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Tubes for High Pressure Water-Tube Boilers.

READ

BY S. F. DOREY, M.Sc., Wh. Ex. (Member),

On Tuesday, November 11th, 1930, at 6 p.m.

CHAIRMAN: MR. H. J. VOSE (Chairman of Council).

The CHAIRMAN, in welcoming Mr. Dorey to give his paper, said that he thought they all realised the extreme importance of the paper to them as engineers, because the future of steam engineering depended to a great extent on the subject with which Mr. Dorey was dealing on this occasion.

INTRODUCTION.

The necessity for increased economy in shipping was never of more vital importance than at the present time. In order to achieve the best results those engineers who are more especially concerned with the steam engine are now devoting very considerable attention to the possibilities of improving the efficiency of the prime mover.

To do this it is essential to increase the steam pressure and the steam temperature and from practical considerations this is only possible by the adoption of the water-tube boiler. The satisfactory experience gained in the operation of high pressure land boilers and the improved efficiency obtained therefrom in comparison with boilers of moderate pressure should give confidence to the expectation that similar results will hold for marine work. To a certain extent this has been borne out by the successful running of the *King George V* during the last two seasons.

A vital feature of water-tube boilers is, of course, the tubes and accordingly it was thought that a paper dealing with the design, working conditions, factors of safety and materials for tubes of marine water-tube boilers might be of interest to the members of this Institute.

For convenience the paper has been divided into six sections. The first deals with the stresses in boiler tubes due to internal pressure and temperature, the second section is devoted to tube temperatures, while in the third section the materials for tubes are discussed. The fourth section contains suggested formulæ for calculating the thicknesses of tubes for high pressure marine water-tube boilers, and the factors of safety associated with the suggested thicknesses are dealt with in the following section. Finally some particulars are given in regard to the behaviour in service of high pressure boiler tubes.

SECTION I.

TUBE STRESSES.

The stresses in a boiler tube subjected to internal pressure may be considered under three headings, viz.: (i) stresses due to internal pressure, (ii) stresses due to the difference of temperature between the inner and outer walls of the tube, (iii) resultant stresses due to temperature and pressure.

It is not proposed to consider here the methods by means of which expressions may be obtained for calculating the various stresses, as these have been thoroughly dealt with in other papers, reference to which will be made later.

(i) *Pressure Stresses.* In the case of a thin tube the stress is considered to be uniform through the wall of the tube, and the circumferential stress is given by the well-known formula:

$$f = \frac{pd}{2t} \quad \text{- - - - - - - - - - -} \quad (1)$$

where f = stress in lb. per sq. in.
d = internal diameter of tube in ins.
t = thickness of tube wall in ins.
p = internal pressure, lb per sq. in.

It is usual to neglect the effect of the longitudinal stress, which is only one half that given above.

Equation (1) forms the basis for most rules formulated for the purpose of readily calculating the thicknesses of tubes, steam pipes, boiler shells, etc.

As the ratio of thickness of tube to diameter increases, the tube can no longer be considered as a thin shell, and stresses require to be calculated by means of Lamé or other equations for thick cylinders. Fig. 1 shows the variation of the hoop

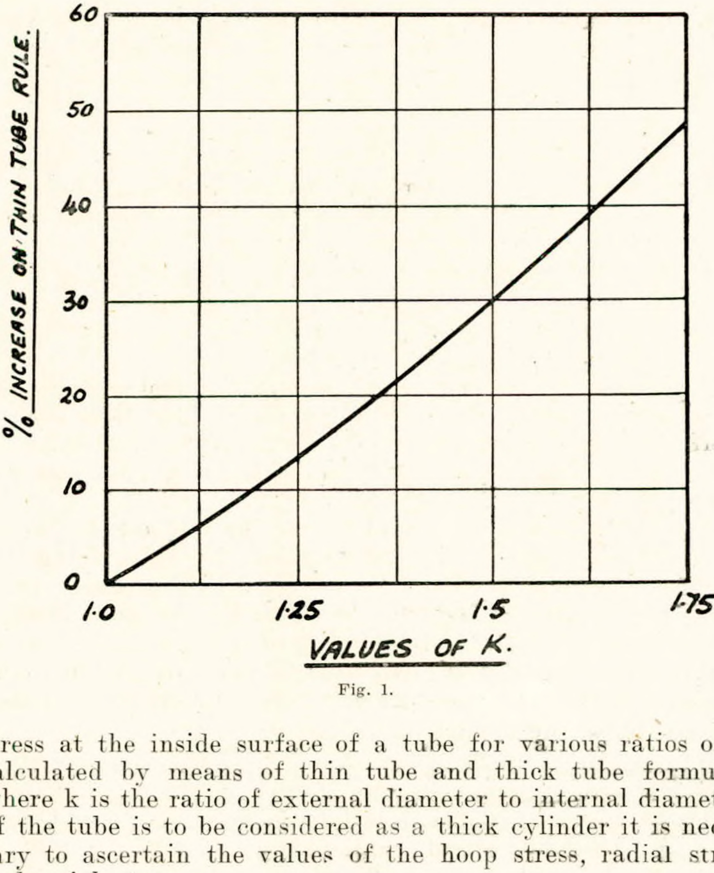


Fig. 1.

stress at the inside surface of a tube for various ratios of k calculated by means of thin tube and thick tube formulæ, where k is the ratio of external diameter to internal diameter. If the tube is to be considered as a thick cylinder it is necessary to ascertain the values of the hoop stress, radial stress and axial stress.

(ii) *Temperature Stresses.* The difference in temperature between the inner and outer walls of a tube causes a stress to be set up in the material due to the unequal expansion of the various layers of the material. A method for calculating these stresses has been developed by J. Case and is given in his book "Strength of Materials." The equations have been reduced to a more simple form by J. G. Docherty, Proc. I. Mech. Engineers 1928. The temperature stresses at the inner and outer surfaces of the tube are the most important, and here also the radial stresses are zero.

The temperature gradient across the wall of the tube will depend upon the rate of heat transmission from the hot gases to the water or steam in the tube, and can be determined from the heat flow equation:—

$$Q = \frac{2K}{D} \times \frac{\theta_1 - \theta_2}{\log_e k} \qquad (2)$$

where Q = heat transmission per unit time per unit area of outside surface.

D = external diameter of tube.

K = coefficient of conductivity.

k = ratio of outside diameter to inside diameter.

θ_1 = temperature at outer wall.

θ_2 = temperature at inner wall.

For mild steel at ordinary room temperature, K may be taken as 6×10^{-4} lb. calories per degree centigrade per inch per second, but its value decreases slightly with increase of temperature. For any particular case the value of Q, the heat flow per sq. ft. in lb. calories per second is known and the temperature gradient in degrees centigrade is then given by:—

$$\theta_1 - \theta_2 = \frac{QD \log_e k}{12 \times 10^{-4}} \ ^\circ C \qquad (3)$$

Having determined the temperature difference between the inner and outer walls of the tube, expressions can be obtained for the hoop, radial and axial stresses.

(iii) *Resultant Stresses due to Temperature and Pressure.* The resultant stresses in any one direction are obtained by adding together stresses in that direction due to both temperature and pressure, and if a small element at the inner or outer surface of the tube wall is considered, it can be shown that stresses acting upon it can be determined from the following three equations, viz.:—

$$\left.\begin{aligned} x &= p\,X_p + MX_T \\ y &= p\,Y_p \\ z &= p\,Z_p + MZ_T \end{aligned}\right\} \quad (4)$$

where x, y and z are hoop, radial and axial stresses respectively p is the internal pressure,

$$M = \frac{E\alpha}{(1\text{-}\sigma)}(\theta_1 - \theta_2)\ ;$$

where E = Young's Modulus of Elasticity.
σ = Poisson's ratio.
α = Coefficient of expansion.
$(\theta_1 - \theta_2)$ = temperature difference as determined by equation (3);
X_p Y_p and Z_p are pressure stress factors.

For inner surface $X_p = \dfrac{k^2+1}{k^2-1}$; $Y_p = -1$; $Z_p = \dfrac{1}{k^2\text{-}1}$

and outer surface $X^1_p = \dfrac{2}{k^2\text{-}1}$; $Y^1_p = O$; $Z^1_p = \dfrac{1}{k^2\text{-}1}$

X_T, and Z_T are temperature stress factors.

