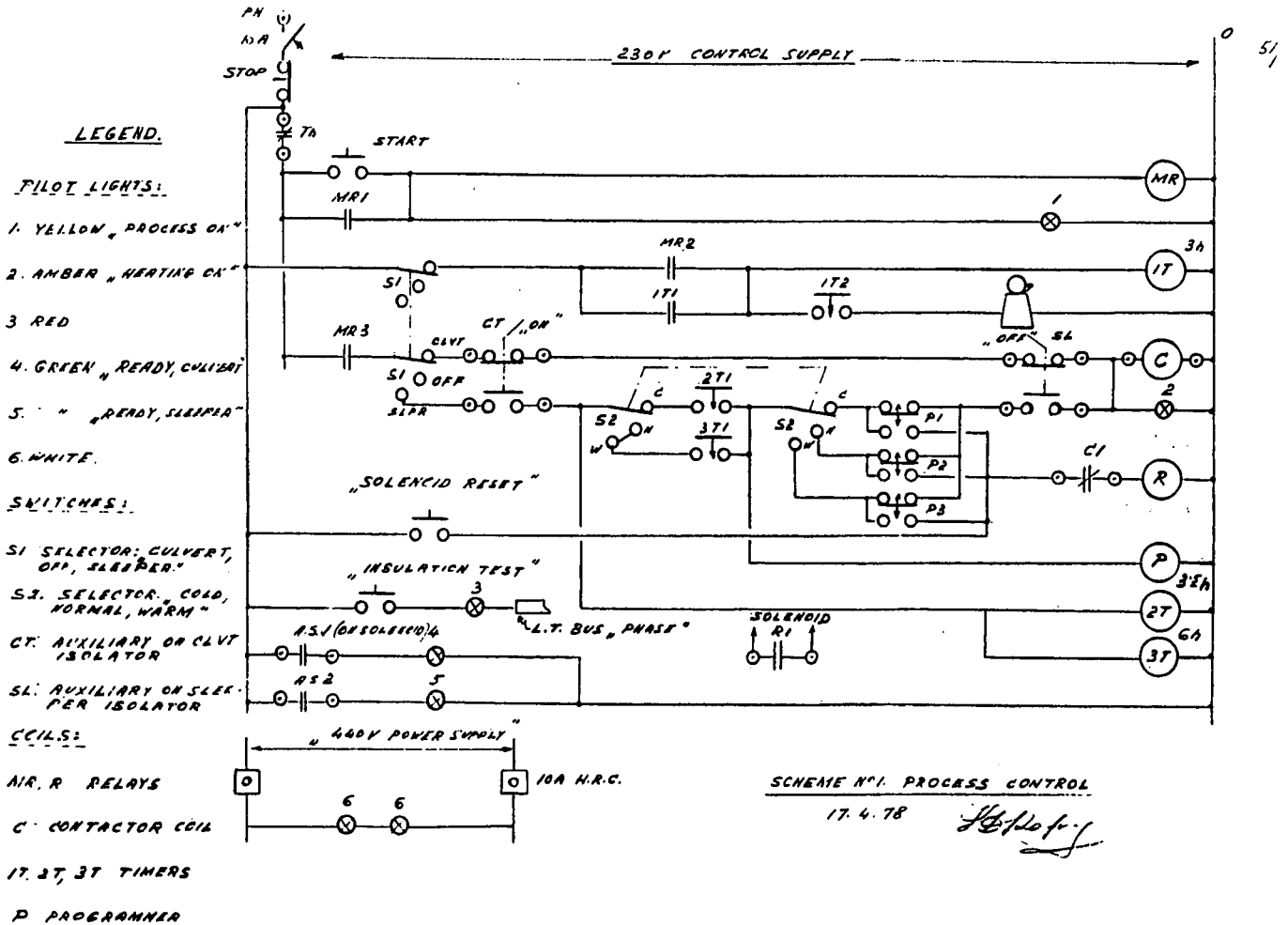


Figure 33 Voltage control by solenoid operated tap changer, for two alternatives (Alt.CLVT-hand operation; Alt.SL-automatic operation)

4.4 Designing the control scheme

It is now clear that some form of power control enhances the performance of a curing scheme. The two, basically differing, methods for the regulation of the input power are variable voltage heating transformers and solid state power controllers.

4.4.1 Variable voltage transformers

Variable voltage transformers are normally step-by-step regulators. Stepless transformers, such as the Variac (i.e. continuously regulated output voltage), are available. However, because DEC requires large units, stepless transformers are not competitive for price or performance, compared to solid state regulators.

The transformer tapings, located conveniently on the primary windings, are brought out to a rotary switch. This can be operated either directly by a hand-wheel, a geared solenoid or motor. The latter could be remote-controlled in conjunction with a programmer. An interlock in the operating mechanism ensures that the actual tap changing takes place with the transformer disconnected from the power supply. This method benefits from the comparatively low cost, particularly in the hand-wheel operated version. The performance with 4 steps is quite satisfactory for schemes where the hardening, and sometimes even the setting, of the concrete takes place during the cooling period. The variable voltage in this case serves only to set the input power level according to the product handled, its moisture content and reinforcement configuration. Its disadvantage lies in the need for some skill on the part of the charge-hand directing the casting operation. Figure 33 shows the diagram of such a control scheme.

No such constraint is imposed on a solenoid or motor operated programmed tap changer. The procedure is preset and automatic, suitable for any curing programme which requires a varied voltage source during the process (Fig. 33). The cost is lower than any solid state controller but this is reflected in the performance. The preset programme is rigid. It is not affected either by variations in the consistency of the concrete, variations of the ambient temperature during the heating, or the maturing process on the whole. The system *has* moving parts, subject to wear and tear. The method is suitable for relatively short heating times without skilled supervision, in particular for RC products. It is not as energy efficient as its solid state counterparts.

4.4.2 Solid state power controllers

Power controllers of the solid state variety are the ideal answer for use with DEC, or indeed all accelerated curing of concrete. The basic components are power thyristors, connected in anti-parallel (Fig. 34). They have no moving parts (except cooling fans, in forced ventilated units) and are able to perform any continuous control function. They are equipped with various safety features such as protection against inrush currents, fluctuations in voltage supply, continuous overload and short circuits. They also act as switching devices.

There are two groups:

1. Burst fire controllers (intermittent firing)
2. Wave-chopping controllers (phase angle shift)

The performance of the burst fire controller is characterized by the supply of power to the load in intermittent bursts, instead of a continuous flow. The magnitude of the power input is determined by the ratio of the length of burst time to total length of the firing cycle. The latter is usually of the order of 1-2Hz. The effective power can be varied between 0 - 100%. The advantage of this control method is that it supplies full-wave pulse trains (Fig. 35), hardly distorting the wave shape or generating harmonics. Switching of the pulse trains occurs at zero current value of the sine wave and

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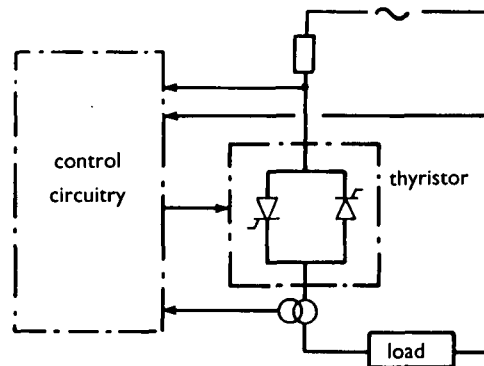


Figure 34 Principle of solid state power controller (single phase)

no D.C. components are generated.

A serious drawback of such a controller is its effect on the supply network and consequently on other consumers. The pulsating power, in step with the power bursts, could cause substantial voltage variations. This may be especially damaging with the use of larger units, which can be located near the termination of a rural distribution line. The effect can be partially overcome by sectionalizing the load (in the case of long production lines) and employing two or more smaller controllers. These will be electronically interlocked in a way that the power bursts of the various units are distributed in time. A near-uniform loading of the network should ideally be obtained although this is not easily achieved. This solution, of course, will be more expensive (Fig. 36). Reducing the size of the controllers will also alleviate the strain imposed on the transformer windings and cable connections, caused by the pulsating power.

Controllers working on the wave chopping principle, are free from the above mentioned predicament. The voltage regulation is effected by shifting the firing phase angle, chopping off part of the sine wave and reducing the effective value of the pressure accordingly (Fig. 37).

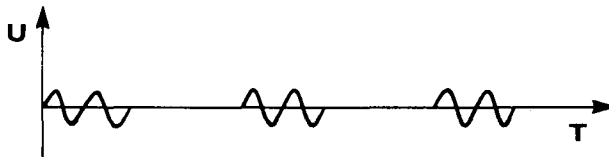


Figure 35 Performance of burst fire controller.

These controllers are very versatile, though more expensive than the burst firing units. However, wave chopping by its very nature introduces harmonics into the supply system. These should be kept within the limits permitted by the respective power supply authority. This should be clarified at an early stage with both the equipment manufacturer and the supply authority. The resulting wave form is not entirely free of D.C. components either; and so at higher flux densities saturation of the transformer core may occur. This is overcome by designing the heating transformer with a maximum flux density of 1 Tesla (10 kGauss).

In addition to the power controller, a control scheme involves the use of numerous other circuit elements, according to the task in hand and the safety features required for a trouble free operation.

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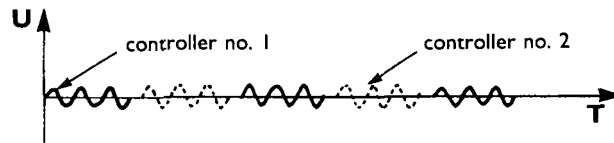


Figure 36 Performance of 2 interconnected burst fire controllers, with identical firing pulse

While starting of the process is usually manual, the consecutive switching of the additional production lines is conveniently effected by the use of a programmer. Stopping the heating of an individual line is achieved either by a temperature sensor, or, for high surface modul products by a timer, or a power operated relay. The latter is the most accurate method, as it measures the concrete maturity reached.

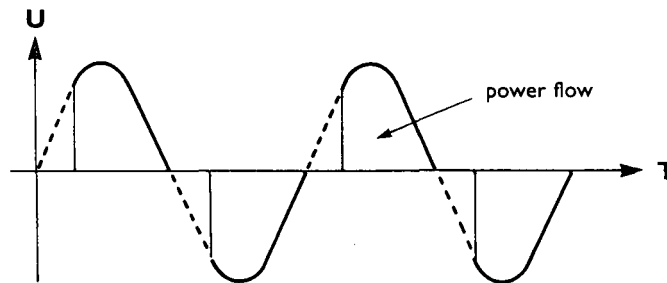


Figure 37 Performance of wave chopping controller

Another feature for schemes with longer heating times would be a set-up ensuring a continuous power supply, i.e. the automatic resumption of the process, after a temporary power failure. If the curing sequence of the production lines varies, selector switches enable the operator to preset the daily programme.

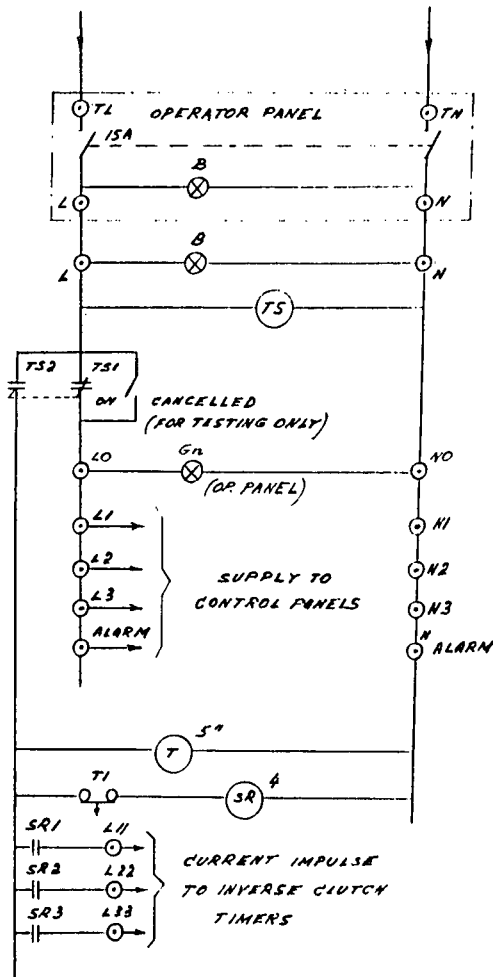
Incorporation of a time switch (synchronous clock, with mechanical reserve) can be useful if the heating times are restricted either from maximum demand or electricity tariff considerations.

Safety features would involve:

- a. Protection of the feeder line at the sub-station, with acoustic and visual fault indication.
- b. Overload and short circuit protection of the power controller, usually by inbuilt quick-acting fuses.
- c. Overload protection of the heating transformers. This can be achieved conveniently by thermal sensing elements built into the windings, actuating contactors for the main and alarm circuit.
- d. Alarm for fault indication in the temperature sensor circuits.

The secondary feeders, on account of the low voltages involved, do not need short circuit protection. Both cables and heating transformers are quite capable of withstanding a dead short at the end of a secondary line, which would burn itself clear before any damage would be done to the equipment. Figure 38 gives a comprehensive picture of such a control scheme.

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5A/a

LEGEND

- TS TIME SWITCH (CLOCK, 24h)
- B BLUE } INDICATOR LIGHT
- Gn GREEN }
- T TIMER
- TERMINAL FOR EXTERNAL CONNECTION

EAGLESCLIFFE D.E.C. (N.C.)

CONTROL DIAGRAMME

"COMMON" PANEL

13.10.82

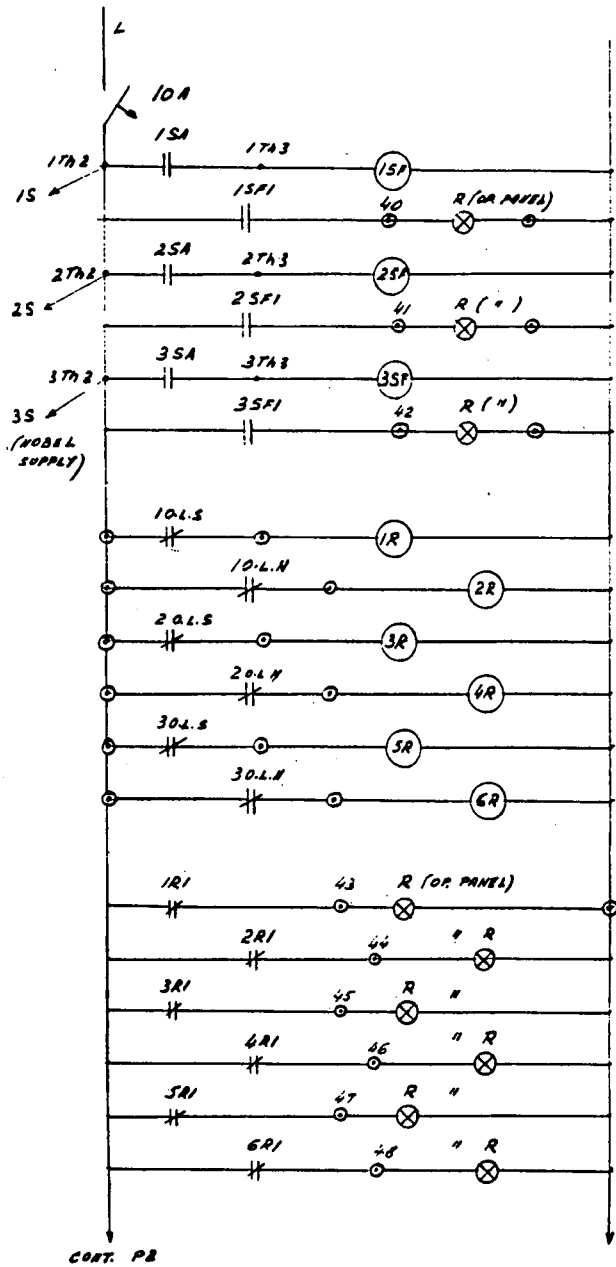
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DRWG 34

Figure 38 Comprehensive control diagram for 3 line prestressed production scheme

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LEGEND.

S.F. SENSOR FAULT RELAY
 IR-GR. TRAF. O.L. (ALARM)

EQUIPMENT.

- 1PC MCB 10A
- 10-RELAY 230V 5A 50Hz
- 2 CONTACT
- 1" 6A FUSE
- 1" HIGH PITCHED SIREN 170 W MIN.
- 1" LUDUS E.L. RELAY
- COMPLETE WITH C/P

CONT. P2

EAGLECLIFFE D.E.C. (H.C.)