For inner surface $X_T = Z_T = \left\{\dfrac{k^2}{k^2\text{-}1} - \dfrac{1}{2\log_e k}\right\}$

and outer surface $X^1_T = Z^1_T = \left\{\dfrac{k^2+1}{2(k^2-1)} - \dfrac{1+\log_e k}{2\log_e k}\right\}$

For the complete expressions see paper by Docherty (loc. cit.)

Having obtained these stresses in three directions at right angles the limiting conditions for safety will depend upon the value of the simple tensile strength equivalent to these three stresses combined. Many hypotheses have been advanced for ascertaining the criterion of strength under combined stresses, most prominent among which are Haigh's Strain Energy Theory and the Maximum Shear Stress Theory or Guest's Law. Within certain limits it can be shown that there is very little difference between the values of the equivalent simple stress "f" given by either of these hypotheses. Haigh's Theory, though giving more consistent results over a wide range, is more difficult to apply than Guest's Law, so that the latter is often preferred.

Using Haigh's theory the conditions of safety are determined by the expression:—

$$\frac{x^2}{f^2} + \frac{y^2}{f^2} + \frac{z^2}{f^2} - 2\sigma\left(\frac{xy}{f^2} + \frac{yz}{f^2} + \frac{xz}{f^2}\right) \not> 1 \text{.........}(5)$$

and in the case of Guest's Law, we have:—

$$\left(\frac{x}{f} - \frac{y}{f}\right) \text{ or } \left(\frac{y}{f} - \frac{z}{f}\right) \text{ or } \left(\frac{z}{f} - \frac{x}{f}\right) \not> \pm 1 \text{...}(6)$$

where x, y and z are obtained from equations (4).

Instead of equations (4) we may write:—

$$\left.\begin{aligned} \frac{x}{f} &= BX_p + AX_T \\ \frac{y}{f} &= BX_p \\ \frac{z}{f} &= BZ_p + AZ_T \end{aligned}\right\} \text{-------------} (7)$$

$$\text{where } B = \frac{p}{f} \text{ and } A = \frac{E\alpha}{(1-\sigma)} \times \frac{\theta_1 - \theta_2}{f}$$

$$\text{and } \frac{A}{B} = \frac{\frac{E\alpha}{1-\sigma}\left(\theta_1 - \theta_2\right)}{p}$$

By substituting the values of $\frac{x}{f}$, $\frac{y}{f}$, and $\frac{z}{f}$ in either (5) or (6) expressions are obtained in terms of A, B and the stress factors, for the limiting conditions at the inner and outer surfaces, and since the stress factors only contain expressions for k equations will be derived in terms of A and B.

Then for any assumed value of A, a value of B can be deduced or *vice versa*, and the maximum permissible pressure for a given heat transmission rate be obtained.

The values of E, α, σ and K require comment. Although these are so-called constants their values vary for the class of material used for tube making and also with temperature. In the case of E, α, and K there is a fair amount of published information for different grades of steel over a wide range of temperatures. There is little available information with regard to the effect of temperature upon Poisson's ratio, but for carbon steels σ can be calculated from the values of the modulus of elasticity in tension and modulus of rigidity in torsion at various temperatures, given in Engineering Research Special Reports No. 1, the relationship being given by—

$$\sigma = \frac{E}{2N} - 1 \quad \text{- - - - - - - - - - -} \quad (8)$$

Fig. 2 shows the variation of E, α, σ, K, and the products $E\alpha$ and $\frac{E\alpha}{K} \times 10^4$, with temperature for ordinary mild steel used in the manufacture of boiler tubes. The values of E lb. per sq. inch are the mean of those given for 0·17 C and 0·24 C steel

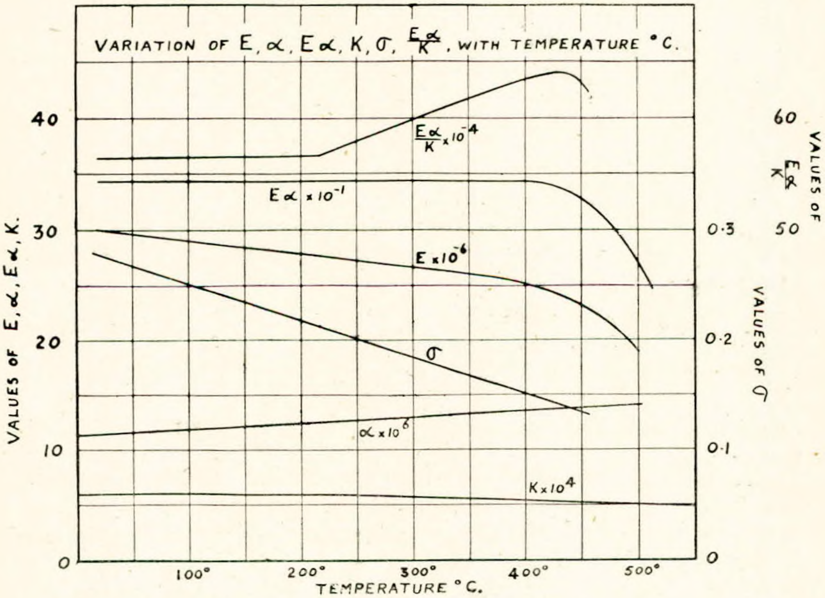


Fig. 2.

in E.R.S.R. No. 1, those for α being the mean for 0·09 C and 0·22 C steel (see Driessen's results for 0·09 and 0·22 carbon steels—International Critical Tables, Volume 2, Page 470).

The values of K are taken from the experimental results of K. Honda and T. Simidu. (Science Reports, Tôhoku University, Sendai.)

The approximate values of σ calculated by means of equation (8) above are also shown in fig. 2.

It will be observed that at temperatures above 450° C., the value of E falls off rapidly, and also that $E\alpha$ is practically constant up to 400° C. (752° F.). For the purpose of stress calculations above 750° F. it would therefore appear that no reliability can be placed on the values of E for ordinary mild steel and consequently on the values of the stresses deduced by the theory of elasticity. For higher temperatures that might possibly arise in superheater tubes it is safer to assume that after a period of time plastic conditions ensue and the stress becomes uniform across the tube wall.

Figs. (3) and (4) show two sets of graphs from which the values of A or B may be deduced for various values of k calculated by means of Haigh's strain energy theory and Guest's law respectively. The full lines are for the inner surface and the dotted lines for the outer surface.

Their use may be illustrated by a simple example:

Example:

Tube 2in. o/d by 0·16in. thick (k = 1·19), working pressure 500 lb. per sq. inch, heat transmission rate 40,000 B.T.U. per sq. ft. per hour, temperature of steam 472° F. (245° C.) $K = 5{\cdot}8 \times 10^{-4}$ per inch per °C.

$$\theta_1 - \theta_2 = \frac{40{,}000}{3{,}600} \times \frac{5}{9} \times \frac{2}{2 \times 5{\cdot}8 \times 10^{-4}} \times \frac{1}{144} \times \log_e 1{\cdot}19$$