CONTROL DIAGRAMME

ALARM PANEL P1.

9.12.82
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Figure 38 continued, part 4

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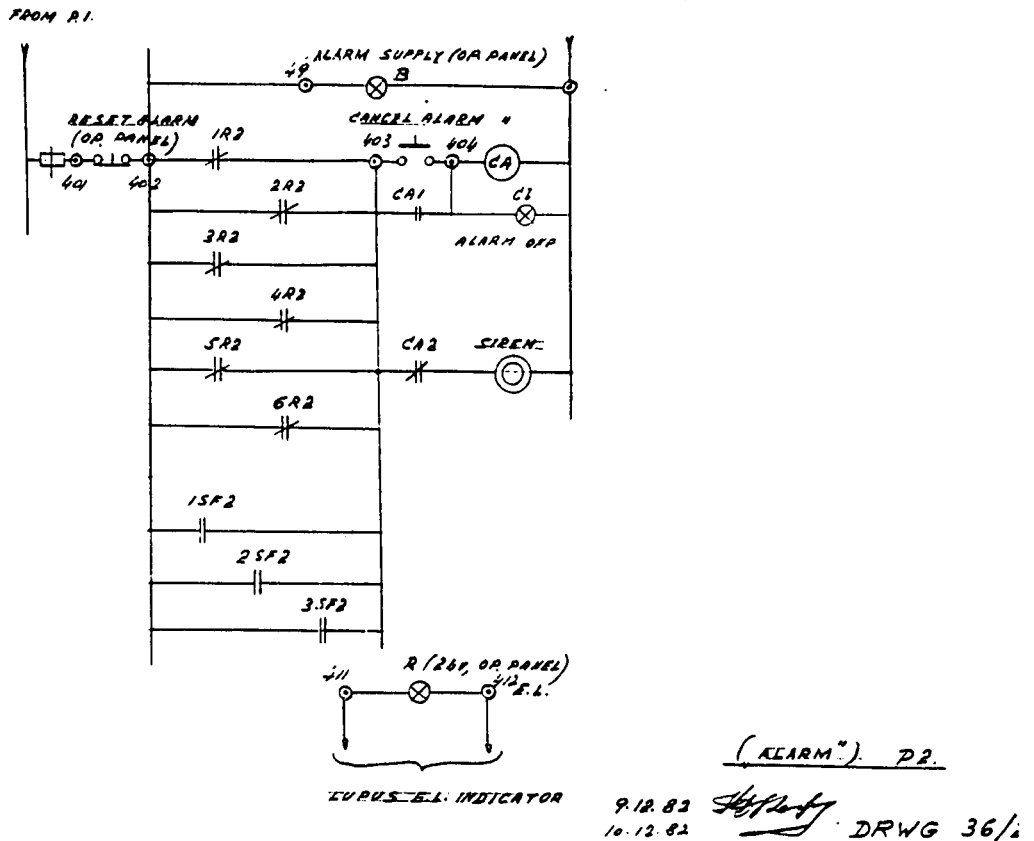


Figure 38 continued, part 5

4.5 Specifying the equipment

When the design work is complete, the next step entails the detailed specification of the equipment. The following guidelines will be helpful.

a. Main feeder

The main feeder will comprise a 2 or 3 core PVC/PVC or XLPE/PVC armoured copper cable, laid underground, protected by a circuit breaker. Current rating of the cable(s) should be based on the maximum load expected at any time, i.e. any overlapping in the heating stage of the various lines should be considered. The circuit breaker should be provided with a trip coil, actuated in addition to the inherent short circuit, and overload sensors by an earth leakage relay and an emergency stop button, the latter located on the main switchboard. An auxiliary contact on the breaker, closing in the tripped position, will serve an alarm circuit.

b. Main switchboard

This unit should be floor mounted, within a dust-proof enclosure with hinged doors and protected ventilation openings (both bottom and top) for cooling the power controller(s). The handles for isolating (safety) switch(es), push buttons, operating switches, indicator lights and instruments should be mounted on the doors. All other equipment is housed within the board, divided functionally into sections of adequate dimensions for easy access. Each and every piece of equipment must be clearly marked by engraved or anodised labels. All the control wiring entering and leaving the board should

5 Design Examples

This chapter presents the detailed design of curing schemes for some precast and in-situ concrete products.

5.1 Precast concrete

The location, general layout of the factories and production lines are usually established parameters. If DEC is being considered from the outset, the production lines can be accounted for early in the planning stage. The provision of cable routes as ducts or trenches, draw-in pits etc. can be provided for during the preparation of the factory floor, and this is highly recommended.

5.1.1 Culverts of rectangular cross section

This is a popular product for large underground sewage systems. The size of individual units may vary, hence schemes for sizes ranging from 2 x 2m to 3 x 3.5m external cross section, with wall thicknesses of 17.5 to 22.5cm, in units 1.5m long (Fig. 39) will be considered.

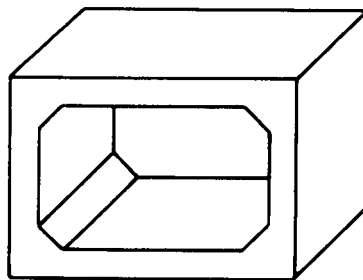


Figure 39 Rectangular culvert element

Following the procedure of "basic data requirement" as laid down in chapter 4 the relevant information is as follows:

- a. Quantity of concrete to be processed in an 8 hour shift:
Maximum: $2 \times (3 + 3.5) \times 1.5 \times 2 \times 0.225 = 8.78\text{m}^3$ (simplified)
Minimum: $2 \times (2 \times 1.5 \times 4 \times 0.175) = 4.2\text{m}^3$ (")
- b. One 8 hour shift
- c. A single mould, cast twice daily
- d. Demoulding strength 12N/mm^2
- e. RHPC, 350kg/m^3 , crushed granite aggregate, W/C 0.4, with plasticizer
- f. As mentioned above
- g. Two mesh of interconnected (partially welded) steel rods, placed at 2.2cm minimum distance from mould sides, forming a single cage.
- h. Base plate, with removable side walls; externals completely, internals partially
- i. After pouring the first load of concrete, power is switched on at a high rate, to bring the concrete temperature to approximately 65°C for small units, and 58°C for big units by the end of the first cast. After thorough revibration, the product is floated off, covered and power is reconnected for the big units at a reduced rate, until the temperature of approximately 65°C has

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been reached. Demoulding occurs 5 hours after beginning the casting.

For the second cast the same procedure follows, except that the final temperature will be 35°C during the winter, with probably no heating in the summer. Demoulding will take place the following morning.

j-k. The manufacturing site will be a closed shed in the U.K. Casting and finished product removal will be by overhead crane. The product will be stored in the open, for at least 24 hours before loading.

l. The existing substation has a spare capacity of 250kVA. The main M.V. distribution board is situated near to the substation, 120m from the casting site.

Two alternatives will be calculated - both for the maximum and minimum culvert sizes - according to differing mould constructions. In the first case, the mould is designed specifically to facilitate the application of DEC. The inner walls are electrically insulated from the base plate, thus the pressure can be applied between inner and outer walls. The advantage of this solution is that all connections to the electrodes are permanent (Fig. 40).

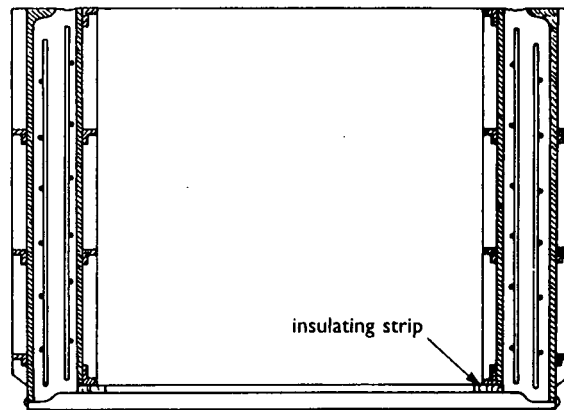


Figure 40 Section of DEC culvert mould

In the second case, any ordinary steel mould can be used without alteration. In this instance, the electrodes are the mould and the reinforcement. The drawback of this method is the need to prepare suitable connections for the reinforcement, which will have to be removed after each casting.

a. Maximum culvert size, produced in DEC mould

In order to determine the magnitude of the installation, the largest unit should be considered first.

CALCULATING THE POWER.

Volume of concrete per cast:	$8.78/2 = 4.39 \approx 4.4\text{m}^3$
Mass " " " " :	$4.4 \times 2400 = 10,560\text{kg}$
Surface " " " " :	$2 \times 3 \times 1.5 = 9.0\text{m}^2$
	$2 \times 3.5 \times 1.5 = 10.5\text{m}^2$
	$2 \times 2.55 \times 1.5 = 7.65\text{m}^2$
	$2 \times 3.05 \times 1.5 = 9.15\text{m}^2$
	$4 \times 2.775 \times 0.225 = 2.50\text{m}^2$

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$$4 \times 3.275 \times 0.225 = \frac{2.95\text{m}^2}{41.75\text{m}^2} \approx 42\text{m}^2$$

Surface modul $\gamma = 42/4.4 = 9.5 \text{ m}^{-1}$

λ (assumed) = $7\text{W/m}^2 \text{ }^\circ\text{C}$

Convection + radiation losses $A\lambda = 42 \times 7 = 294\text{W/}^\circ\text{C}$

Approximate mass of mould steel, 5mm plates, in intimate contact with the concrete:

$$(9 + 10.5 + 7.65 + 9.15) \times 40 = 1452\text{kg}$$

Time constant of the system = $\tau = [(10560 \times 0.22) + (1452 \times 0.11)] / 0.294 \times 860 = 9.8\text{h}$

Hydration heat = $Q_{\text{hy}} = (350 \times 70 \times 4.4) / 860 = 125.35 \text{ kWh}$

Considering for the first cast a total curing time $T_t = 5\text{h}$, the fraction of 3 day hydration heat released during that time $\eta \approx 0.5$, the corresponding hydration power

$$P_{\text{hyl}} = (125.35 \times 0.5) / 5 = 12.535 \text{ kW}$$

$$\text{and } \theta_{\text{mhyl}} = 12.535/0.294 = 42.6^\circ\text{C}$$

The minimum ambient temperature to be reckoned with in the casting shed is $t_o = 5^\circ\text{C}$. For the high rate heating stage, the final temperature aimed at is $t_{\text{na}} = 58^\circ\text{C}$, a temperature rise $\theta_{\text{na}} = 53^\circ\text{C}$. Assuming $T_{\text{h1a}} = 1.5\text{h}$

$$P_{1a} = \frac{53 \times 0.294}{1 - \epsilon^{-\frac{1.5}{9.8}}} = 109.792 \text{ kW}$$

and the electric power requirement

$$P_e = P - P_{\text{hy}}; P_{e1a} = 109.792 - 12.535 = 97.257 \approx 98 \text{ kW}$$

After thorough revibration and floating off, for the second heating stage:

$$t_{\text{nb}} = 65^\circ\text{C}; \theta_{\text{nb}} = 60^\circ\text{C} \text{ starting from } 53^\circ\text{C}; T_{\text{h1b}} = 0.5\text{h}$$

The equation reflecting the above conditions is:

$$\theta_f = \theta \epsilon^{-\frac{T_h}{\tau}} + \theta_m (1 - \epsilon^{-\frac{T_h}{\tau}}); \theta_m = \frac{\theta_f - \theta \epsilon^{-\frac{T_h}{\tau}}}{1 - \epsilon^{-\frac{T_h}{\tau}}}; P = \theta_m A \lambda$$

Substituting $\theta_f = 60$, $\theta = 53$, $T_h = 0.5$, $\tau = 9.8$ produces

$$P_{1b} = \frac{(60 - 53 \epsilon^{-\frac{0.5}{9.8}}) \times 0.294}{1 - \epsilon^{-\frac{0.5}{9.8}}} = 56.96\text{kW}$$

and

$$P_{e1b} = 56.96 - 12.535 = 44.425 \text{ kW}$$

CHECKING FOR MATURITY OBTAINED

Heating

Considering the first heating stage: $\theta_{\text{m1a}} = 109.792/0.294 = 373^\circ\text{C}$

and for the second $\theta_{\text{m1b}} = 56.96/0.294 = 194^\circ\text{C}$,

we see that the pertinent parts of the heating curves, due to the high time constant, will be almost

straight lines (Fig. 41). Accordingly the average temperature rise will be:

$$\begin{aligned}\theta_{\text{hav}} &= \frac{S1+S2+S3}{T_2} = \frac{1}{T_2} \left[\frac{T_1 \theta_{\text{fla}}}{2} + (T_2 - T_1) \left(\theta_{\text{fla}} + \frac{\theta_{\text{flb}} - \theta_{\text{fla}}}{2} \right) \right] \\ &= \frac{1}{2} \left[\frac{1.5 \times 53}{2} + 0.5 \left(53 + \frac{60 - 53}{2} \right) \right] = 34^\circ \text{C}\end{aligned}$$

$$t_{\text{hav}} = \theta_{\text{hav}} + t_0 = 34 + 5 = 39^\circ \text{C}; \text{ and } M_h = 2 \times 2.33 = \underline{4.66}$$

Cooling

From the foregoing, the available cooling time $T_c = T_i - T_h = 3$ hours. The average cooling temperature (see page 23):

$$\theta_{\text{cav}} = \frac{1}{3} \left(9.8 \times 60 (1 - e^{-\frac{3}{9.8}}) + 42.6 \left[3 + 9.8 (e^{-\frac{3}{9.8}} - 1) \right] \right) = 57.6^\circ \text{C}$$

$$t_{\text{cav}} = 57.6 + 5 = 62.6^\circ \text{C}; \text{ and } M_c = 3 \times 4.77 = \underline{14.31}$$

The total resulting maturity $M_t = M_h + M_c = 18.97 \approx 19$ i.e. the strength, equivalent to the one obtained when curing the same at 20°C for 19 hours. The respective curing curve shows this value to be slightly above the required demoulding strength of 12N/mm^2 . Accordingly, the envisaged time-temperature schedule for the shortest curing time at the lowest ambient temperature, i.e. the worst conditions, meets the strength required.

As we have seen, the actual casting and curing of the first unit is feasible within 5 hours. Adding to it $\frac{3}{4}$ hour for the demoulding of the second cast from the previous day, another $\frac{3}{4}$ hour for the setting up, and $\frac{3}{4}$ hour for the demoulding of the first cast, leaves $\frac{3}{4}$ hour for the setting up of the second cast, all within the 8 hour work shift specified. However, to this must be added $1\frac{1}{2}$ hours for the casting, floating off and covering of the second unit. Thus the production shift at worst, will have to be extended to 9.5 hours.