$$= 12{\cdot}85^\circ\text{C } (23^\circ\text{F})$$

Take $E\alpha = 343$ and $\sigma = 0{\cdot}3$

$$A = \frac{343}{f} \times \frac{12{\cdot}85}{0{\cdot}7} = \frac{6{,}300}{f}$$

$$B = \frac{500}{f} \quad \therefore \quad \frac{A}{B} = 12{\cdot}6$$

(*a*) *Haigh's Theory*

$$\text{Inside } f = \frac{500}{\cdot 075} = 6{,}670 \text{ lb. sq. inch;}$$

$$\text{Outside } f = \frac{500}{\cdot 091} = 5{,}500 \text{ lb. sq. inch.}$$

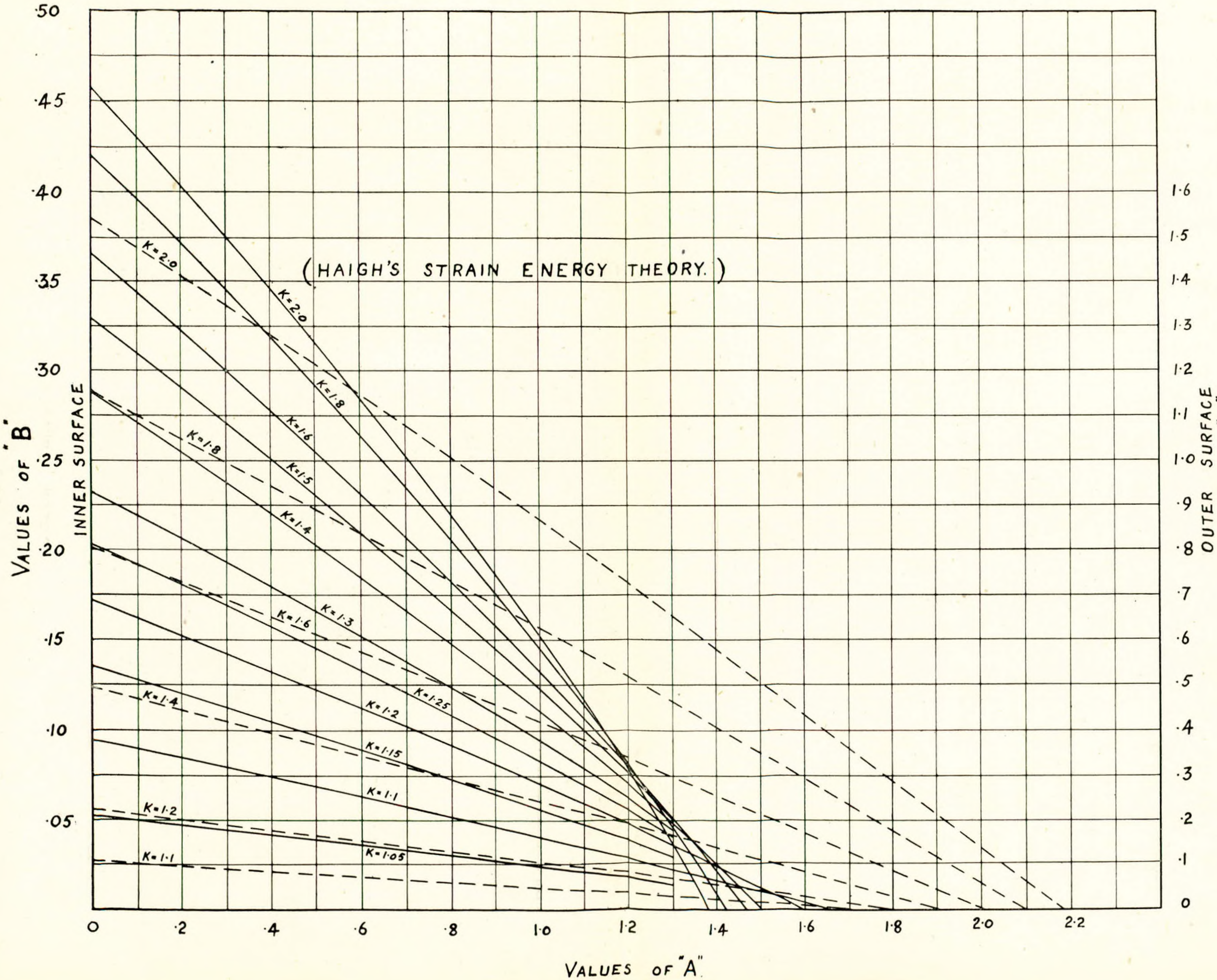
(*b*) *Guest's Law*

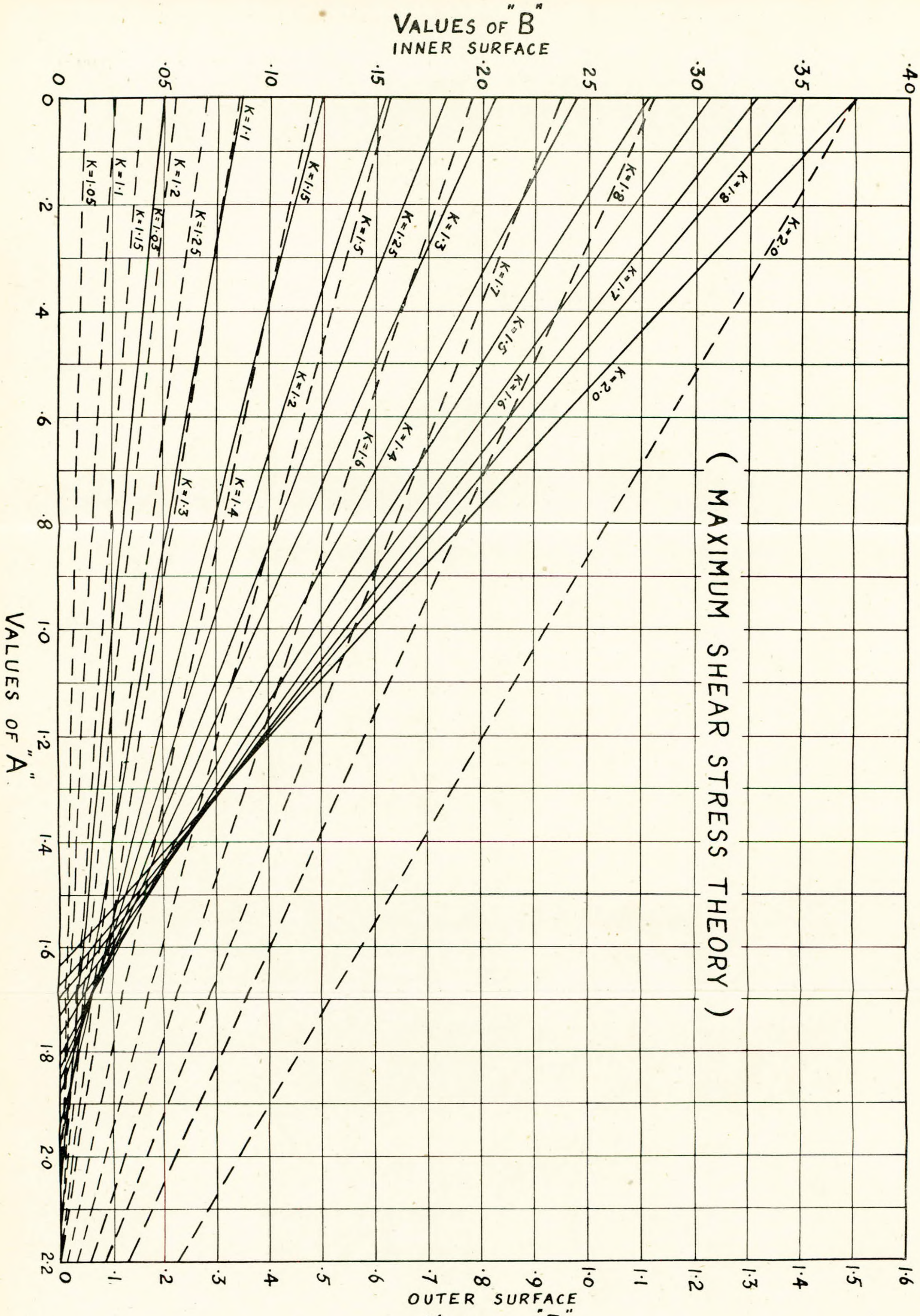
$$\text{Inside } f = \frac{500}{\cdot 075} = 6{,}670 \text{ lb. sq. inch;}$$

$$\text{Outside } f = \frac{500}{\cdot 092} = 5{,}430 \text{ lb. sq. inch.}$$

(*c*) *Thin tube formula*

$$f = \frac{500}{1{\cdot}19 - 1} = 2{,}630 \text{ lb. sq. inch.}$$


(HAIGH'S STRAIN ENERGY THEORY.)
VALUES OF "B"
INNER SURFACE
OUTER SURFACE
VALUES OF "B".
VALUES OF "A"
·50
·45
·40
·35
·30
·25
·20
·15
·10
·05
0
·2
·4
·6
·8
1·0
1·2
1·4
1·6
1·8
2·0
2·2
1·6
1·5
1·4
1·3
1·2
1·1
1·0
·9
·8
·7
·6
·5
·4
·3
·2
·1
K=2·0
K=1·8
K=1·6
K=1·5
K=1·4
K=1·3
K=1·25
K=1·2
K=1·15
K=1·1
K=1·05
Fig. 3.



VALUES OF "B"
INNER SURFACE
0 ·05 ·10 ·15 ·20 ·25 ·30 ·35 ·40
(MAXIMUM SHEAR STRESS THEORY)
VALUES OF "A"
0 ·2 ·4 ·6 ·8 1·0 1·2 1·4 1·6 1·8 2·0 2·2
K=1·05
K=1·1
K=1·15
K=1·2
K=1·25
K=1·3
K=1·4
K=1·5
K=1·6
K=1·7
K=1·8
K=2·0
0 ·1 ·2 ·3 ·4 ·5 ·6 ·7 ·8 ·9 1·0 1·1 1·2 1·3 1·4 1·5 1·6
OUTER SURFACE
VALUES OF "B".

Fig. 4.

The foregoing methods have been employed for calculating the stresses in tubes for different values of k and various heat transmission rates. Figures (5) and (6) show the variations of maximum stress obtained by employing Haigh's strain-energy theory for tubes of $1\frac{3}{8}$in., 2in., 3in. and 4in. external diameter, for various values of k and internal pressures from 250 lbs. per sq. in. and upwards. In the case of Fig. 5 the heat transmission rate assumed is 40,000 B.T.U. per sq. ft. per hour; that for Fig. 6 being 20,000 B.T.U. per hour. These heat transmission rates are considered applicable for fire row tubes and ordinary row tubes respectively for marine boilers. It will be observed that all these curves show a distinct minimum point, which, incidently, is more marked as the heat transmission rate is increased. Fig. 7 shows similar calculations for $1\frac{3}{8}$in., 2in. and 3in. o/d tubes with a heat transfer rate of 80,000 B.T.U. per sq. ft. per hour, a rate which might be obtained in the fire row of land boilers or highly forced naval boilers. The effect of the heat intensity on the walls of the tube is shown by the abrupt rise of stress as the thickness of the tube is increased above the optimum value. It will thus be apparent that at high heat transfer rates increase of thickness of tube walls above the optimum value does not provide an increase in factor of safety; on the contrary the material is subjected to higher stresses. Thus on the one hand if the thickness of the tube be decreased an increase of stress arises on account of the pressure stresses, while on the other hand if the thickness is increased, greater stresses are included due to the temperature effect.

With low rates of heat transfer the rise due to temperature stresses is less marked. Fig. 8 shows the stresses calculated for 2in., $1\frac{3}{4}$in., $1\frac{3}{8}$in. and $1\frac{1}{8}$in. external diameter tubes with a heat transmission rate of 8,000 B.T.U. per sq. ft. per hour, and these are considered to be applicable to ordinary convection superheaters. It will be observed that the rise of stress over a wide range of tube thickness is slight. In each of the diagrams of tube stresses it will be found that a straight line can be drawn from the origin to pass through practically all the minimum values of resultant stress for different working pressures, and such lines have been drawn in the figures shown. Fig. 9 is an interesting diagram which has been obtained from calculations made in a similar manner to those given in Figs. 5 to 8. By means of this diagram it is possible to obtain with a reasonable degree of accuracy the optimum value

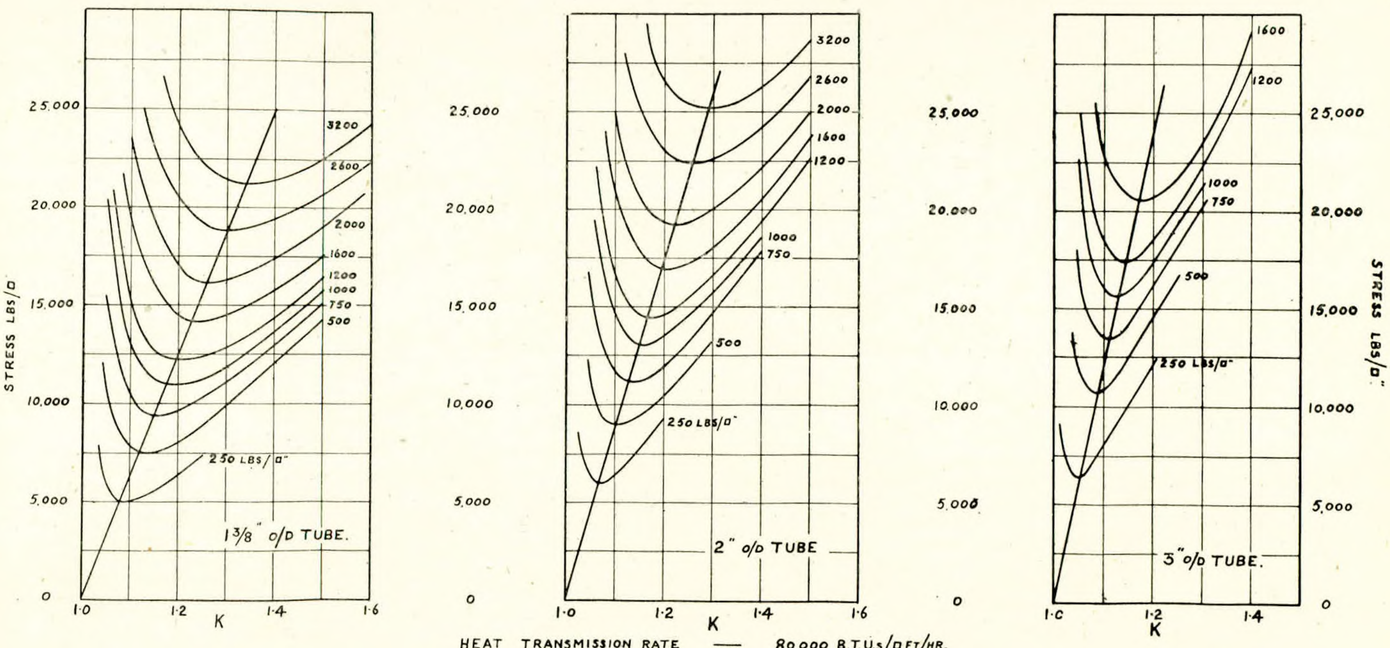

STRESS LBS/□"
25,000
20,000
15,000
10,000
5,000
0
1·0
1·2
1·4
1·6
K
3200
2600
2000
1600
1200
1000
750
500
250 LBS/□"
1⅜" o/D TUBE.
2" o/D TUBE
250 LBS/□"
3" o/D TUBE.
250 LBS/□"
HEAT TRANSMISSION RATE — 80,000 B.T.U.s/□ FT/HR.

Fig. 7.

of k and the resultant maximum combined stress for any diameter of boiler tube for any heat transfer rates encountered in present water tube boiler practice. This may be done in the following manner.

The working pressures in lb. per sq. in. are shown as abscissæ to the right of the origin, values of k as ordinates and values of maximum combined stress as abscissæ to the left of the origin. The numbers against the radiating lines are the products of outside diameter of tube in inches and heat transmission rate in lb. calories per sq. ft. per second (for heat transmission rate in B.T.U. per sq. ft. per second multiply numerals by 1·8). Suppose for example the value of k and maximum combined stress is required for a 2in. o/d tube with a heat transmission rate of 15 lb. calories per sq. ft. per sec. (corresponding to 97,200 B.T.U. per sq. ft. per hour) the working pressure being 1,300 lb. per sq. in. From point A in diagram corresponding to working pressure of 1,300 lb. sq. in. draw a vertical line cutting curve $QD = 2 \times 15 = 30$ at B. From B draw a horizontal line cutting vertical axis at C giving a value of $k = 1{\cdot}16$. Continuing, the stress for this value of k is found to be 17,000 lb. per sq. in. The values found in this manner will be the same as for a 4in. o/d tube with a heat transmission rate of 7·5 lb. calories per sq. ft. per sec. From this it will be obvious that for the same degree of safety there comes a limit up to which it is considered advisable to use large tubes and, as pressures are increased, the heat transmission remaining the same, or *vice versa*, the diameter of the tube must be decreased or distortion will take place.