For the second cast, the available total curing time will be $T_i = 24 - 8 = 16$ hours. The hydration power, acting during this length of time works out to be:

$P_{\text{hy2}} = (125.35 \times 0.75)/16 = 5.875 \text{ kW}$, considering $\eta = 0.75$ and $\theta_{\text{mhy2}} = 5.875/0.294 = 20^\circ \text{C}$
Let us assume $T_{\text{h2}} = 4$ hours, $T_{\text{c2}} = 12$ hours, $t_0 = 5^\circ \text{C}$, $t_{\text{h2}} = 35^\circ \text{C}$, $\theta_{\text{h2}} = 30^\circ \text{C}$, then the power requirement will be:

$$P_2 = \frac{30 \times 0.294}{1 - e^{-\frac{4}{9.8}}} = \underline{26.318 \text{ kW}}; P_{\text{c2}} = 26.3 - 5.875 = \underline{20.443 \text{ kW}}$$

CHECKING FOR MATURITY

$$\theta_{\text{m2}} = 26.318/0.294 = 89.5^\circ \text{C}$$

Heating

$$\theta_{\text{hav}} = \frac{89.5}{4} \left[4 + 9.8 \left(\epsilon^{-\frac{4}{9.8}} - 1 \right) \right] = 16^\circ\text{C} ; t_{\text{hav}} = 16 + 5 = 21^\circ\text{C}$$

$$M_h = 4 \times 1.06 = \underline{4.24}$$

Cooling

$$\theta_{\text{cav}} = \frac{1}{12} \left(30 \times 9.8 \left(1 - \epsilon^{-\frac{12}{9.8}} \right) + 20 \left[12 + 9.8 \left(\epsilon^{-\frac{12}{9.8}} - 1 \right) \right] \right) = 25.8^\circ\text{C}$$

$$t_{\text{cav}} = 25.8 + 5 = 30.8^\circ\text{C}; M_c = 12 \times 1.68 = \underline{20.16}$$

$$M_t = 4.24 + 20.16 = \underline{24.56}$$

which is more than adequate, showing that our initial estimate of 35°C for t_2 has been high. A value around 30°C should be sufficient. This should modify θ_2 to 25°C and reduce the power requirement to

$$P_{2\text{mod}} = 25/30 \times 26.318 = 21.932 \text{ kW and } P_{e2\text{mod}} = 21.392 - 5.875 = \underline{16.057 \text{ kW}}$$

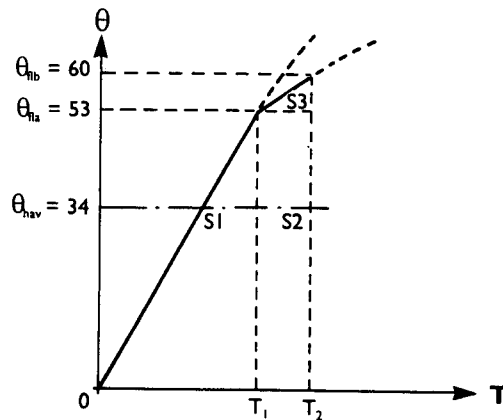


Figure 41 Average temperature rise in two stage heating

CALCULATING THE VOLTAGE AND CURRENT

The inner and outer mould sides form the parallel electrodes and the average electrode area will be

$$F = \frac{1}{2} (9 + 7.65 + 10.65 + 9.15) = 18.15\text{m}^2$$

The distance between the electrodes $d = 22.5\text{cm}$. Assuming a resistivity of 700 Ωcm for the concrete,

$$r = 700 \times 22.5 = 15,750 \Omega\text{cm}^2$$

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For the first cast, first heating stage

$$P_{e1a} = 98/(18.15 \times 10^4) = 0.54 \text{ W/cm}^2,$$

$$U_{1a} = (0.54 \times 15750)^{1/2} = \underline{92.2 \text{ V}}$$

$$i_{1a} = 92.2/15750 = 0.00585 \text{ A},$$

$$I_{1a} = i_{1a} \times 18.15 \times 10^4 = \underline{1062 \text{ A}}$$

For the first cast, second heating stage

$$P_{e1b} = 44.425/(18.15 \times 10^4) = 0.245 \text{ W/cm}^2,$$

$$U_{1b} = (0.245 \times 15750)^{1/2} = \underline{62 \text{ V}}$$

$$i_{1b} = 62/15750 = 0.00394 \text{ A},$$

$$I_{1b} = i_{1b} \times F = \underline{716 \text{ A}}$$

For the second cast

$$P_{e2mod} = 16.057/(18.15 \times 10^4) = 0.0884 \text{ W/cm}^2,$$

$$U_2 = (0.0884 \times 15750)^{1/2} = \underline{37.7 \text{ V}}$$

$$i_2 = 37.3/15750 = 0.00237 \text{ A},$$

$$I_2 = i_2 \times F = \underline{430 \text{ A}}$$

b. Maximum culvert size, produced in an ordinary mould

If the ambient temperature and general conditions remain the same, the power calculations remain unaltered for the masses involved. However, the pressures and currents *do* change, due to the differing electrode configurations. As pointed out, the mould sides (forming now an equipotential surface), and the reinforcement comprise the electrodes. The electrical resistance of the system will depend of course on the shape of the reinforcement.

In the case study, the reinforcement is a double cage square mesh, 15 x 15cm, made up of 9mm dia. M.S. rods. Although in practice both the size of the mesh and the rods may differ (and probably will!) in the outer and inner cages, for simplicity we shall assume uniformity.

Due to the proximity of the reinforcement to the mould faces, we cannot use the algebraic solution for the determination of the resistance. The graphic method however, gives a good approximation of 1.8 times the resistance of that between two parallel plates, for the indicated configuration. Accordingly, the resistance between the two mould faces and the reinforcement will be:

$$r = (2.2 \times 700 \times 1.8)/2 = 1386 \ \Omega \text{ cm}^2$$

For the first cast, first heating stage

$$P_{e1a} = 0.54 \text{ W/cm}^2; \quad U_{1a} = (0.54 \times 1386)^{1/2} = \underline{27.4 \text{ V}}$$

For the first cast, second heating stage

$$P_{e1b} = 0.245 \text{ W/cm}^2; \quad U_{1b} = (0.245 \times 1386)^{1/2} = \underline{18.4 \text{ V}}$$

For the second cast

$$P_{e2mod} = 0.0884 \text{ W/cm}^2; \quad U_2 = (0.0884 \times 1386)^{1/2} = \underline{11 \text{ V}}$$

DIRECT ELECTRIC CURING OF CONCRETE

The respective currents will be:

$$I_{1a} = (27.4/1386) \times F = \underline{3588A};$$

$$I_{1b} = (18.4/1386) \times F = \underline{2410A};$$

$$I_2 = (11/1386) \times F = \underline{1440A}$$

c. Minimum culvert size, produced in DEC mould

CALCULATING THE POWER

Volume of concrete per cast:	4.2/2 = <u>2.1m³</u>	
Mass " " " " :	2.1 x 2400 = <u>5,040kg</u>	
Surface " " " " :	4 x 2 x 1.5 =	12.0m ²
	4 x 1.65 x 1.5 =	9.9m ²
	8 x 1.825 x 0.175 =	<u>2.56m²</u>
		24.46 - <u>24.5m²</u>

Surface modul $\gamma = 24.5/2.1 = 11.66m^{-1}$; λ (assumed) = 7W/m²

Convection + radiation losses $A\lambda = 24.5 \times 7 = \underline{172W/^\circ C}$

Mass of mould steel in intimate contact with the concrete (approx.): $(12 + 9.9) \times 40 = \underline{876kg}$

Time constant of the system, τ , = $\{(5040 \times 0.22) + (876 \times 0.11)\}/(0.172 \times 860) = \underline{8.1h}$

Hydration heat, Q , = $(350 \times 70 \times 2.1)/860 = \underline{59.825kWh}$

Assuming again a total curing cycle for the first cast, $T_{t1} = 5h$, $\eta = 0.5$,

$$P_{hyl} = (59.825 \times 0.5)/5 = \underline{5.982kW}; \text{ and } \theta_{mhyl} = 5.982/0.172 = \underline{34.8^\circ C}$$

In view of the much smaller concrete mass involved, the heating can take place in a single stage, even in the first cast. Allowing for $T_{h1} = 1$ hour, and $T_{c1} = 4$ hours at $t_{f1} = 65^\circ C$, $\theta_{f1} = 60^\circ C$

$$P_1 = \frac{60 \times 0.172}{1 - e^{-\frac{1}{8.1}}} = \underline{88.858kW}; P_{e1} = 88.858 - 5.982 = \underline{82.876kW}$$

$$\text{and } \theta_{m1} = 88.858/0.172 = \underline{517^\circ C}$$

The revibration and floating off in this case will take place by the end of the heating period.

CHECKING FOR MATURITY

Heating

For the heating stage, practically

$$\theta_{hav} = \theta_f / 2 = 60/2 = 30^\circ C \text{ and } t_{hav} = 30 + 5 = 35^\circ C; M_h = 1 \times 2.01 = \underline{2.01}$$

DIRECT ELECTRIC CURING OF CONCRETE

Cooling

$$\theta_{\text{cav}} = \frac{1}{4} \left(60 \times 8.1 (1 - e^{-\frac{4}{8.1}}) + 34.8 \left[4 + 8.1 (e^{-\frac{4}{8.1}} - 1) \right] \right) = 54.7^\circ \text{C}$$

$$t_{\text{cav}} = 54.7 + 5 = 59.7^\circ \text{C}; M_c = 4 \times 4.42 = 17.68; M_t = 2.01 + 17.68 = \underline{19.69}$$

This amply satisfies the specified strength requirement. The power demand, in spite of the shorter heating time, is still considerably lower than the one for the maximum size - which stands to reason, in view of the smaller mass. Assuming a half-hour demoulding time and the same for setting up the mould, the production of two units is feasible within an 8 hour working shift.

For the second cast, the available curing time will be $T_{c2} = 24 - 7 = 17$ hours. The expected hydration power works out accordingly, to

$$P_{\text{hy2}} = (59.825 \times 0.75)/17 = \underline{2.639\text{kW}} \text{ and } \theta_{\text{mhy2}} = 2.639/0.172 = \underline{15.3^\circ \text{C}}$$

$$\text{Assuming } T_{h2} = 4 \text{ hours, } T_{c2} = 13 \text{ hours, } t_{h2} = 30^\circ \text{C, } \theta_{h2} = 25^\circ \text{C}$$

$$P_2 = \frac{25 \times 0.172}{1 - e^{-\frac{4}{8.1}}} = \underline{11.033\text{kW}}; P_{c2} = 11.033 - 2.639 = \underline{8.394\text{kW}}$$

$$\theta_{m2} = 11.033/0.172 = 64^\circ \text{C}$$

CHECKING FOR MATURITY

Heating

$$\theta_{\text{hav}} = \frac{64}{4} \left[4 + 8.1 (e^{-\frac{4}{8.1}} - 1) \right] = 13.5^\circ \text{C}; t_{\text{hav}} = 13.5 + 5 = 18.5^\circ \text{C}$$

$$M_h = 4 \times 0.92 = \underline{3.68}$$

Cooling

$$\theta_{\text{cav}} = \frac{1}{13} \left(25 \times 8.1 (1 - e^{-\frac{13}{8.1}}) + 15.3 \left[13 + 8.1 (e^{-\frac{13}{8.1}} - 1) \right] \right)$$

$$t_{\text{cav}} = 20.1 + 5 = 25.1^\circ \text{C}; M_c = 13 \times 1.31 = \underline{17.03}$$

$$M_t = 3.68 + 17.03 = \underline{20.71}$$

This is more than adequate.

DIRECT ELECTRIC CURING OF CONCRETE

CALCULATING THE VOLTAGE AND CURRENT

The calculation will be based on the assumption of a similar concrete resistivity $\rho = 700 \Omega\text{cm}$. The average electrode area

$$F = \frac{1}{2} (12 + 9.9) = 11\text{m}^2; \quad d = 17.5\text{cm}$$

$$P_{e1} = 82876 / (11 \times 10^4) = 0.753\text{W/cm}^2;$$

$$r = 700 \times 17.5 = 12250 \Omega\text{cm}^2$$

$$U_1 = (0.753 \times 12250)^{1/2} = \underline{96\text{V}};$$

$$I_1 = (96/12250) \times F = \underline{862\text{A}}$$

$$P_{e2} = 8394 / (11 \times 10^4) = 0.0736 \text{ W/cm}^2$$

$$U_2 = (0.0736 \times 12250)^{1/2} = \underline{30.6\text{V}};$$

$$I_2 = (30.6/12250) \times F = \underline{275\text{A}}$$

d. Minimum culvert size, produced in an ordinary mould

Again the power calculations are not affected. If the same reinforcement data is assumed as for the maximum culvert size, the unit resistance remains the same. This is a simplification and, in practice, the reinforcement is likely to be different! The respective pressures and currents will thus be:

$$r = 1386 \Omega\text{cm};$$

$$U_1 = (0.753 \times 1386)^{1/2} = \underline{32.3\text{V}};$$

$$I_1 = (32.3/1386) \times F = \underline{2564\text{A}}$$

$$U_2 = (0.0736 \times 1386)^{1/2} = \underline{10.1\text{V}};$$

$$I_2 = (10.1/1386) \times F = \underline{802\text{A}}$$

DIRECT ELECTRIC CURING OF CONCRETE

PROJECT DESIGN AND SPECIFICATIONS

A diversity of power requirements, pressures and currents result from the calculations, as tabulated below.

	$P_e(\text{kW})$	$U(\text{V})$	$I(\text{A})$
a. 1a	98.00	92.2	1,062
1b	44.25	62.0	716
2 _{mod}	16.057	37.3	430
b. 1a	98.00	27.4	3,588
1b	44.25	18.4	2,410
2 _{mod}	16.057	11.0	1,440
c. 1	82.876	96.0	862
2	8.394	30.6	275
d. 1	82.876	32.3	2,564
2	8.394	10.1	802

These figures refer to the extremes, i.e. maximum and minimum product sizes. The equipment will also have to deal with the intermediate sizes. The building of DEC moulds will be justified only if either a new mould would be required anyway, or a large number of that particular component is on order. For short series, existing ordinary moulds would be used. The equipment must therefore be designed to accommodate all the requirements.

The Heating Transformer

The secondary pressures tabulated are the ones on the electrodes. To these must be added the pressure drops in the installation. The current within the mould/reinforcement is distributed via steel conducting paths, resulting in a high inductive resistance of the system. For the worst case, b1.a, assuming a transformer to mould distance of 3.5m, a pressure drop of up to 20% should be catered for in the secondary cables plus a 5% drop in the heating transformer, on full load. This would indicate a power factor of roughly 0.8 for the system. Considering an overall efficiency of 96%, the rating of the transformer would work out to

$$P_{Tr} = 98 / (0.8 \times 0.96) = \underline{127.6\text{kVA}}$$

This indicates a single phase unit. However, in order to cater for the diversity of pressures and currents and at the same time keep the rating of the equipment within reasonable limits, it may be necessary to deviate slightly from the calculated values. A workable solution would be to use a secondary winding split into three sections which could be connected either in series or parallel giving the following values:

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	U (V)	I (A)
Series	100	1,200
Parallel	33.33	3,600

Accordingly, the transformer rating would become

$$P_{Tr} = (100 \times 1200)/0.96 = \underline{125kVa}$$

The series connection, with added voltage control, should satisfy the requirements for DEC moulds, while the parallel connection can be used for ordinary moulds.

There is a wide variation in culvert sizes between the maximum and minimum which warrants the use of a power controller. However, for improved performance, the transformer should also be provided with two additional taps on the primary side to supply 70% and 45% nominal output pressures. The tap changer is switched offload by a geared motor which is push-button operated. Indicator lights show the actual position of the tap changer. In order to satisfy the safety regulations, the middle section of the trafo secondary must be centre-tapped and earthed (Fig. 42). This necessitates mounting the moulds on insulating strips.

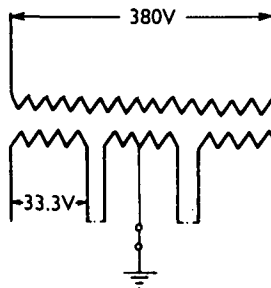


Figure 42 Heating transformer for culvert moulds

The Power Controller

The controller should have the capacity to switch and carry continuously the trafo primary full load current at the rated voltage. In our case

$$U_1 = 380V; I_1 = 329A; \text{ Single phase}$$

The next size up will be chosen from the manufacturer's catalogue. The critical stage for the culverts is the first cast. The resistivity of the concrete during the heating stage remains practically constant and the controller is used to limit the current to the maximum pre-set value. During the longer heating period of the second cast, the maintenance of a constant or gradually-increasing power level, is a useful feature.

In view of the moderate size of the load, a burst fire controller can be used. The controller should have a set of 3 reference rheostats, adjusted to the required values chosen by a selector via relays. There will also be a rheostat for continuous manual setting of any required power output.

Temperature Control

On one of the inner mould walls near the centre, a steel or aluminium pocket is mounted, accommodating two temperature sensors (Fig. 43). One sensor will be connected to an adjustable electronic temperature controller and its setting will determine the cut off temperature of the cast and disconnect the supply once this has been reached. In the quoted examples, it will be set to 65°C (in the winter) for the first cast, 30°C for the second. With the large units, the final temperature of the intermediate stage should have been reached by the end of casting. The power is disconnected manually and reconnected after the floating off and covering of the mould. At higher ambients, the temperature settings can be lowered to the extent that would still meet the demoulding strength requirement.

The second sensor will monitor the product temperature to a comparator, controlling the heating of a test cube (or cubes) in a DEC mould which is provided with a third sensor and fed from a small heating transformer. The cube mould current is switched on and off, to keep the cube(s) temperature in step with that of the product (Fig. 44). Lifting off the cast should take place after one of the test cubes has been crushed and the results found to be satisfactory.