In the case of a thin tube of large diameter such as the shell of a cylindrical boiler, the stress calculated in the usual manner as a thin tube is six tons per sq. in., say 13,500 lb. per sq. in. This gives a factor of safety of about two on the elastic limit at moderate temperature. The shell plate is, however, not subjected to the action of the flame and it is considered that for a boiler tube the stress should not exceed 12,500 lb. per sq. inch, and in any case not greater than about two-thirds of the elastic limit for the material at a temperature slightly in excess of that corresponding to the working pressure. An examination of Figs. 5 and 6 shows that for a stress of 12,500 lb. per sq. in. the limiting working pressure for a 4in. fire row tube is about 800 lb. per sq. in. For a 3in. tube the corresponding pressure is about 1,250 lb. per sq. in., and for

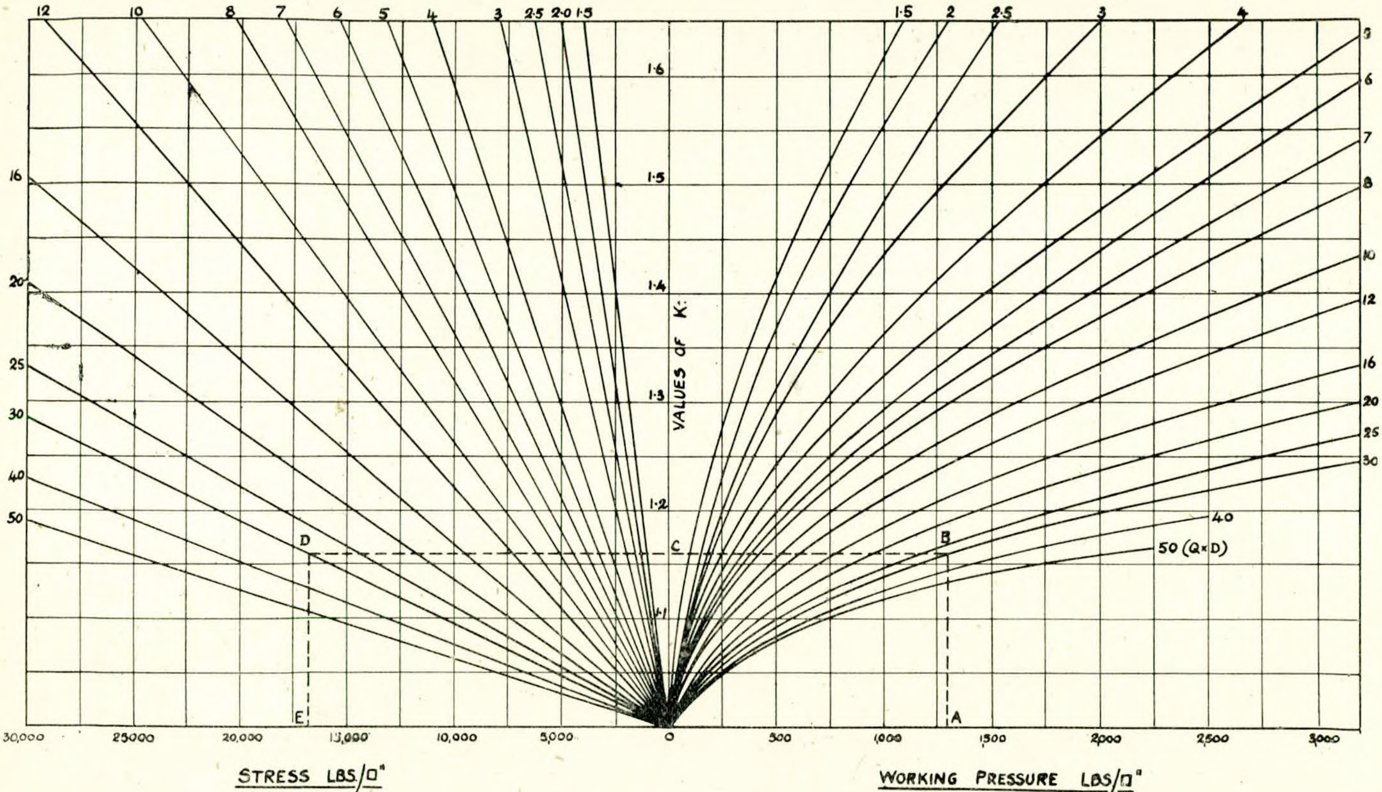

12
10
8
7
6
5
4
3
2.5
2.0
1.5
1.5
2
2.5
3
4
5
6
7
8
10
12
16
20
25
30
40
50 (Q×D)
16
20
25
30
40
50
1.6
1.5
1.4
1.3
1.2
1.1
VALUES OF K:
A
B
C
D
E
30,000
25000
20,000
15,000
10,000
5,000
0
500
1,000
1,500
2,000
2,500
3,000
STRESS LBS/□"
WORKING PRESSURE LBS/□"

Fig. 9.

a 2in. tube the pressure would be limited to about 1,600 lb. per sq. inch. It might be mentioned that in the Benson boiler, which works at a pressure of 3,200 lb. per sq. inch, the thickness of the tubes is 6·5 mm. (·256in.) for an outside diameter of 33 mm. (1·3in.), and allowing for a heat transfer rate of 40,000 B.T.U. per sq. ft. per hour (a rate about double the mean transfer rate given in the results of trials in Engineering, 17th January, 1930), the maximum stress at the inner surface works out at about 16,500 lb. per sq. in., special material being employed for the tubes.

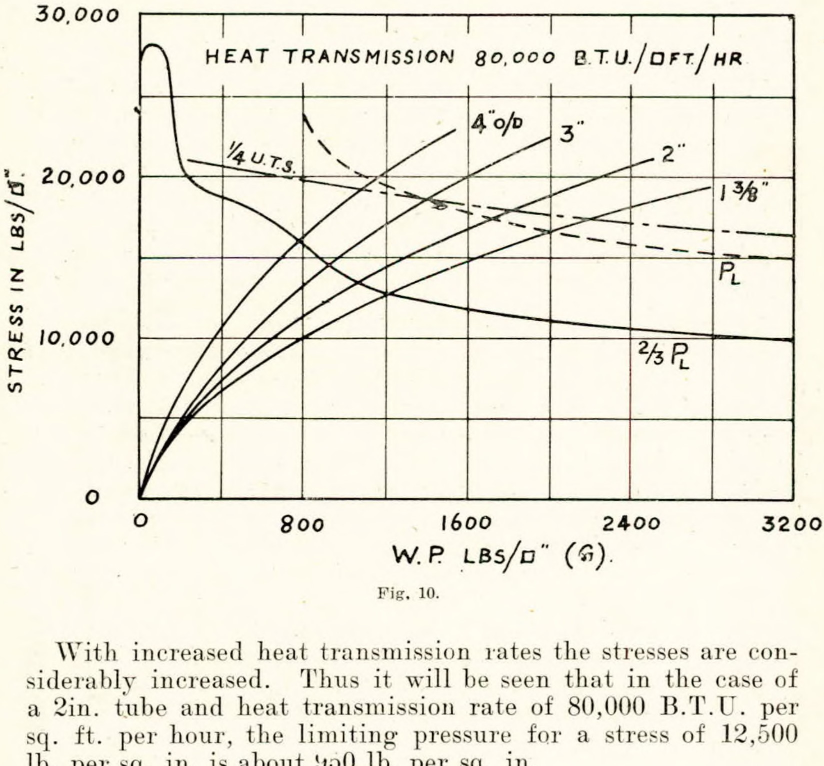


Fig. 10.

With increased heat transmission rates the stresses are considerably increased. Thus it will be seen that in the case of a 2in. tube and heat transmission rate of 80,000 B.T.U. per sq. ft. per hour, the limiting pressure for a stress of 12,500 lb. per sq. in. is about 950 lb. per sq. in.

Fig. 10 shows the optimum stresses for $1\frac{3}{8}$in., 2in., 3in. and 4in. o/d tubes plotted against the working pressure, together with a curve, shown dotted, giving the value of the elastic limit at the temperature corresponding to the steam pressure.

This dotted curve has been obtained from E.R.S.R. No. 1, and represents the values given for 0·17 carbon steel boiler tube. Values of $\frac{2}{3}P_L$ and also one quarter of the ultimate tensile strength for ·17 C steel have also been included. It will be apparent that with increased pressures and heat transmissions the stresses become so high that ordinary mild steel tubes may not be satisfactory and a superior quality of steel becomes desirable.

SECTION II.

TUBE TEMPERATURES.

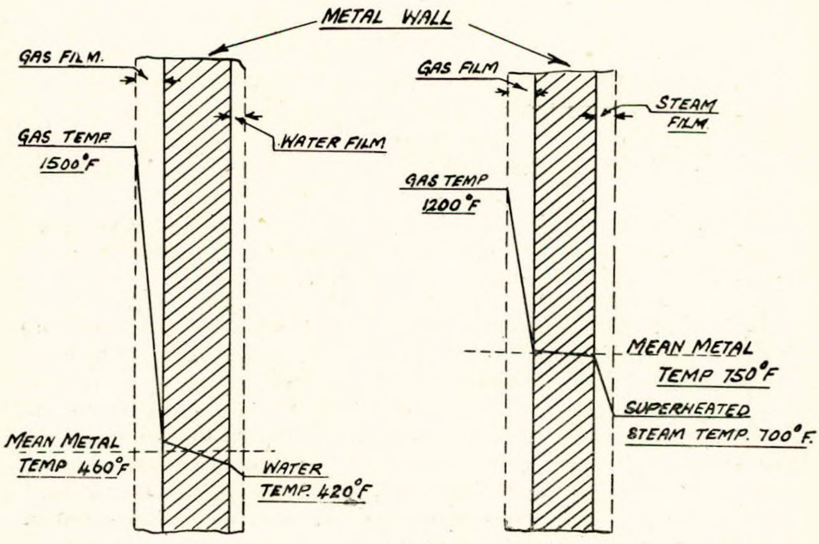
The temperature of a tube which is so placed that there is a flow of heat from the hot gases on the outside to the cooler gas or fluid inside depends almost entirely upon the resistance to heat transmission offered by the gas film on the outside surface and gas or fluid film on the inside surface. The resistance or drop in temperature across the thin metal wall is comparatively negligible, as will be found by employing the equation for temperature difference used in the previous section.

For many years it had been known that the principal resistance to heat transmission from a flame or hot gases to a metal was due to the existence of a cold gas film, but Professor Nicholson in a paper read before the Junior Institution of Engineers in 1909 drew particular attention to the effect of gas velocity on the rate of heat transmission through a metal wall, and the relative temperatures of the gas, metal and water. Since that time a number of laws of heat transmission have been established by various investigators as a result of experiments carried out under various conditions of heat flow, but in using any particular law it is necessary to consider the actual conditions of test and the range to which the laws or empirical formulæ so deduced can be applied. In some cases these formulæ have been deduced from one set of experiments and applied to practical cases entirely out of the range of the original experiments, so giving results which may be misleading.

The temperature distribution through the walls of a boiler tube may be represented qualitatively by the diagrams (*a*) and and (*b*) in Fig. 11 in which (*a*) represents a water tube and (*b*) a superheater tube.

These diagrams also illustrate the reduction in effective temperature head due to difference in the resistance to heat transmission offered by the water film and the superheated steam film. The overall heat transmission coefficient will depend largely upon the velocity of the media on each side of the tube wall.

With increased hot gas velocity more of the cold gas film will be swept away and the greater the heat transfer rate. The same applies to the inside of the tube. With water tubes it has been shown by experiment that the velocity of the water



(a) Fig. 11. (b)

when it is increased above one foot per second has little effect on the overall transmission coefficient, whereas for superheated steam it may be necessary to employ high speeds in order to keep the tube temperature within satisfactory limits. For superheater tubes there also appears to be a critical point above which any further increase of velocity has little influence in the coefficient of heat transfer, this critical velocity increasing with increase in diameter of tube. With good circulation and reasonably clean surfaces no great error is made in assuming that the temperature of the inner surface of the tube is the same as that of the water when the outer surface is in contact with the hot gases of combustion. Although increase in velocity above about 3ft. per sec. does not have any appreciable effect on the rate of heat transfer, it is important that the steam bubbles should be quickly swept off the tube wall, otherwise a group of bubbles may coat the surface with a film which may lead to overheating.

To find the temperature of the metal wall of a superheater tube the following method may be employed:—

Let h_g = heat transmission coefficient for gases to metal
h_s = ,, ,, ,, metal to steam
T_g = temperature of gases
T_m = ,, ,, metal
T_s = ,, ,, steam

Then since the total heat transmission remains the same

$$h_g\,(T_g - T_m) = h_s\,(T_m - T_s)$$

$$\text{whence } \frac{h_s}{h_g} = \frac{T_g - T_m}{T_m - T_s} = \phi \quad \text{- - - - - - - - -} \quad (9)$$

$$\text{and } T_m = \frac{h_g\,T_g + h_s\,T_s}{h_s + h_g} = \frac{T_g + \phi\,T_s}{\phi + 1} \quad \text{- - - -} \quad (10)$$

In the ordinary type of convection superheater, *i.e.* not exposed to radiant heat of the flame, and it is extremely doubtful whether any other type will be used in marine work unless independently fired and so definitely controlled, the heat transmission in B.T.U. per sq. ft. of heating surface per hour is low and the temperatues of the inner and outer surfaces are for all practical purposes identical. Fig. 12 shows the temperature drop across the walls of 3in. and $1\frac{3}{4}$in. o/d tubes subjected to heat transfer rates of 40,000 and 8,000 B.T.U. per sq. ft. per hour respectively plotted against working pressure in pounds per sq. in. From this diagram it will be seen that with the ordinary small superheater tubes in general use the temperature difference between the inner and outer surfaces of the tubes does not reach 10° F. even for very high pressures requiring thick tubes. Fig. 13 shows the variation of temperature drop with heat transmission for a 2in. o/d tube subjected to various internal pressures, the thickness being, of course, increased accordingly.

The effect of the ratio of the heat transmission coefficients for gas to metal and metal to steam, that is ϕ, on the metal temperature is well illustrated in Fig. 14, which has been obtained by using equation (10), for different gas and steam temperatures.

It will be observed that increasing ϕ above 20 has very little effect on the metal temperature, and with $\phi = 30$ the tube tem-

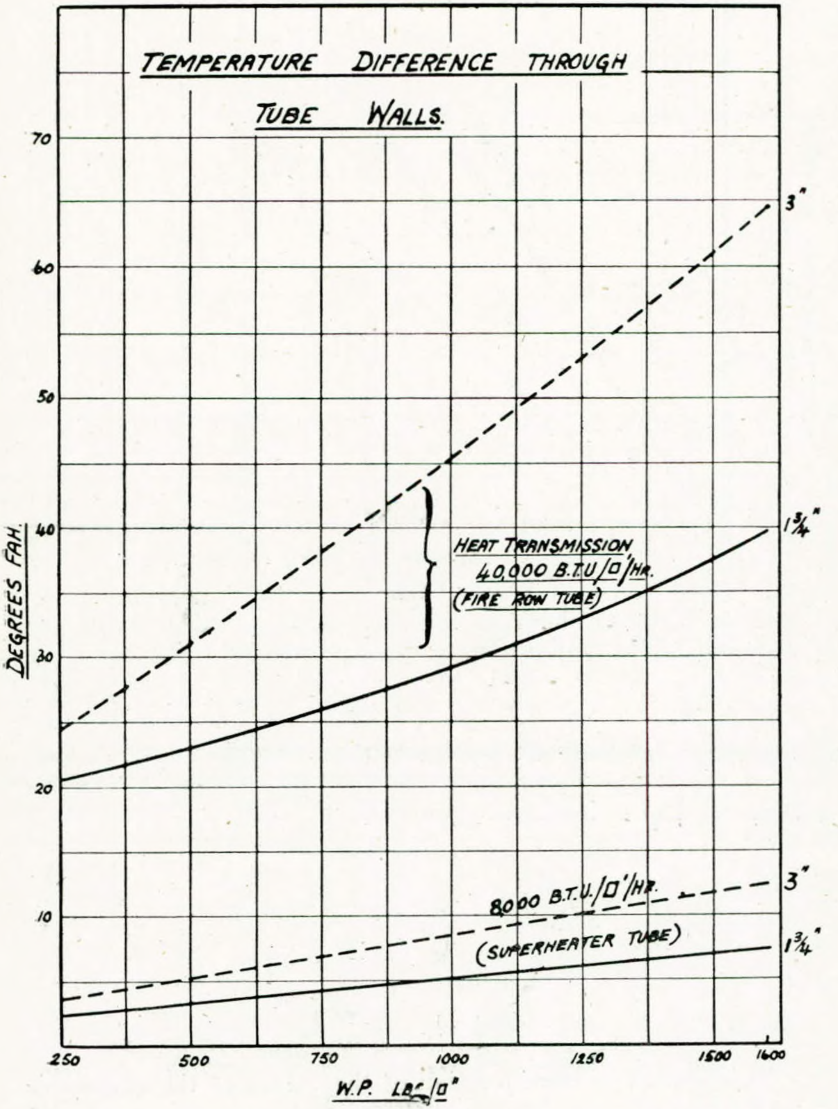


Fig. 12.