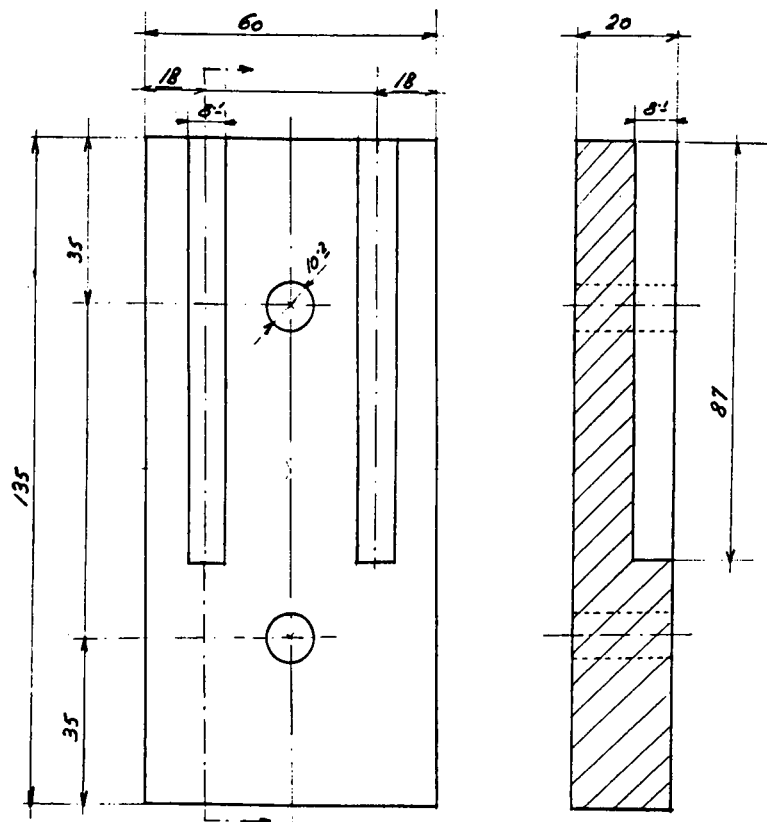


Figure 43 Double sensor pocket

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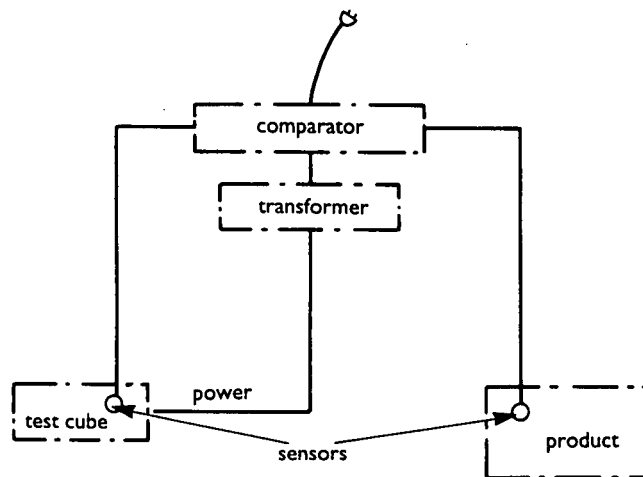


Figure 44 Schematic for temperature control of test cube, in step with the product temperature

Cables

M.V. cables

A 400V 3ph 50 cycle supply at the sub-station allows for a 20V drop in the 120m long feeder, at 329A and 0.8 PF. Using a 4 x 70mm² PVC/PVC SWA copper cable, laid into the ground, with two cores each connected in parallel, gives a pressure drop of around 8.84V and ample current-carrying capacity. In view of the earth leakage protection a 25mm² copper conductor can be used for the earth wire.

The 230V supply for the relays, indicator lights, etc. in the switchboard will be derived from a 380/230V service transformer. It is more economical - and safer - than running a neutral conductor from the sub-station. Flexible, sheathed cables form the M.V. connections to the switchboard and the transformer.

L.V. cables

Single core, sheathed solid aluminium PEX insulated cables provide the best solution. Eight cables of 300mm² connected in parallel, laid into a sand filled concrete trench will carry the maximum current of 3600A. The cables should be evenly distributed at the load end with two conductors connected to each of the four mould sides.

With ordinary moulds, the cables supplying the reinforcement will be connected to a common copper bus-bar. From there, the current is carried by flexible welding cables to the "flags" (Fig. 45) welded onto the reinforcement. In this case 16 Hypalon-sheathed copper welding cables of 70mm² will provide a trouble-free operation for the maximum size.

The above data clearly show the superiority of the DEC mould. With the ordinary mould, the trafo secondary windings and L.V. cable sections need to be rather heavy, pressure drops and losses become considerable, and connections have to be made and undone for each cast. Although the use of an electric nut-driver greatly reduces the time required, it is still a wasteful operation.

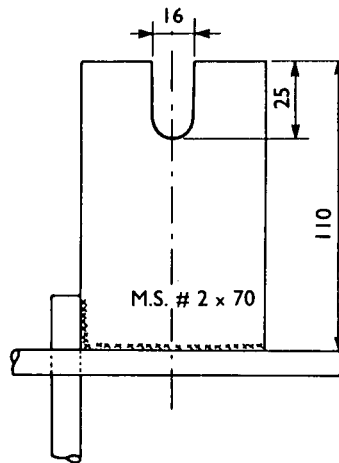


Figure 45 "Flag" welded onto reinforcing bars

An additional drawback of using an ordinary mould is the dependence on the reinforcement as the second electrode. If a *very* light cage satisfied the structural requirements, it might prove insufficient for carrying the specified curing current and parts of the cast may be left undercured. This is a rare occurrence, but must be considered.

For additional details, the guidelines in section 4.3 to 4.5 are valid. Figure 25 with the added power controller, reflects the single line diagram; and Figure 26 the layout. Three casts in a single shift will be possible with the same DEC equipment if two moulds are available.

5.1.2 Tunnel lining segments cast in a battery

Battery casting as stated previously (section 4.3), is probably the most efficient method for the mass production of identical or similar precast elements, shape and reinforcement configuration permitting. As such, it is ideally suited to the manufacture of lining segments for long, large diameter rail, road or waterway tunnels. Several batteries would be needed to meet the production target for a major project and both the concrete supply system and the work organization would be much more efficient than for a single unit. However, a single unit will be considered here, highlighting the principles involved. Two alternatives will be evaluated:

- I. Single shift, one daily turnover
- II. Two shift, two daily turnover operation.

The product considered will be segments for the circular lining of a water conduit, 6.6m outside dia., 25cm thick (Fig. 46). The battery will produce one complete ring of 1.5m length per cast, made up of 6 segments.

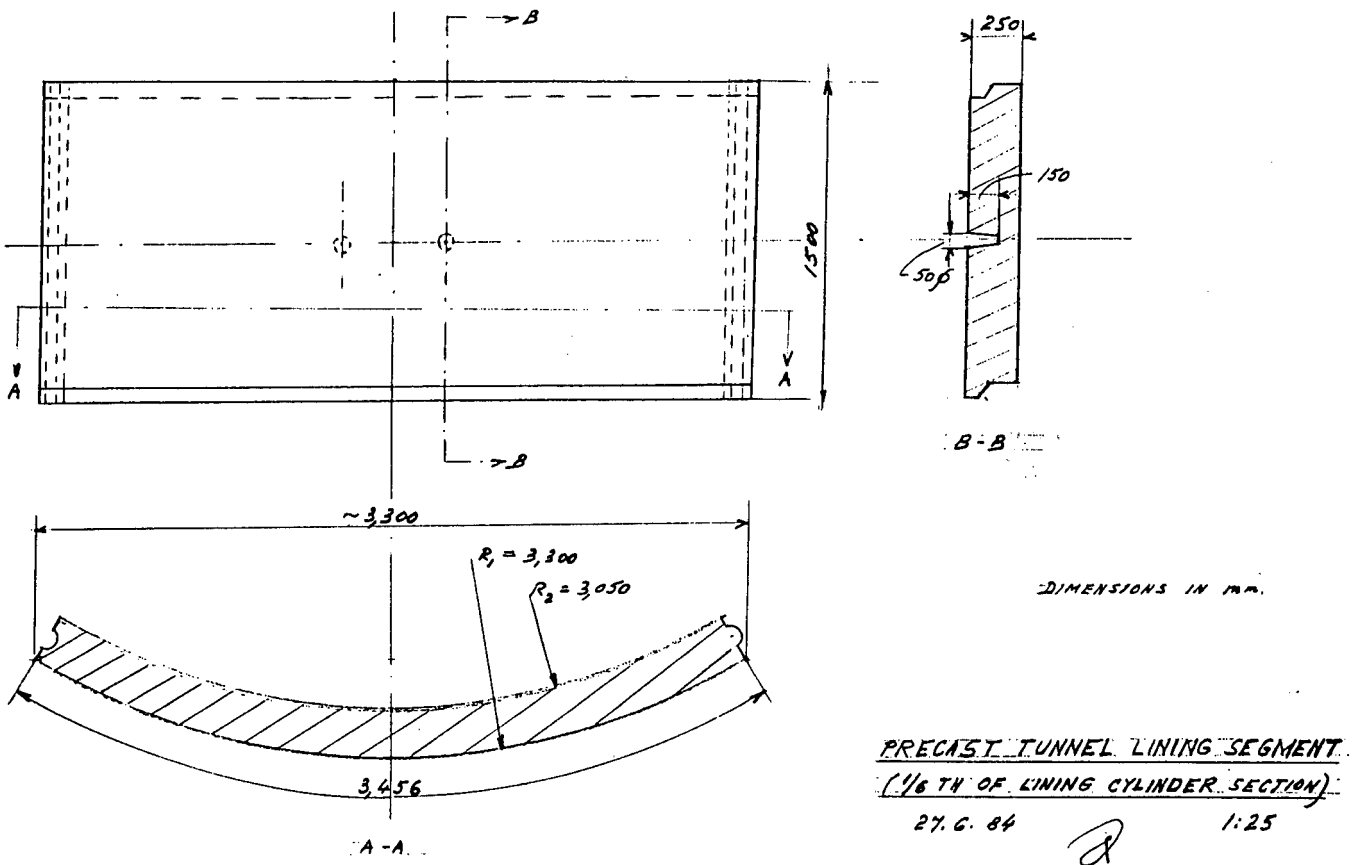


Figure 46 Precast tunnel lining segment

The basic data:

- a. Quantity of concrete to be processed in an 8 hour shift: 7.5m³.

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- b. One shift, or two shifts, in 24 hours.
- c. One battery of 5 leaves + 2 bulkheads with thermal insulation, cast once or twice daily.
- d. Demoulding strength: 12N/mm²
- e. Same as for the culverts.
- f. As shown in Figure 46.
- g. Single prefabricated square mesh 20 x 20cm, made up of 12mm dia. Sigma rods, placed at 7cm from the outer face.
- h. As shown in Figure 47.
- i. Similar to the one for culverts, with a single heating stage.
- j-k. The same as for the culvert scheme.
- l. The same as for the culvert scheme.

I. SINGLE SHIFT, SINGLE CAST OPERATION

The aim is to fit a work organization and curing regime into an 8 hour working shift. Assuming the following work phases:

Demoulding and lifting off the product	1.5 hours
Cleaning and setting up the battery	3.5 hours
Casting the battery	<u>2.0 hours</u>
	7.0 hours

leaves us $24 - 7 + 1.5 = 18.5$ hours for the curing cycle. The extra 1.5 means that the heating will actually start half an hour after casting begins, i.e. after approximately one quarter of the battery will have been filled.

CALCULATING THE POWER

Volume of concrete per cast		<u>7.5m³</u>	
Mass " " " "	$7.5 \times 2400 =$	<u>18,000 kg</u>	
<i>Free surface of concrete</i>			
Top + bottom $2 \times 6.35 \times 3.14 \times 0.25 \approx$		10.0m ²	
Sides $2 \times 1.5 \times 0.25 \times 6 =$		<u>4.5m²</u>	<u>14.5m²</u>
<i>Indirect surface of concrete to air, via leaf walls, approximately</i>		14.5m ²	
<i>Insulated surface of concrete to bulk heads, $2/6 \times 6.35 \times 3.14 \times 1.5 \approx$</i>		<u>10.0m²</u>	<u>24.5m²</u>

Assuming the heat losses of the indirect and insulated parts to be 50% (a rather prudent figure) of the direct losses, the *effective* area to be considered for the heat loss calculations will be:

$$14.5 + (\frac{1}{2} \times 24.5) = \underline{27m^2}$$

Accordingly, surface modul $\gamma = 27/7.5 = 3.6m^{-1}$
 λ (assumed) : 7W/m² ; $A \lambda = 27 \times 7 = \underline{189W/C^\circ}$

The approximate mass of mould steel in intimate contact with the concrete, using 5mm plates:
 $40 (6.35 \times 3.14 \times 1.5 \times 2 + 0.25 \times 1.5 \times 2 \times 6) = 2574kg$

The time constant $\tau = [(18000 \times 0.22) + (2574 \times 0.11)] / (0.189 \times 860) = \underline{26.1h}$

The hydration heat $Q_{hy} = (350 \times 70 \times 7.5) / 860 = \underline{213.66kWh}$

With a total curing cycle of 18.5 hours, taking $\eta = 0.75$,
the hydration power $P_{hy} = (213.66 \times 0.75) / 18.5 = \underline{8.66kW}$ and $\theta_{mhy} = 8.66 / 0.189 = \underline{45.8^\circ C}$

DIRECT ELECTRIC CURING OF CONCRETE

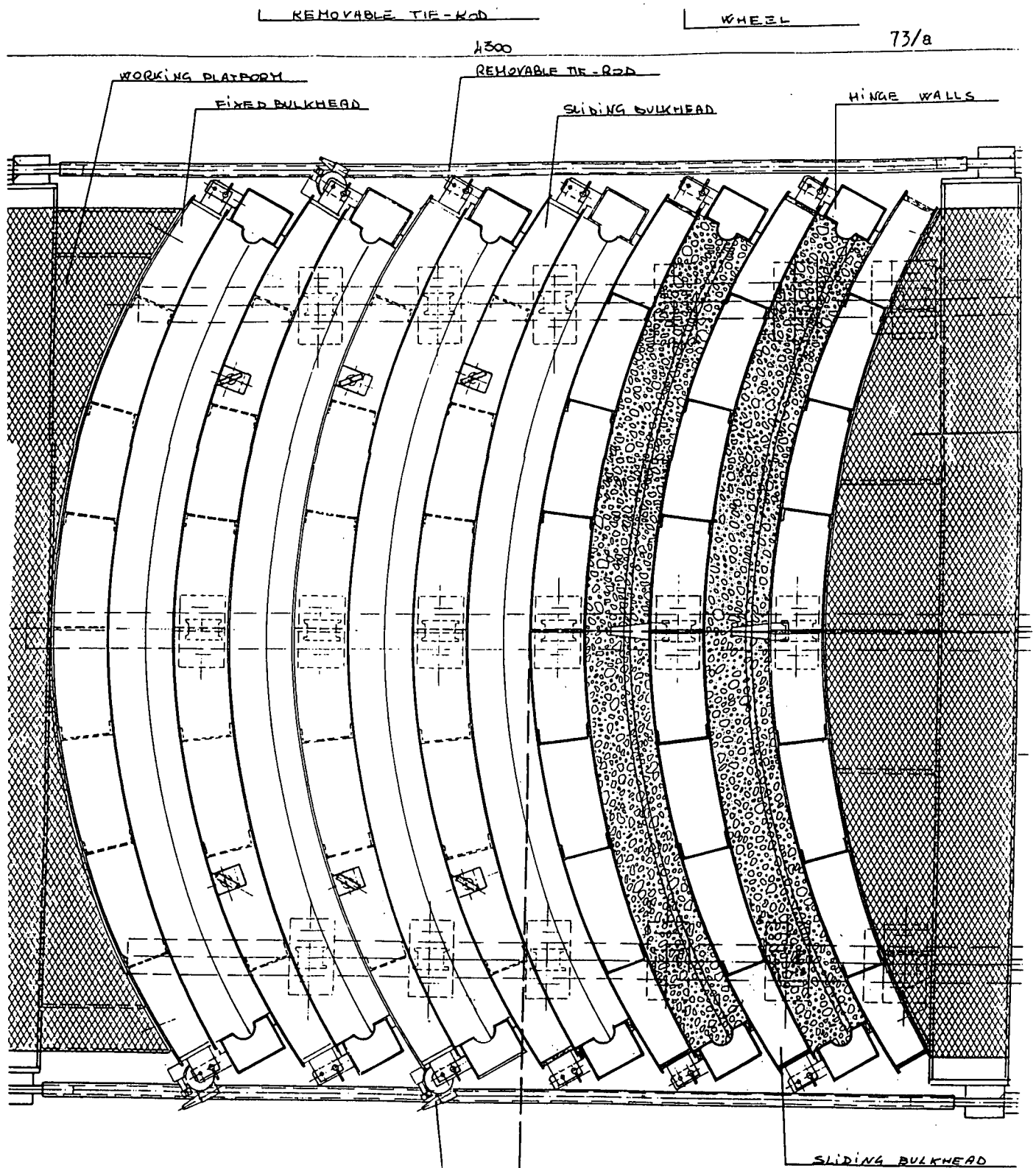


Figure 47 Battery casting machine for DEC of tunnel lining segments (plan)

DIRECT ELECTRIC CURING OF CONCRETE

This would indicate that hydration power by itself *could* generate sufficient heat to obtain the maturity of 19, for the specified demoulding strength. In exploring this possibility we find

$$\theta_{\text{hav}} = \frac{45.8}{18.5} \left[18.5 + 26.1 \left(\epsilon^{-\frac{18.5}{26.1}} - 1 \right) \right] = 13$$

$t_{\text{hav}} = 13 + 5 = 18^\circ\text{C}$; $M = 18.5 \times 0.89 = 16.46$
 which is somewhat low. A small external power boost is still needed.