perature is only a few degrees above the steam temperature. As the value of ϕ increases the overall coefficient of heat trans-

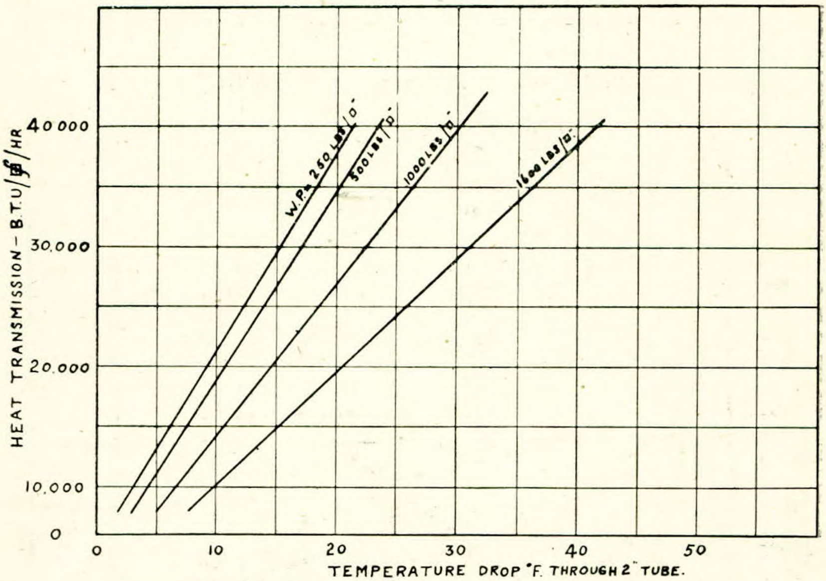


Fig. 13.

mission becomes closer to the value of the coefficient for gas to metal. This follows from the equation of resistance

$$\frac{1}{h_o} = \frac{1}{h_s} + \frac{1}{h_g} + \frac{1}{h_m} \quad \text{- - - - - - - - - -} \quad (11)$$

where h_o = overall heat transmission coefficient.
h_m = heat transmission coefficient for metal.

Since h_m may be neglected it follows that

$$\frac{1}{h_o} = \frac{1}{h_s} + \frac{1}{h_g}$$

and with $\phi = 20$ & 30

$$_{20}h_o = \frac{20}{21} h_g$$

$$\text{and } _{30}h_o = \frac{30}{31} h_g$$

This leads to a consideration of the values of the respective coefficients of heat transmission for hot gases to metal and

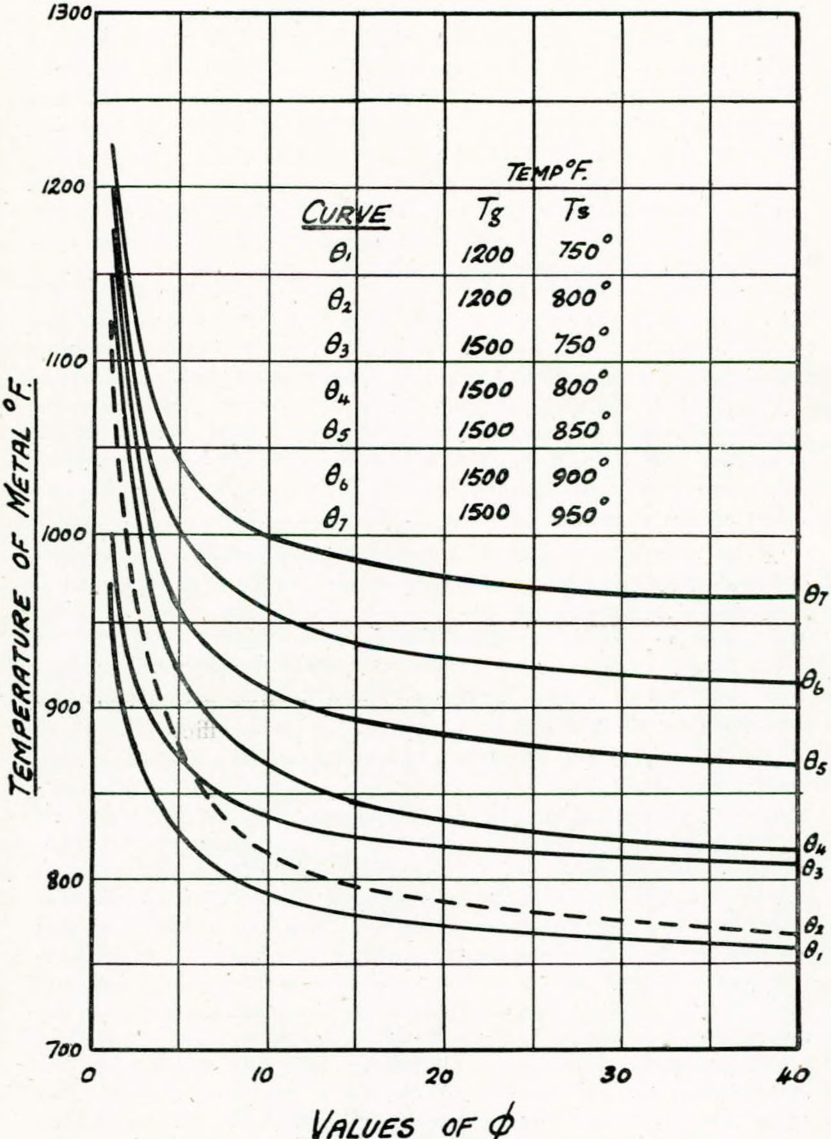

1300
1200
1100
1000
900
800
700
TEMPERATURE OF METAL °F.
0
10
20
30
40
VALUES OF φ
TEMP°F.
CURVE
Tg
Ts
θ1 1200 750°
θ2 1200 800°
θ3 1500 750°
θ4 1500 800°
θ5 1500 850°
θ6 1500 900°
θ7 1500 950°
θ7
θ6
θ5
θ4
θ3
θ2
θ1

Fig. 14.

metal to superheated steam. In recent years a number of investigations have been carried out and empirical formulæ deduced for calculating these coefficients. Most of the experiments have been made with apparatus in which hot air flows on one side of a tube and steam or water flows inside. In very few cases has the temperature of the hot air exceeded 700° F., and where steam has been used on the inside of the tube the pressures have not exceeded about 200 lb. per sq. in. When applied to actual cases in boilers care must be exercised in adapting experimental data to existing conditions. Two examples will suffice to indicate this; (*a*) as the temperature of hot gases is increased the radiation effect becomes more pronounced in comparison with the heat transfer by convection only and h_g becomes correspondingly increased, (*b*) with increase of steam pressure the specific heat of superheated steam increases and so for a constant mass flow and heat transmission rate from hot gases to steam the value of the coefficient from metal to steam will increase.

Brief reference might be made to some recent experiments in heat transmission which are useful in considering actual conditions appertaining to boilers. For those interested in the general subject of heat transmission up to the time of Nicholson's experiments, Professor Dalby's report on "Heat Transmission" (Proc. I. Mech. Engs., Part 3-4, 1909) will be found of great value.