Assuming $T_h = 2\text{h}$, $T_c = 16.5\text{h}$, $t_f = 15^\circ\text{C}$, $\theta_f = 10^\circ\text{C}$

$$P = \frac{10 \times 0.189}{1 - \epsilon^{-\frac{2}{26.1}}} = 25.62\text{kW}; P_e = 25.62 - 8.66 = \underline{17\text{kW}}$$

CHECKING FOR MATURITY

Heating

$$\theta_{\text{hav}} = \theta_f / 2 = 5^\circ\text{C} \text{ practically ; } t_{\text{hav}} = 5 + 5 = 10^\circ\text{C}$$

$$M_h = 2 \times 0.52 = \underline{1.04}$$

Cooling

$$\theta_{\text{cav}} = \frac{1}{16.5} \left(10 \times 26.1 \left(1 - \epsilon^{-\frac{16.5}{26.1}} \right) + 45.8 \left[16.5 + 26.1 \left(\epsilon^{-\frac{16.5}{26.1}} - 1 \right) \right] \right) = 19.3$$

$$t_{\text{cav}} = 24.3 ; M_c = 16.5 \times 1.25 = \underline{20.63} ; M_t = \underline{21.66}$$

which is more than adequate. As we have seen, due to the very low surface modul of the system and the fairly long curing cycle available, the heat is supplied predominantly by the hydration. It is noticeable that during the "cooling" stage (after disconnection of the electric power) the temperature of the concrete actually rises from 15 to 34.5°C. This is a well-known phenomenon observed during the casting of massive concrete structures, and sometimes requiring artificial *cooling* to be provided.

CALCULATING THE VOLTAGE AND CURRENT

The electric power per segment involved will be

$$P_{\text{es}} = 17/6 = 2.83\text{kW} ;$$

The average electrode area $F = (6.35 \times 3.14 \times 1.5)/6 = 5\text{m}^2$;

The distance between electrodes $d = 25\text{cm}$.

With $\rho = 700 \Omega\text{cm}$, $r = 700 \times 25 = 17,500 \Omega\text{cm}^2$

$$p = 2.83/50,000 = 0.0566\text{W/cm}^2 ; U = (0.0566 \times 17500)^{1/2} = \underline{31.5\text{V}}$$

$$i = 31.5/17,500 = 0.001798\text{A} ; I = i \times F = \underline{90\text{A}}$$

II. TWO SHIFT, TWO DAILY CAST OPERATION

With this option the length of the curing cycle available will be different. The duration of the two working cycles, $2 \times 7 = 14$ hours, leaving $(24 - 14 + 3)/2 = 6.5$ hours curing time per cast. This will modify the hydration power to

$$P_{hy} = (213.66 \times 0.5)/6.5 = 16.435\text{kW} \text{ and } \theta_{mhy} = 16.435/0.189 = \underline{87^\circ\text{C}}$$

CALCULATING THE POWER

Assuming $T_h = 2\text{h}$, $T_c = 4.5\text{h}$, $t_f = 55^\circ\text{C}$, $\theta_f = 50^\circ\text{C}$

$$P = \frac{50 \times 0.189}{1 - e^{-\frac{2}{26.1}}} = 128.108\text{kW}; P_e = P - P_{hy} = \underline{111.673\text{kW}}$$

CHECKING FOR MATURITY

Heating

$$\theta_{hav} = 50/2 = 25^\circ\text{C}; t_{hav} = 30^\circ\text{C}; M_h = 2 \times 1.63 = \underline{3.26}$$

Cooling

$$\theta_{cav} = \frac{1}{4.5} \left(50 \times 26.1 \left(1 - e^{-\frac{4.5}{26.1}} \right) + 87 \left[4.5 + 26.1 \left(e^{-\frac{4.5}{26.1}} - 1 \right) \right] \right) = 53$$

$$t_{cav} = 58^\circ\text{C}; M_c = 4.5 \times 4.23 = \underline{19.03}; M_t = M_h + M_c = \underline{22.3}$$

CALCULATING THE VOLTAGE AND CURRENT

The electric power per segment will be $111.673/6 = 18.612\text{kW}$

$$p = 18,612/50,000 = 0.372\text{W/cm}^2;$$

$$U = (0.372 \times 17500)^{1/2} = \underline{80.7\text{V}}$$

$$I = (80.7/17500) \times 50000 = \underline{230\text{A}}$$

Project Design and Specifications

As we have seen, the power requirement for Scheme I is very small and even for Scheme II rather moderate, less than 15kW/m^3 , in a $6\frac{1}{2}$ hour curing cycle. If single open moulds were used with the same curing method, the power and energy demand would be at least 50% higher, considering that the surface modul of such a unit would be around 10m^{-1} .

In addition, the heating between plate electrodes results in a more homogeneous product than with any other method. The reinforcement in this case does not affect the outcome. Finally, due to its construction, the battery takes up less factory space than other moulds of equivalent capacity.

Considering the respective merits of the two schemes, it is judicious to design the equipment for the two shift operation. This will also serve the single shift, with a much shorter heating time. During the greater part of the year, with ambient temperatures above 10°C , no additional heating will be required for the single shift operation.

Heating Transformer

Although the plant capacity involved is modest, it is convenient to use three-phase power. The advantage becomes more pronounced when several units are heated simultaneously. Here, we can assume a $\cos \phi = 0.9$ on full load, so the calculated transformer rating would be

$$P_{Tr} = 111.673 / (0.9 \times 0.96) \approx \underline{130kVA}$$

Primary: 380V, 198A, 3ph, 50 cycles, delta connected

Secondary: 94V, 796A, 3ph, 50 cycles, zig zag connected, with the star point earthed.

The stationary bulkhead will have to be insulated from earth. In principle, no voltage regulation is needed because the equipment is purpose-built for the manufacture of *one* particular product with a short heating time. However, to allow for possible variations in the resistivity of the concrete, it is useful to provide the trafo primary windings with tappings of +10%, +20% and -10% nominal output pressure. Tap changing will be off load. In this case, the use of a hand wheel should meet the operational requirements. A safety barrier around the battery must be provided.

Temperature Control

The set-up will be similar to the one used for culverts with sensor pocket(s) located in the stationary bulkhead with suitable access provided. For accuracy during commissioning, it is advisable to take comparative temperature readings from the concrete itself. This makes allowance for the temperature gradient through the mould wall.

*Cables*M.V. cables

Based on similar deliberations to the previous scheme, the substation - switchboard feeder will be 3 x 95mm², PVC/PVC, SWA copper cable, laid direct, with a 25mm² copper earth conductor.

The same cable will be used from the switchboard to the transformer with the latter located as near to the battery as operational constraints will permit. The trafo should have a shield, protecting it from accidental concrete spillage.

L.V. cables

These are flexible welding cables, laid in a short concrete trench to, and alongside, the battery. The connections to the individual battery leaves should be at mid-height, allowing sufficient slack for the leaf movement. In this case, 120mm² rubber, or 95mm² hypalon-sheathed copper welding cables can be used, 2 per phase. Alternatively, pairs of 50mm² and 35mm² cables can be installed, instead of the single ones, whichever is the more convenient.

The control scheme should differ little from that for the culverts, except for the safety aspect. Due to the thickness of the product, the statutory 50V equipment-to-earth potential could be exceeded in cases of light or no load. Covering the sides and the top of the leaves with a thin, tough, insulating strip and hooding the connections, will provide the battery with a "dead" front in the closed position. In order to prevent it becoming inadvertently energized when open, a couple of limit switches connected in series in the main contactor circuit should ensure safe operation.

5.2 In-situ casting

DEC can also be a very useful tool in speeding up the construction rate of cast in-situ concrete structures. Its advantages become more pronounced with large building projects, where the same shuttering is being used all over again, and the speed of progress largely depends on the length of the curing cycle.

This exercise concerns a group of high rise building blocks, some already erected, using natural curing. The introduction of DEC will be investigated, with a view to bringing forward the completion dates.

The constructional elements to be considered are the cast in-situ concrete floors. The basic data - somewhat modified - for one building, will be as follows:

- a. Quantity of concrete to be cured in the shortest possible time: 3 floor slabs of 30 m³ each.
- b. Not relevant.
- c. Three independent sections of a floor level, cast consecutively.
- d. With natural cure, the shuttering can be removed in the worst weather conditions (lowest ambient temperature) after 5 days, at a cube crushing strength of 20N/mm²; the latter being cured isothermally in water at 20°C. The same strength is aimed at, using DEC.
- e. 360kg OPC/m³, 20mm crushed granite aggregate, Zone 2 River Sand, 0.5 W/C ratio, with plasticizer.
- f. Slab area: 200m², thickness: 15cm.
- g. A single prefabricated square mesh of 15 x 15cm, built up of 7mm dia. M.S. rods, placed at 3.5cm above the shuttering.
- h. Modular steel shuttering.
- i. A complete floor is prepared at one time and the three discreet slabs cast consecutively. The completed cast is covered by polythene sheets. Preparation, casting and removal of the shuttering takes two 12 hour working days. With natural curing, a floor level is completed in a 7-day working week.
- j. The building site is in Hong Kong, with the following climatic data:
 Summer. Ambient temperatures 20 - 33°C. Humidity 40 - 95%
 Winter. Ambient temperatures 2 - 20°C. Humidity 60 - 99%
- k. As above
- l. There is a 1.5MVA, 346V 3ph 50 cycle substation already on site, for the future supply of the housing estate. Distance from the furthest block: 110m.

As stated, the objective is to curtail the erection time. The scheme will be evaluated both for the winter and summer conditions. Due to the rather long curing times expected, the use of average temperature values will be admissible. As a first step, the *actual* maturity of the product must be established, at the lowest average ambient, i.e. $t_0 = 11^\circ\text{C}$.

The hydration heat per m² floor area will be

$$Q = (360 \times 0.15 \times 74) / 860 = 4.646 \text{ kWh}$$

Considering $\lambda = 12$, $A = 2$, $A\lambda = 24 \text{ W}^\circ\text{C}$, $T_t = 5 \text{ days} = 120 \text{ h}$

$$P_{\text{hy}} = 4.646 / 120 = 0.0387 \text{ kW} \text{ and } \theta_{\text{mhy}} = 0.0387 / 0.024 = 1.61^\circ\text{C}$$

In view of the very long curing time involved

$$\theta_{\text{nav}} \approx \theta_{\text{mhy}} \approx 1.6^\circ\text{C}, t_{\text{nav}} = 11 + 1.6 = 12.6^\circ\text{C}$$

$$M_n = M_t = 120 \times 0.63 = \underline{75.6}$$

(*By interpolation for the 5 day 0.5 W/C ratio paste heat evolution of OPC at 20°C. From G.J.Verbeck, *Sym. Washington* 1960, 453; V.Danielson, *ibid*, 519.)

DESIGNING THE ACCELERATED CURING CYCLE, WITH THE RESPECTIVE POWER DEMAND

Let us take as the objective a curing cycle of 1 day = 24 hours duration. The times and temperatures allocated to the various components of the cycle will have to be determined by trial and error. But first, let us see the characteristic data of the product with the proposed curing cycle.

$$Q = (360 \times 0.15 \times 60) / 860 = 3.767 \text{ kWh} ;$$

$$P_{hy} = (3.767 \times 0.85) / 0.24 = 0.1334 \text{ kW}$$

$$\theta_{mhy} = 0.1334 / 0.024 = 5.5^\circ\text{C} \quad \gamma = 2 / 0.15 = 13.3 \text{ m}^{-1}$$

$$\tau = (0.15 \times 2400 \times 0.22) / (0.024 \times 860) = \underline{3.8 \text{ h}}$$

Due to the open nature of the site with winds, the coefficient of convection and radiation losses assumed is comparatively high and despite the moderate γ value, the time constant is low. This would indicate that the inclusion of an isothermal stage could be advantageous.

a. Winter conditions

1. Assuming $T_n = 2\text{h}$, $T_h = 6\text{h}$, $T_i = 8\text{h}$, $T_c = 8\text{h}$, $t_0 = 11^\circ\text{C}$, $t_f = 66^\circ\text{C}$, $\theta_f = 55^\circ\text{C}$

$$\theta_m = \frac{55}{1 - e^{-\frac{6}{3.8}}} = 69^\circ\text{C}$$

$$M_n = (2/120) \times 75.6 = \underline{1.26}$$

$$\theta_{hav} = \frac{69}{6} \left[6 + 3.8 \left(e^{-\frac{6}{3.8}} - 1 \right) \right] = 34.3^\circ\text{C}; t_{hav} = 45.3^\circ\text{C}$$

$$M_h = 6 \times 2.9 = \underline{17.4} \quad M_i = 8 \times 5.19 = \underline{41.52}$$

$$\theta_{cav} = \frac{1}{8} \left(55 \times 3.8 \left(1 - e^{-\frac{8}{3.8}} \right) + 5.5 \left[8 + 3.8 \left(e^{-\frac{8}{3.8}} - 1 \right) \right] \right) = 26.1^\circ\text{C}; t_{cav} = 37.1^\circ\text{C}$$

$$M_c = 8 \times 2.18 = \underline{17.44} \quad M_t = M_n + M_h + M_i + M_c = \underline{77.6}; \text{ which is adequate.}$$

The respective power requirement:

$$\frac{P}{m^2} = \frac{55 \times 0.024}{1 - e^{-\frac{6}{3.8}}} = 1.656 \text{ kW}; P_c = P - P_{hy} = 1.5226 \text{ kW}; \text{ and } P_{et} = P_c \times 200 = 304.52 \text{ kW}$$

However, the latter seems to be somewhat high. The cooling period contributes comparatively little in this case. On the other hand, a prolonged heating up time would certainly reduce the power demand; the more so if t_f could be reduced as well. This will be explored in our second attempt.

2. $T_n = 2\text{h}$, $T_h = 8\text{h}$, $T_i = 10\text{h}$, $T_c = 4\text{h}$, $t_0 = 11^\circ\text{C}$, $t_f = 61^\circ\text{C}$, $\theta_f = 50^\circ\text{C}$

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$$\theta_m = \frac{50}{1 - e^{-\frac{8}{3.8}}} = 57^\circ \text{C}$$

$$M_n = \underline{1.26}$$

$$\theta_{\text{hav}} = \frac{57}{8} \left[8 + 3.8 \left(e^{-\frac{8}{3.8}} - 1 \right) \right] = 33.3^\circ \text{C}; t_{\text{hav}} = 44.3^\circ \text{C}$$

$$M_h = 8 \times 2.81 = \underline{22.48} \quad M_i = 10 \times 4.57 = \underline{45.7}$$

$$\theta_{\text{cav}} = \frac{1}{4} \left(50 \times 3.8 \left(1 - e^{-\frac{4}{3.8}} \right) + 5.5 \left[4 + 3.8 \left(e^{-\frac{4}{3.8}} - 1 \right) \right] \right) = 33^\circ \text{C}$$

$$M_c = 4 \times 2.78 = \underline{11.12} \quad M_t = \underline{80.56}$$

The power demand:

$$P = \theta_m \times A\lambda = 57 \times 0.024 = 1.368 \text{ kW/m}^2; P_e = P - P_{\text{hy}} = 1.2346 \text{ kW/m}^2$$

$$P_{\text{et}} = P_e \times 200 = \underline{247 \text{ kW}}$$

These results are more favourable and the specific power demand of 8.233 kW/m^3 is quite acceptable. Of course the longer heating times entail a higher energy expenditure. The expected consumption is:

$$E_h = P_{\text{et}} \times T_h = 247 \times 8 = 2056 \text{ kWh};$$

$$E_i = (\theta_f \times A\lambda - P_{\text{hy}}) \times A_i \times T_i = (50 \times 0.024 - 0.1334) \times 200 \times 10 = 2133 \text{ kWh}$$

$$E_t = 2056 + 2133 = 4189 \text{ kWh} \quad \text{and} \quad E_s = 4189/30 \approx 140.0 \text{ kWh/m}^3$$

This is a high figure. However, considering that the actual duration of a building project is limited (as against that of a precast production line for instance) the size and weight of the equipment are more important factors. These are likely to be equally important factors in the final cost analysis.

b. Summer conditions

The influence of the higher ambient temperature on the various stages of the curing cycle must be checked first when endeavouring to achieve the same maturity within the same timespan.

I. The natural curing stage

At $t_0 = 26.5^\circ \text{C}$ the 5 day maturity by natural curing of the slab will be:

$$t_{\text{nav}} = 26.5 + 1.6 = 28.1^\circ \text{C}; \quad M_n = 120 \times 1.5 = \underline{180}$$

This would indicate that a longer natural curing time could be more efficient.

II The heating up stage

From the equipment rating, we can calculate the heating up time to reach the same final temperature.

$$t_0 = 26.5^\circ\text{C}; t_f = 61^\circ\text{C}; \theta_f = 34.5^\circ\text{C}; \theta_m = 57^\circ\text{C}$$

$$T_h = -\tau \ln\left(1 - \frac{\theta_f}{\theta_m}\right) = -3.81 \ln\left(1 - \frac{34.5}{57}\right) = 3.5\text{h}$$

III The isothermal stage could be shortened.

IV The cooling stage could be extended.

Let us explore the following scenario.

1. $T_n = 6.5\text{h}; T_h = 3.5\text{h}; T_i = 6\text{h}; T_c = 8\text{h}$

$$M_n = \{6.5/120\} \times 180 = \underline{9.75}$$

$$\theta_{\text{hav}} = \frac{57}{3.5} \left[3.5 + 3.8 \left(e^{-\frac{3.5}{3.8}} - 1 \right) \right] = 19.8^\circ\text{C}; t_{\text{hav}} = 19.8 + 26.5 = 46.3^\circ\text{C}$$

$$M_h = 3.5 \times 3.0 = \underline{10.5} \quad M_i = 6 \times 4.57 = \underline{27.42}$$

$$\theta_{\text{cav}} = \frac{1}{8} \left(34.5 \times 3.8 \left(1 - e^{-\frac{8}{3.8}} \right) + 5.5 \left[8 + 3.8 \left(e^{-\frac{8}{3.8}} - 1 \right) \right] \right) = 17.6^\circ\text{C}; t_{\text{cav}} = 44^\circ\text{C}$$

$$M_c = 8 \times 2.78 = \underline{22.24} \quad \text{and} \quad M_t = \underline{69.91}, \text{ which is somewhat low.}$$

2. By extending the isothermal stage to $T_i = 8.5\text{h}$ at the expense of the natural curing time, $T_n = 4\text{h}$, the picture will modify to:

$$M_n = (4/120) \times 180 = \underline{6} \quad M_h = \underline{10.5} \quad M_i = 8.5 \times 4.57 = \underline{38.84} \quad M_c = \underline{22.24} \quad M_t = \underline{77.6}$$

The energy expenditure will be:

$$E_h = 247 \times 3.5 = 864.5\text{kWh}; E_i = (34.5 \times 0.024 - 0.1334) \times 200 \times 8.5 = 1180.82\text{kWh}$$

$$E_t = E_h + E_i = 2045\text{kWh}, \text{ and } E_s = 2045/30 = 68.2\text{kWh/m}^3$$

Accordingly, considering 9 months summer and 3 months winter temperatures, the calculated yearly average energy consumption will work out to

$$E_{\text{sav}} = \{(9 \times 68.2) + (3 \times 140.0)\}/12 = \underline{86.2\text{kWh/m}^3}$$

As the various assumptions were rather liberal, i.e. on the safe side, the actual figure will probably be 10% - 15% lower.

CALCULATING THE VOLTAGE AND CURRENT

In the previous examples the heating times were quite short, so the power was supplied to the concrete while in the plastic stage.

The present case represents the other extreme, i.e. very long heating stages. In winter conditions, the curing will have advanced well into the hardening phase by the end of the heating up time. It means that the resistivity will have to be related to the hardening phase. Applying the test cube method for its determination (pp. 27,28), it will be realistic to use the ρ value obtained after 8 hours. With a good quality cement for this example we can assume $\rho = 1500 \Omega \text{ cm}$.

For a reinforcement configuration similar to the one used for the culverts (except for the slightly different bar size, which has a negligible effect on the shape of the electric field), the unit resistance between the reinforcement and shuttering will be

$$r = 3.5 \times 1500 \times 1.8 = 9450 \Omega \text{ cm}^2$$

$$P_e = 1234.6 \times 10^{-4} = 0.1235 \text{ W/cm}^2; \quad U = (0.1235 \times 9450)^{1/2} = \underline{34.2 \text{ V}}$$

$$i = 34.2/9450 = 0.00361 \text{ A} \quad I = i \times 10^4 \times 200 = \underline{7230 \text{ A}}$$

Project design and specifications

With the objective of speeding up the construction programme, we have to consider the simultaneous preparation and curing of a whole floor level, i.e. 3 slabs at a time (Fig. 48). This would indicate a total power requirement of some 750kW. The reinforcement is supposed to be non-continuous (the building consists of three discreet wings around an elevator and services shaft) and the steel shuttering of the slabs will have to be separated by strips of timber, for example 4" wide, bolted to the steel. The heating units of the slabs will be connected to different pairs of phases, giving a more or less balanced 3 phase load.

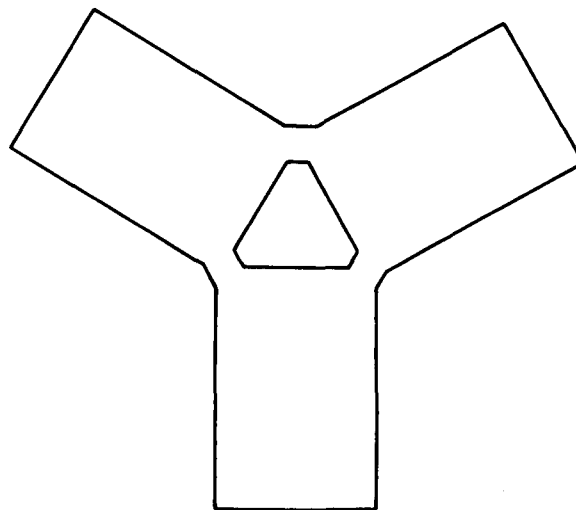


Figure 48 Schematic of 3-winged floor level

The building blocks under consideration are 30 storeys high and thus the individual pieces of equipment and supply lines should be of moderate weight and dimensions. Clearly the planning requires careful thought.

In spite of the problems faced, there is considerable time and consequent cost saving using DEC.

By cutting the construction time of a floor level from 7 to 3 days, the erection time of each block is shortened by 3 months.

Heating transformers

A power factor of 0.88 will be a reasonable assumption because the load is similar to that for the culverts, albeit of a much higher resistivity. It will be spread among 4 units per slab. Accordingly, the rating of a heating transformer will be:

$$P_{Tr} = 247 / (4 \times 0.88 \times 0.95) = 74 \text{ kVA Single phase}$$

Primary: 346V, 50Hz, 214A

Secondary: 41V, 50Hz, 1800A

It is assumed that the substation transformer is provided with adequate tapplings, to compensate for the voltage drop in the primary cables. The outdoor units will be mounted on 4" wheels with ball bearings and rubber rims, for mobility.

Switchboard

The feeder from the substation will terminate in a self-supporting, portable distribution board, by way of a connection box. It could be located at the bottom of the central elevator shaft. Once the block has reached the 15th floor, the switchboard will be moved to this new position and the feeder extended from the connection box.

The switchboard will have circuit breakers fitted with earth leakage relays and power controllers for the three transformer groups (Fig. 49). It will also house all the ancillary equipment (section 4.5). Safety switches will be mounted on the primary side of the transformer. A stop button on site for each group would trip the respective breaker in case of an emergency.

Temperature control

A pocket with sensors will be mounted on the shuttering of each slab near the centre controlling its group of four heating trafos and sample cubes. Their function will differ only in that at the final temperature the heating will not be cut off permanently, but maintained at that level. The process will be terminated by a timer.

Power controllers

These will be single phase wave chopping controllers. There will be a preset current value maintained, with the input power gradually increasing with advancing maturity, until the full rated voltage and power have been reached. Towards the second half of the isothermal stage, current and power will start to decline slowly, in step with the resistivity increasing beyond the specified value.

Cables

M.V. cables

The rather substantial total load of 888 kVa at 346V, involves heavy currents and a correspondingly large feeder. A suitable choice would be 3 x 240mm² per phase copper cables, XLPE/PVC insulated, SWA, with an additional earth wire, laid directly into the ground.

The supply from the switchboard to the heating transformers should be via flexible screened

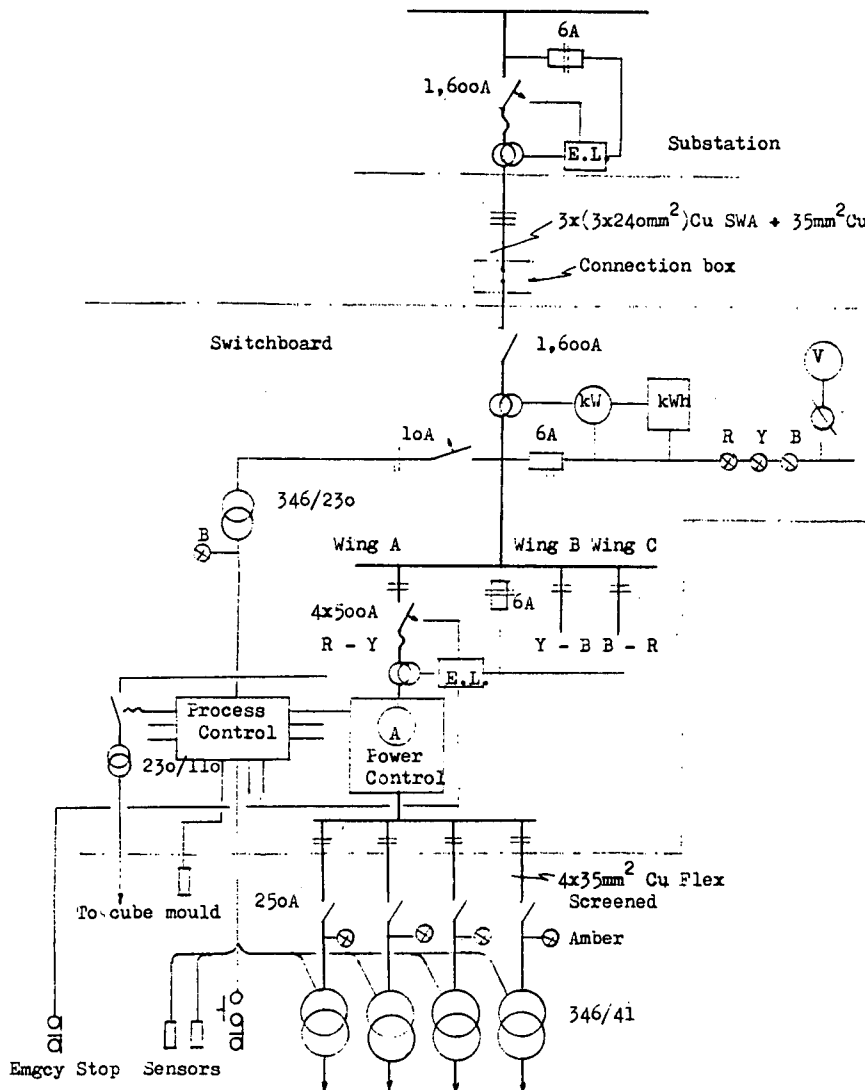


Figure 49 Tower block DEC Scheme. Single line diagram

cables, wound on freewheeling cable drums. The cable lengths should be just sufficient to reach the farthest heating trafo on the 15th floor comfortably. Cables (4 x 35mm²) with two cores each in parallel, should be adequate, with the screen forming the earth conductor.

L.V. cables

Two prefabricated 5 x 80mm copper bars will form the heating trafo shuttering connection, terminated in short flexible copper strips of the same section. The brass connecting bolts should be brazed into the shuttering. The terminations to the reinforcement of each unit will be by 9 copper welding cables, 70mm², rubber or neoprene sheathed, bolted to "flags" welded to the reinforcement. They will be

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equally spaced around the periphery of the slab. The flags will have to be cut off on completion. A disc grinder is well suited to the job.

As an alternative, the reinforcement itself could be bent at the edges, to protrude above the concrete. In such a case, the cables would be provided with lugs, similar to those for battery connections.

From the foregoing it transpires that a substantial investment will be required for the DEC equipment and cables for a project of such magnitude, i.e. the curing of 90m³ concrete in 24 hours, on site. There will be also some operational labour costs and the energy expenditure to be added. These have to be favourably balanced by the cost saving due to the reduced construction time. With a consecutive erection programme, on a 3 block estate the time saving will amount to 9 months; and for 6 buildings, 1½ years. This is often the usual size of such projects.

In the final analysis, the feasibility of such a DEC project - as with any manufacturing or construction programme - depends on the benefits versus expenditures to be expected.

6 DEC in Comparison to Other Accelerated Curing Methods

6.1 General

As pointed out in chapter 1, the use of admixtures, i.e. chemical acceleration, involves some hazards due to possible corrosive attack on the reinforcement. Vacuum curing did not become popular because it necessitates elaborate equipment and skilled operators and did not give consistent results. The various forms of thermal curing are the most widely adopted means to obtain early strength.

Of all the systems using an external heat source, steam gained most prominence. Steam generation became a well-established art in the days of low fuel prices when energy was cheap. Large amounts of heat energy are released when steam reverts to water. Over a steam-concrete interface, the heat transfer by condensation is over a hundred times greater than by convection. This obviates the need for a steep temperature gradient.

In *steam curing*, live steam is brought directly to the concrete and mould, covered by a hub or sheeted down, via perforated steam lines laid underneath the moulds. A substantial part of the heat energy is absorbed by the concrete flooring which is usually not insulated. In addition there are losses in transmission. Also, the condensate produced can be irksome and messy, flooding the shop floor.

Steam heating does not suffer from this drawback, as the steam is circulated either directly, or by way of a steam coil through closed vessels which form the mould. The condensate is collected in the hot well and pumped back into the boiler. However, the mould becomes more expensive and bulky.

With *steam injection*, live steam is injected into the concrete during the mixing stage, producing an almost uniformly heated mass of fresh concrete. The disadvantages of this seemingly efficient process are:

- a. Excessive heat losses during distribution of the concrete and casting, especially on long production lines.
- b. The need for frequent cleaning of the mixers and distribution equipment, to prevent the rather quick setting of the hot concrete residue.
- c. The not infrequent clogging of the equipment, despite the precautions.

Curing tunnels are a more efficient means of live steam curing for continuous production lines, but the investment costs are rather high. The application of *autoclave* curing, utilising high pressure steam at temperatures above 100°C is essentially restricted to the production of porous (gas) concrete.

Oil heating uses high temperature differences. Comparatively small quantities of the heating agent are circulated at a high temperature through finned heating coils. Temperature gradients with this method are substantial.

Hot water installations carry low grade heat, and unless the water is available as a waste product, the method is rather uneconomical. The same holds good for raising the temperature of the concrete by blowing *hot air* or some other hot gases over its surface. Special care must be taken with this form of curing, to avoid undesirable loss of moisture from the product.

Infra-red curing requires similar precautions, although this method is more efficient. Even so, the energy consumption is considerable: 120-160kWh/m³ of concrete cured. Its main field of application is the continuous production of thin sections.

Electric heating pads supplied in modular units probably have the highest overall efficiency of those systems using an external heat source. However, the equipment is portable and suffers a good deal of wear and tear, and their proper application requires some skill.

The *semi-direct* methods, involving the generation of the curing heat within the concrete (apart from the heat of hydration, a chemical process) are described in chapter 1.

6.2 Thermal efficiency

Until recently, energy costs played a negligible role in most manufacturing industries, the exception being some special processes based on the use of very large quantities of - mostly electrical - energy. Nowadays, as the price of energy becomes an ever-increasing part of the cost of the final product, industrialists have to be energy conscious. This applies equally within the concrete industry, and a closer investigation of the energy requirements of alternative curing methods for any particular product may reveal the chance of making substantial savings.

A specific example will enable a comparison to be made between the efficiency of DEC and other thermal curing processes. The product considered will be a precast concrete slab of the dimensions: 3 x 4 x 0.3m.

a. A probable production method using external heat curing for such an article would be the steam-heating of a horizontal casting table (housing a steam chamber) and its movable hollow cover, the concrete slab being sandwiched between the two (Fig. 50).

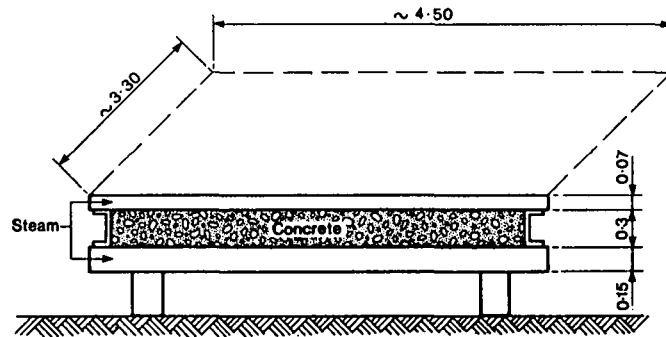


Figure 50 Curing table with cover

The steam, throttled to an appropriate pressure at the inlets, heats up the walls of both vessels, which in turn pass on the heat to their surroundings. The faces adjacent to the slab heat the concrete, the other faces dissipate heat energy to the surrounding air. Heat flow from the table and cover to the concrete will continue until, ideally, the whole concrete mass reaches the temperature of the adjacent faces. However, the process is stopped long before that. The heat flow gradually changes with the temperature difference between the heating medium and the concrete, and diminishes to a trickle after a while. The equation describing the phenomenon is:

$$\frac{dQ_c}{dT} = \frac{A_1 k}{l} (\theta_v - \theta_{c1})$$

where A_1 = total area of adjacent faces.

On the other hand, the heat flow to the surroundings taking place simultaneously becomes a constant value after the maximum is reached. The respective equation is:

$$\frac{dQ_a}{dT} = A_2 \lambda \theta_v$$

where A_2 = total area of all other mould surfaces in contact with free air. The sum of the two equations:

$$\frac{dQ_c}{dT} + \frac{dQ_a}{dT} = \frac{dQ_i}{dT}$$

which is the total heat flow that has to be supplied to the system.

The thermal phenomena are best illustrated by an hydraulic analogy, as depicted in Figure 51. Like most analogies, this one has its limitations, but it reflects the basic idea. The notations are those of a thermal system $1/A_1 k$ and $1/A_2 \lambda$ representing thermal resistances. Disregarding hydration heat (although the heat of hydration is by no means negligible, it has a fairly constant value for a certain product, regardless of the curing method), the temperature changes in the slab can be defined in rectangular co-ordinates by the equation

$$\frac{\delta t}{\delta T} = \alpha \left(\frac{\delta^2 t}{\delta x^2} \right)$$

where α = thermal diffusivity = 0.06×10^{-5} for concrete.

To obtain a numerical solution, we may divide the slab into finite sub-slabs and calculate the temperature variations in each of them. In this case we shall divide the slab into 6 sub-slabs, each 0.05m thick (Fig. 52). Assuming a linear temperature rise of the heating surfaces of 20°C/h and up to 90°C , the temperature distribution in the concrete, starting from 10°C ambient, will be as shown in Table 3 (for calculation details see: Simonson, J.R., *Engineering Heat Transfer*. Macmillan, 1975).

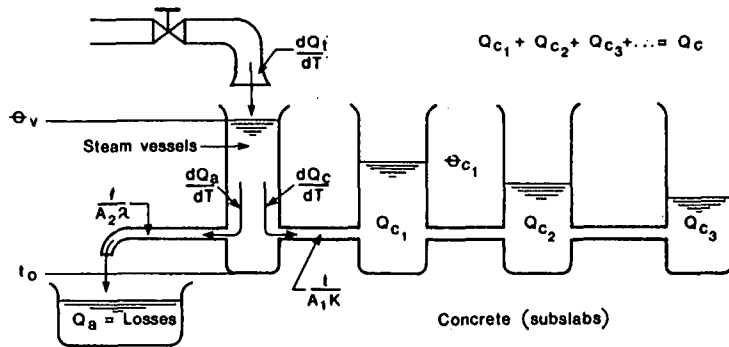


Figure 51 Hydraulic analogy for thermal phenomena

Accordingly, the average temperature of the concrete after 8 hours heating will be 76.5°C , and the average temperature rise

$$\theta_{c \text{ av.}} = 66.5^\circ\text{C}$$

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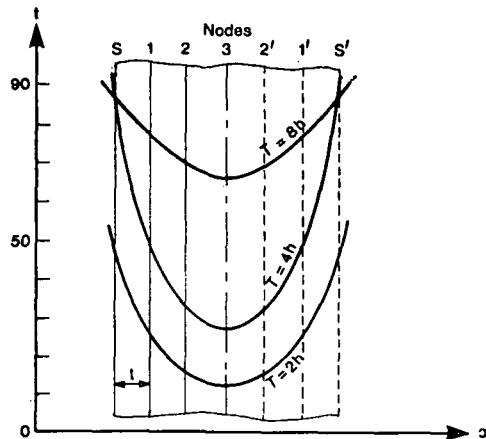


Figure 52 Temperature distribution for external-heat cured slab (calculated)

This corresponds to an energy transfer to the slab of

$$Q_c = \frac{A_1 k}{l} \int_0^8 (\theta_v - \theta_{cl}) dT \approx \underline{147 \text{ kWh}}$$

as shown in graph a. of Figure 53.

With an uninsulated table but heat insulated cover (a common occurrence in practice) $A_2 \lambda \approx 0.3 \text{ kW/}^\circ\text{C}$ (for the present configuration) and the heat losses to the surroundings will be represented by graph b. of Figure 53:

$$Q_A = A_2 \lambda \int_0^8 \theta_v dT \approx \underline{144 \text{ kWh}}$$

The total heat energy supplied to the mould during 8 hours will be:

$$Q_t = Q_c + Q_a \approx \underline{291 \text{ kWh}}$$

Assuming a steam distribution efficiency of 75% (a reasonable figure in practice) and a boiler efficiency of 60%, the required energy input contained in the fuel will be:

$$Q_{t \text{ gross}} = 291 / (0.75 \times 0.6) = \underline{647 \text{ kWh}}$$

and the thermal efficiency of the system:

$$\eta = 100 \times (147/647) = \underline{22.7\%}$$

The above figure is valid (approximately) for a comparatively new and well maintained boiler and pipe work. In practice, with installations over 5 years old, it seldom exceeds 18%, depending on the distances between the boiler and the points of utilization.

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T (hours)	t (° C)						
	surface	1	2	3	2'	1'	surface'
0	10	10	10	10	10	10	10
1	30	14.3	10	10	10	14.3	30
2	50	25.0	14.2	11.6	14.2	25.0	50
3	70	37.8	21.8	17.2	21.8	37.8	70
4	90	52.2	32.0	26.0	32.0	52.2	90
5	90	63.5	44.6	37.0	44.6	63.5	90
6	90	69.3	54.4	48.7	54.4	69.3	90
7	90	73.9	62.0	57.7	62.0	73.9	90
8	90	77.4	68.0	64.8	68.0	77.4	90

Table 3 Temperature distribution in the concrete

b. For internal heat curing the slab lends itself very well to DEC. Provided that the reinforcement does not distort the electric field, the table and cover can, with some modifications, be used as the electrodes. This configuration gives a very evenly distributed current flow and consequent temperature rise. For all practical purposes, the temperature distribution remains uniform during the heating process. This follows the equation:

$$\theta_c = \theta_m (1 - e^{-\frac{T}{\tau}})$$

as shown in Figure 54a, where θ_c = uniform temperature rise of the concrete.

For the sake of comparison, we shall use the same parameters as in the previous example:

Convection + radiation losses $A_2 \lambda = 0.3 \text{ kW/}^\circ\text{C}$

Average rate of temperature rise: 20°C/h ; $\theta_r = \theta_{c, av} = 66.5^\circ\text{C}$

Corresponding heating time $T_h = 66.5/20 = 3.3 \text{ h}$

The energy used to heat up the concrete will obviously be the same as previously; i.e. 147kWh. However, with the shortened heating time, the losses will be reduced substantially, as shown in Figure 54b:

$$Q_a = A_2 \lambda \int_0^{3.3} \theta_m (1 - e^{-\frac{T}{\tau}}) dT \approx \underline{36 \text{ kWh}}$$

and the total energy supplied to the system

$$Q_t = Q_c + Q_a = 147 + 36 = \underline{183 \text{ kWh}}$$

Assuming an electrical distribution efficiency of 98% and a conversion efficiency of 95% in the heating equipment, the total electrical energy consumption as metered on the M.V. side of the substation will be:

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$$Q_{t \text{ gross}} = 183 / (0.98 \times 0.95) = \underline{197 \text{ kWh}}$$

and the thermal efficiency: $100 \times (147/197) = \underline{75\%}$

In the U.K., most electrical energy is generated from fossil fuels. However, the comparatively low price of heavy fuel oil and coal (around 55-60% of the price for light fuel oils burnt in small industrial boilers) consumed in large, highly efficient power stations, renders DEC an energy saver and a viable proposition. This is especially so, if one uses off-peak, or partially off-peak loading. The control facilities of electrical energy are far superior to those of even a sophisticated steam installation.

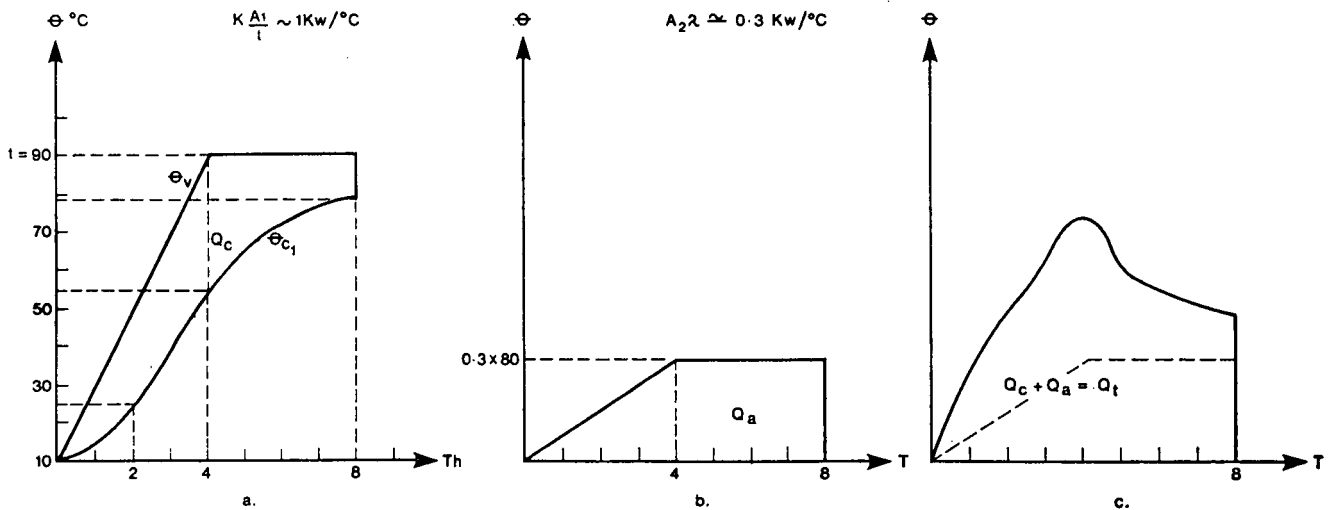


Figure 53 Energy diagrams for external-heat curing

An illustrative example is the case of a precast factory unit, producing prestressed railway sleepers. Until 1978, conventional steam curing was used at Dow Mac Concrete Limited's factories. In June 1978 a 100kVA experimental DEC unit was introduced at the Tallington factory, followed by the commissioning of a 2 x 350kVA capacity plant in October 1979, in the modernised main production area. The specific electric energy consumption measured during the year 1.7.80 - 30.6.81 was found to be 19kWh/m³ concrete produced. This meant a cost saving of over 80% against steam curing. The DEC system was subsequently adopted for the company's Gloucester and Eaglescliffe factories and was used later on foreign contracts.

The use of DEC for reinforced concrete products is worth mentioning in its application for the company's (Dow Mac) culvert manufacturing lines. The specific energy consumption on a 1560 ton production batch, using two moulds for three casts in an 8 hour working shift, has been 41.3kWh/m³.

On an experimental project for Redland Concrete Limited, aiming at shortened demoulding times for centrifugated RC pipes, the specific energy consumption was 44.7kWh/m³, with a total curing time $T_t = 2\text{h} + 55\text{min}$.

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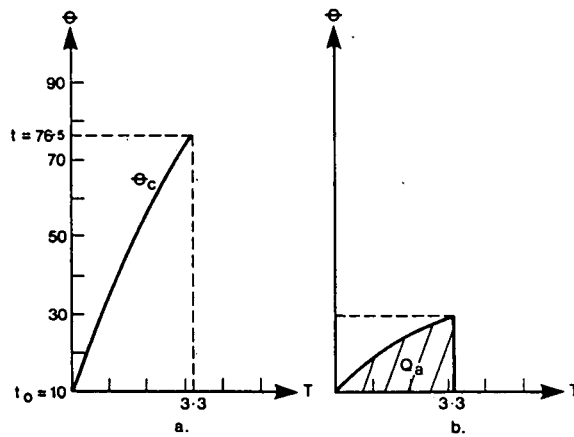


Figure 54 Heating curve and loss diagrams for Direct Electric Curing

6.3 Quality control

Concrete is a complex compound and many of its characteristics and its later behaviour depend on the curing procedure. A good deal has been written about the subject, with somewhat differing views expressed by the various authors. However, there seems to be a broad concensus about the following basic principles.

- The temperature rise of the product should be controlled in conformity with the strength development, to prevent the formation of voids and fissures. An exception to this rule is, of course, the use of hot concrete or its production within the mould, i.e. the very rapid heating up in the fluid-plastic state.
- A thorough vibration of the concrete during casting promotes the formation of a uniform structure. The limiting factor in amplitude, frequency and length of application is the danger of segregation.
- Undue moisture loss is to be prevented during curing, especially from dry, stiff mixes. Failure to observe this principle results in incomplete hydration of the cement and loss of strength.
- On demoulding, the product should be protected from thermal shock.

The above applies to DEC as well as to any other curing system. For the fulfilment of (a), DEC is better suited than any other (see sections 4.3 and 4.4). However, with DEC, an additional factor was investigated: the possible influence of electric current on the reinforcement. Before acceptance of the method by British Rail, for the production of prestressed sleepers, a thorough examination was carried out by a team of metallurgists from Aston University, Birmingham.

Two DEC sleepers, one steam-cured sleeper from an adjacent line, and a piece of unused prestressing wire were sent for testing. The essence of the test results is summarized in the following quote from the Test Report:

"The statistical results of the analysis indicated that:

- (a) there were no significant differences between the means of variances of strengths recorded for the sets of wires from the three sleepers;
- (b) there was no significant difference between the mean percentage reductions in area recorded for the three sets of wires and no significant difference between their variances.

In optical and scanning electron microscope examination the quality of the concrete appeared to be high in all cases, with minor quantities of voids present throughout the mixes.

Visual inspection of prestressing wires indicated that there was significantly more rust associated with regions of the surfaces of some tendons removed from the steam cured sample than for the electrically-cured samples."

The test samples were chosen at random from a production batch by Dow Mac's Chief Engineer at the time.

The possible long term effects of DEC on quality have been investigated both on RC and prestressed products by the author. On a batch of RC channel segments (half-culverts) designed to 40N/mm² 28-day strength, one third of it rapid cured, the 7-day strength tests by Schmidt Hammer produced an average reading corresponding to 36N/mm², and the 28-day tests to 44N/mm². The product was stored in an open courtyard, uncovered, without any further treatment after demoulding.

Some 150mm³ test cubes were cast and electro-cured simultaneously with the above product. The cubes were monitored automatically by the product temperature and subsequently water cured at 20°C. After 90 days the cubes were crushed at an average pressure of 56N/mm². A water absorption test, comparing electrically-cured specimens with steam-cured ones showed less than 3% water absorption in favour of DEC.

Prestressed railways sleepers with a demoulding strength of 35N/mm², subject to various curing régimes, were also investigated at some length. The normally available curing time with an 8 hour single working shift per day, $T_t = 16h$ for this article. Five such normally cured units were selected at random from a batch and stored in the open courtyard without any further treatment. They were tested with the Schmidt Hammer at 90 days, with the average result corresponding to 70N/mm². Twenty-four hour load test results were better than those for steam-cured sleepers.

Age	Crushing strength N/mm ²
1 hr before detensioning	35.5, 35.5
On detensioning	36, 39.5
100 days	73.5

Table 4 Cube crushing strength of rapid cured concrete

In the wake of an enquiry from abroad, involving the production of very large quantities of sleepers, the possibility of shorter curing times was investigated.

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At the Tallington plant on 21st August, 1980, a line of sleepers was cast, cured and detensioned, with a total curing time (completion of casting to releasing tension) of $T_t = 9.5$ hours. Test cubes cast and cured simultaneously (subsequently water-cured) gave the results shown in Table 4. Three sleepers chosen at random from the batch, were stored in the courtyard and Schmidt Hammer tested at various ages. The observed values appear in Table 5.

Age	Schmidt Hammer readings (average of 10 readings)
14 days	43.5, 40.6, 42.1
28 days	43.5, 43, 42.4
360 days	44.8, 43.7, 43.0

Table 5 Non-destructive strength tests of rapid-cured prestressed sleepers (values converted to N/mm^2)

One sleeper load tested after 17 months' storage, has shown results equally as good as sleepers cured normally. One year later, at the Gloucester plant a similar experiment was carried out, but with $T_t = 7.5h$. The maximum rate of temperature rise observed during the process was $21^\circ C/h$. The simultaneously treated (and subsequently water-cured) cube results are displayed in Table 6.

Age	Crushing strength N/mm^2
28 days	75.5, 77.5
80 days	79.0, 83.0
180 days	82.0, 82.5
360 days	85.0, 88.5

Table 6 Cube crushing strengths of super-rapid cured concrete

No discernible immediate or delayed effects concerning shrinkage, creep or ingress of moisture have been found due to the application of DEC. This seems to be supported by the findings in a French factory, producing prestressed poles for use in electricity supply. On demoulding, shrinkage cracks often appeared near the bottom end of the heavier poles when using live steam curing. On DEC-cured poles these cracks did not appear.

In the production of prestressed floor slabs on long beds, with cut-outs to close tolerances, DEC treatment proved equally satisfactory. No shrinkage cracks were observed anywhere.

6.4 Cost effectiveness

The viability of DEC as far as running costs for curing go, has been amply demonstrated in Section 6.2. However, running costs are only part of the picture. The capital investment requirement for a curing scheme is of equal importance, as is maintenance and depreciation. The latter is closely related to the duration of the scheme.

Each project has its problems, and the cost-effectiveness must be evaluated. In order to shed some light on the principal parameters involved, a worked example illustrates the cost comparison between various curing methods for the production of RC tunnel lining segments (dealt with in section 5.2). The six segments make up a 1.5m length of lining ring forming part of a water conduit, some 60km long, laid into a tunnel driven through a range of hills. The total volume of concrete involved will be approximately 300,000m³. The intention is that the lining will be produced in step with the tunnel boring operation, the segments being placed in position by an attachment to the boring machine itself.

Based on the results of a geological survey, the estimated rate of advance of the boring machine will be 35m per day, requiring the daily production of 144 segments, i.e. 180m³ of concrete precasts per boring machine. Using two boring machines and starting from both ends of the tunnel, the whole operation could be completed in four years, with a 20% allowance for unforeseen emergencies. Provision will have to be made for the concrete to undergo some sort of accelerated curing, to ensure it reaches the necessary demoulding strength throughout the year, maintaining daily mould turnover.

For the purpose of cost comparison (Table 7), three different types of factory unit have been considered, the output being based on the need for one unit to supply one boring machine. The three schemes considered are as follows:

- a. A carousel arrangement involving the casting of each segment in a separate mould mounted on wheels, and forming an endless chain passing through the production area and the curing tunnels. Curing would be by live steam, in two or three thermally-insulated parallel tunnels with a controlled rate of advance of the mould train. The design would provide for one daily mould turnover, and the total length of the curing cycle, i.e. from finishing casting to demoulding, would be 14 hours.
- b. A steam-heated battery casting arrangement, involving the production of 6 segments per battery cast, of 7.5m³. Provision is made for one daily mould turnover, and a total length of curing cycle of 14 hours.
- c. Similar to b, but using direct electric curing instead of steam heating. This method has been evaluated for two alternatives:
 - c1. One daily mould turnover in a single shift operation, with $T_i = 14$ h.
 - c2. Two daily mould turnovers in a two shift operation, with $T_i = 5.5$ h.

(The figure of 14 hours is out of the theoretically available 18.5 hours (Section 5.2). The equipment cost was calculated for a higher output, to ensure spare production capacity. The figure of 5.5 hours is based on similar deliberations.)

For scheme a, the use of 3 double production lines will be envisaged, each one with 2 x 24 moulds and 3 parallel curing tunnels. This should keep the production lines to manageable sizes. For schemes b and c1 a total of 24 batteries would be required; for scheme c2 this number will be reduced to 12 with a considerably higher rating of the DEC equipment for the latter.

In all the schemes considered, it is envisaged that the concrete will be distributed from the mixers to the moulds by an overhead system controlled centrally with the batching and mixing operations.

Demoulding would be by gantry cranes onto mobile transfer platforms. The manpower requirement for all four schemes is assumed to be the same; except, in the case of scheme c2, it would be divided into two 8 hour shifts.

Overall, DEC is the most cost-effective. In comparison to the carousel arrangement the use of DEC batteries would result in the following savings on the project:

With single shift operation $2 \times 4(811,894 - 541,523) = \underline{\$2,162,968}$

With two shift operation $2 \times 4(811,894 - 338,911) = \underline{\$3,783,224}$

The saving on the two shift operation may be reduced by higher labour costs on the second shift. This depends upon the local labour market. The costing reflects 1985 price levels in US\$. The pricing of the various parts of the equipment has been obtained either from consultations with, or quotations from, equipment manufacturers.

An additional advantage of DEC compared to steam curing systems, not reflected directly in the investment and running costs, is its reliability. The equipment has few moving parts, is subject to very little wear and tear and requires minimum attention. Very few breakdowns were reported throughout years of continuous operation. By contrast, steam installations in concrete works tend to deteriorate fairly rapidly, even if they are looked after. Leaks develop at joints, lagging peels off steam pipes, valves become stuck or leaky and equipment corrodes. The rate of wear and tear is high and because repairs can be awkward and messy, production stoppages are not infrequent. This is a latent source of increased production costs.

6.5 Environmental aspects

In the fight against air pollution, DEC can make a modest contribution. Although much of the electrical energy in the U.K. today is derived from the burning of fossil fuels, this may not be the case in other countries. Even in Europe, other sources of energy are preponderant in some places. Switzerland uses the "white coal", i.e. hydro-power, and France hydro-power and nuclear energy.

However, the elimination of small, inefficient, industrial boiler installations, should help to reduce the level of CO₂ and SO₂ emission in this country as well. The change to DEC from steam curing, also brings some local benefits to the environment in workplaces:

- a. A dry, clean, shopfloor, free from pools of condensate.
- b. Elimination of corrosion damage to electrical installation and constructional steel parts of the production building.
- c. Reduction of fire risk if, through necessity, large amounts of boiler fuel have to be stored.

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Table 7 Cost comparisons (US\$)

<i>1. Capital Expenditure</i>					
No.	Item	Carousel Steam	Battery Steam	Battery DEC 1 shift	Battery DEC 2 shifts
	1. Material handling and washing plant-if required. Unit	1	1	1	1
	2. Batching and mixing plant 20m ³ /h capacity 30m ³ /h capacity 40m ³ /h capacity	186,000	240,000	240,000	133,000
	3. Concrete distribution system: monorails, hoppers and spreader(s) as required	230,000	280,000	280,000	154,000
	4. Moulds & curing equipment (a) 3 x (2 x 24) = 144 single moulds on wheels connected into trains + rails + 9 double width curing tunnels. 2 x 1.5T/h boilers + auxiliary plant Steam distribution network (b) 24 steam heated battery at 28,000 (c) 24 DEC battery at 26,000 (d) 12 DEC battery as above Electrical equipment for the above: switchboards, heating transformers, cables. Substation for the above: 1MVA 33/o, 4kV, inc. HV gear and MV distribution board	1,210,000 71,000 45,000	71,000 68,000 672,000	624,000 92,000 28,000	312,000 77,000 28,000
	5. Demoulding and product removal. 2pcs OH cranes with 2 x 4T hoist each. 4pcs as above	152,000	152,000	152,000	76,000
	6. Production building. Steel structure supported roof, concrete floor. No side walls. Cost/m ² : 250mm RC floor 84.- Roof support str. 84.- Roofing 11.- 179.- 670m ² 1260" 1560"	279,240	225,540	225,540	119,930
	7. Storage area, loading gear and facilities, auxiliary buildings. Unit	1	1	1	1
		2,173,240	1,708,540	1,641,540	899,930
	Yearly capital cost of the above, at 9% interest, 4 years' depreciation. (Expected duration of the production programme)	670,879	527,426	506,743	277,808

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Table 7 continued

2. Running Costs					
No.	Item	Carousel Steam	Battery Steam	Battery DEC 1 shift	Battery DEC 2 shifts
	1. Energy cost, based on a yearly average ambient temperature of 18°C				
	Bunker C fuel oil at \$244 ton, price/m ³ concrete cured	2.82	2.42		
	Electrical energy at \$0.061/kWh, price/m ³			0.64	1.27
	Yearly energy cost, assuming 250 working days	129,015	110,715	29,280	58,103
	2. Yearly maintenance of the curing plant, estimated (based on past experience)	12,000	10,000	5,500	3,000
		141,015	120,715	34,780	61,103
3. Total Yearly Costs					
	1. Capital costs	670,879	527,426	506,743	277,808
	2. Running costs	141,015	120,715	34,780	61,103
		811,894	648,141	541,523	338,911

Appendix

The principles underlying the accelerated curing of concrete and in particular direct electric curing dealt with in this review, have general validity. However, sections 4.3 to 4.5 and the whole of chapter 5 relate to electric heating utilizing power from a 50Hz AC source. This is the domain of the author's experience, and has been tested in some quite substantial projects. Notwithstanding, the treatise would not be complete without touching on DEC using different power sources mentioned in the literature.

1. *Low frequency heating*

J. Vala and G. Wagner (1966) report small scale experiments, carried out with a 0.05Hz supply, derived from a DC source by way of a pole changing contactor with 1 change over per 10 sec described as optimal. The consumption figures and strengths obtained compare very favourably to those gained by curing with a 50Hz supply. The improved results of the low frequency treatment are ascribed to its beneficial chemical influence, in addition to the heating effect.

Experiments by the author, with a *higher* power frequency, notably 150Hz, have shown an increased power consumption for identical maturity. This would indicate the probability of a "stirring" action of an alternating current, actually retarding the setting process with increasing frequency.

Commercial exploitation of the low frequency heating on an industrial scale would need additional equipment for the frequency conversion. However, the greater investment cost *may* be offset by savings in the energy expenditure.

2. *High frequency heating*

The approach here is basically different. Instead of utilizing the conductivity of the fresh cement paste for resistance heating, dielectric heat is generated in the non-conducting or semi-conducting aggregate and sand, which forms the bulk of the concrete mix. Accordingly, the temperature rise is extremely rapid and while the heating is on, void formation should be prevented by constant vibration.

The radio frequency used, in the low MHz band, precludes the application of the method to heavily reinforced concrete due to the shielding effect of the reinforcement (Faraday cage). Its usefulness is probably restricted to non-reinforced products, such as concrete blocks. However, the equipment is rather expensive, its life expectancy comparatively short and the efficiency low.

3. *Induction heating*

The heating of steel shuttering and reinforcement rods by induced currents is an indirect method. In theory, eddy currents are produced in the concrete as well, but due to its very high resistivity compared to steel, the effect is negligible.

Induction heating, according to D.D. Danilov and B.M. Krasnovskij (1966) has been applied successfully to in-situ cast constructional elements, such as columns. The heavier the reinforcement, the more efficient is the method. A careful design should prevent the overheating of the reinforcement and its immediate vicinity. The energy expenditure seems to be higher than with DEC.

Bibliography

1. Danielson, V. (1960). Sym. Washington pp.519
2. Danilov, N.N. and Bocarov V.I. (1960). Primenenie infrakasnyh lucej pri proizvodstve sbornych železobetonnych konstrukcij i detalej. (Anwendung von Infrarotstrahlen bei der Herstellung von Stahlbetonfertigteilen). Moskau, Gosstrojizdat, .
3. Danilov, N.N. and Krasnovskij, B.M. (1966). *Beton i železobeton* (Concrete and Reinforced Concrete) pp.12
4. Darroch, A.S. and Kafry, I.D. (1983). Recent developments in Direct Electric Curing. *Concrete*
5. Fenner, R.T. (1974). *Computing for Engineers*. McMillan
6. Freeman, E.M. (1980). Report. Imperial College, 1980.
7. Ganin, V.P. (1964). RILEM - Symp. Moskau, Strojizdat
8. Gendin, V.J. (1961). Elektroprogrej v proizvodstve sbornych železobetonnych izdelij i blokov. (Elektrobehandlung in der Vorfertigung von Stahlbetonbauteilen). Moskau, Gosstrojizdat:
9. Gendin, V.J. and Lejrich, V.E. (1964). *Stroit. truboprovodov* pp.10
10. Hayt, W.H. Jr. (1958). *Engineering Electromagnetics*. McGraw Hill, New York
11. Kafry, I.D. (1977). A comparative review of the energy requirements for the accelerated curing of concrete. *Precast Concrete*
12. Kafry, I.D. (1986). Direct Electric Curing applied to battery casting machines. *Concrete Plant and Production*.
13. Kafry, I.D. (1987). Building site applications of Direct Electric Curing. *Concrete Plant and Production*.
14. Kaplin, V.S. (1962). *Beton i železobeton*, pp.8
15. Kostenko, M. and Piotrovsky, L. (1969). *Electrical Machines Vol. 2*, Mir Moscow
16. Koenig, P. (1967). *Baustoffindustrie* pp.10
17. Krylov, B.A. and Kopylov, V.D. (1967). *Beton i železobeton* pp.13
18. Malinin, J.S. and Lenskij, S.E. (1967). *Stroit. mater.* pp.13
19. Martinet, C. (1963). *Betonsteinzeitung* pp.29

20. Mironov, S.A. and Malinina, L.A. (1964). Uskorenje tverdenija betona. (Schnellerhärtung des Betons). Moskau, Gosstrojizdat
21. Neville, A.M. (1977). *Properties of Concrete*. Pitman
22. Nickol, D. (1962). Untersuchungen ueber die Anwendung und den Einfluss des Vibroaktivierens und des Vibromischens bei der Herstellung von Beton. Diss. Cottbus.
23. Mčedlov-Petrosjan, O.P. and Bunakov, A.G. (1961). Silikattechnik pp.12
24. Nurse, R.W. (1964). RILEM-Symp. Moskau, Strojizdat.
25. Reinsdorf, S. (1964). Generalbericht. RILEM-Symp. Moskau, Strojizdat.
26. Saul, A.G.A. (1951). *Magazine of Concr. Res.* V2 No. 6, March
27. Simonson, J.R. (1975). *Engineering Heat Transfer*. McMillan
28. Schuisky, W. (1951). Elektromotoren. Springer, Wien.
29. Verbeck, G.J. (1960). Sym. Washington. pp.453
30. Vala, J. and Wagner, G. (1965). Baustoffindustrie pp.8
31. Vala, J. and Wagner, G. (1966). Dissertation. Leipzig
32. Vasil'ev, P.J. and Kononov, J.J. (1965). Beton i železobeton pp.11
33. Wagner, K. (1966). Betonsteinzeitung pp.32
34. CIRIA Research Report 36. (1973). Cement and Concrete Association Training Centre

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