An investigation to obtain heat transmission data under conditions similar to those existing in an actual water-tube boiler was carried out under the supervision of H. O. Croft and was published in University of Illinois Bulletin, No. 168. In these experiments steam was generated in a boiler consisting of a single water-tube so arranged that water circulation occurred under conditions similar to those in a Babcock and Wilcox boiler, the heat being obtained by burning illuminating gas and passing the products of combustion parallel to the axis of the tube. The coefficient of heat transmission of the apparatus was found to vary with (i) the rate of gas flow, (ii) the temperature difference between flue gas and water, (iii) the steam pressure, (iv) the temperature of the hot gases. The mass flow of gases varied from 0·15 to 0·51 lb. per sq. ft. of flow area per second, the temperature of hot gases varied from 900° F. to 1700° F. and steam pressures from 20 to 160 lb. per sq. in. absolute. Various rates of water circulation were tried and it was found that the water velocity had slight effect on the overall coefficient of heat transmission. The following empirical formula was determined from the results:—

$$K_c = 0\cdot000977\,\Delta T + 0\cdot0025 T_w + 0\cdot0855\,W_a + 0\cdot00294\,T_g - 1\cdot83$$

where K_c = overall "convection coefficient" of heat transmission per sq. ft. per deg. F. per hour.

ΔT = log. mean temperature difference between flue gases and water in tube.

T_w = temperature of water in tube in °F.

W_a = rate of gas flow $\left(\frac{W}{A}\right)$ in lb. per minute per sq. ft. of gas passage area.

T_g = average temperature of gas in °F.

The writer has simplified this formula for practical use as follows, viz.:—

$$h_o = 0\cdot0011 + 0\cdot0014\left(\frac{w}{a}\right) \quad \text{- - - - - - - - - - -} \quad (12)$$

where h_o = overall transmission coefficient in B.T.U. per sq. ft. per sec. per deg. F, and may be taken as h_g (hot gas to metal).

$\left(\frac{w}{a}\right)$ = mass flow of gas in lb. per sq. ft. per sec.

In this form the equation (12) is similar to that adopted by Osborne Reynolds, who expressed the heat transmitted per unit of surface per degree temperature difference per unit time as—

$$h = A + B\rho v.$$

Where A and B are constants, ρ is the density of the fluid and v its velocity.

Some experiments on heat transmission in superheater tubes are described and the results obtained are given in a thesis entitled "Heat Transmission in Superheater Elements," by John T. McIntyre, in the Transactions of this Institute for November, 1927. In these experiments hot air was used at a temperature not exceeding about 500° F., the steam having a temperature of the order of 250° F, and pressure 24 lb. per sq. in.

The results were expressed in the form of a straight line law.

$$h_s = 0\cdot003 + 0\cdot0024 \left(\frac{w}{a}\right) \text{ - - - - - - - } (13)$$

where h_s and $\left(\frac{w}{a}\right)$ have the meanings previously assigned to them.

This equation may be considered suitable for mass flows up to 8 lb. per sec. per sq. ft. of area of flow. Reference was made in this thesis to the experimental work of O. Sneeden on preheated air for combustion, and a diagram was included showing a straight line law for the heat transmission coefficient of air to metal and metal to air. For all practical purposes the value of h_g may be taken as for air and may be expressed by the following equation:—

$$h_g = 0\cdot001 + 0\cdot0011 \left(\frac{w}{a}\right) \text{ - - - - - - - - } (14)$$

giving a result about half that of steam for the same mass flow, which might be expected since with the limiting conditions of the test the specific heat of steam is about twice that of air. Values of h_g obtained from this expression are slightly less than those given by equation (12) but of course the highest gas temperatures used in these experiments were appreciably less than in the Illinois experiments. At the same time in the latter experiments the mass flow of gas did not exceed 0·51 lb. per sq. ft. per sec., whereas Sneeden's results are applicable for gas flows up to 8 lb. per sq. ft. per sec.

In an interesting paper entitled " The Rational Use of Heat Transmission Factors on Design " (Trans. of I.E.S.S., Vol. LXXII), J. S. Brown has analysed numerous experiments carried out by R. Royds, which are described in various papers in the Transactions of the Institution of Engineers and Shipbuilders in Scotland, and finds that the results may be expressed in the form—

$$h_g = A \left(\frac{w}{a}\right)^{\frac{2}{3}} \text{ - - - - - - - - - - - - - } (15)$$

where A is a constant and for the range of experiments quoted is ·0014. In tests made by Royds a steel tube carrying heated air was enclosed in a water jacket and the heat transfer coefficient obtained from measurements made of the temperatures and flow quantities on both the water and gas sides of the tubes. The above equation only holds good up to say

700° F. Above this temperature the radiant heat factor and specific heat of gas will augment the heat transmission. Brown suggests that the case of the flame tube would appear to be met by the equation—

$$h_g = 0{\cdot}0021 \left(\frac{w}{a}\right)^{\frac{2}{3}} \text{ - - - - - - - - - - - - - } (16)$$

It will be found on plotting curves of the form $h_g = A \left(\frac{w}{a}\right)^{\frac{2}{3}}$ that the curve is fairly flat within the working range and for mass flows up to the limits of Sneeden's and McIntyre's experiments there is little difference between the straight line law and the curve obtained from equation (16).

The empirical formula suggested by Brown can be shown to be practically correct from theoretical considerations and is particularly useful for handling by engineers. It is a slight modification of the Nusselt equation—

$$h = A \left(\frac{w}{a}\right)^{\cdot 786}$$

where A may be taken as 4·11 for air and 7·68 for superheated steam, the temperatures in each case being very moderate.

The writer has therefore decided to adopt this type of formula, and has applied it to the experimental results of Sneeden, McIntyre and Croft, the following equations being deduced, viz.:—

$$h_g = 0{\cdot}0025 \left(\frac{w}{a}\right)^{\frac{2}{3}} \text{ - - - - - - - - - } (17)$$

$$h_s = 0{\cdot}0052 \left(\frac{w}{a}\right)^{\frac{2}{3}} \text{ - - - - - - - - - } (18)$$

For water tube boilers the value of $\left(\frac{w}{a}\right)$ for the mass flow of hot gases is seldom greater than 1·5 through the superheater tubes, and in the case of marine work is of the order of about 0·5 lb. per sq. ft. of flow area per sec.

The above equation for h_s may be considered as suitable for superheated steam up to a temperature of 300° F. the specific heat of steam being taken as 0·52 compared with 0·25 for hot gases. For high pressures and high temperatures the value of the constant 0·0052 would require to be correspondingly increased, and for all practical purposes may be taken as *mean specific heat of steam.*

Taking a value of $\left(\frac{w}{a}\right) = 1$ for hot gases then for $\phi = 30$ the mass flow for steam is given by—

$$\left(\frac{w}{a}\right)^{\frac{2}{3}} = \frac{30\ h_g}{0{\cdot}0052} = \frac{{\cdot}075}{{\cdot}0052} = 14{\cdot}42$$

and $\left(\frac{w}{a}\right) = 55$ lb. per second,

and for $\phi = 20$

$$\left(\frac{w}{a}\right) = 29{\cdot}8 \text{ lbs. per second.}$$

From this it will be apparent that for any gas flow rates the area of steam flow can be adjusted to keep the temperature of the metal as close as possible to the steam temperature. It follows from the foregoing that with constant gas flow and increased steam pressures, the specific heat of steam will increase slightly and mass flow could be correspondingly reduced with reduction of drop of pressure through superheater and without increase of tube temperature. It also follows that since specific volume decreases with pressure lower steam velocities can be employed with high pressure steam than with low pressure steam for the same degree of superheat or conversely by employing high mass flow at high pressures, without increase of energy cost compared with much lower mass flow rate, the metal temperatures can be considerably reduced.

It will be observed that the mass flow rates for steam will be appreciably greater than the limit given in Sneeden's and McIntyre's experiments, viz. 8 lb. per sq. ft. per second. At a mass flow rate of 30 lb. per sq. ft. per second the heat transmission coefficient using the formula $h_s = {\cdot}0052\left(\frac{w}{a}\right)^{\frac{2}{3}}$ is only $\frac{2}{3}$ of that given by employing the formula $h_s = {\cdot}003 + {\cdot}0024\left(\frac{w}{a}\right)$ and errs on the right side by giving a slightly greater tube temperature. In any case it is as well not to assume too high a value for h_g or h_s as there always exists some uncertainty regarding the cleanliness of the tube surfaces.

The existence of any scale on the internal surface will affect considerably the temperature of the metal. Some additional experiments were carried out by Croft (loc. cit.) to find the effect on the heat transmission coefficient due to the presence of scale. The results were a little uncertain, but with maximum gas flow of about ·32 lb. per sec., tube 3·93in. o/d, 0·13in.

thick, scale 0·083in. thick, temperature of gases 1400° F., temperature of water 325° F., the overall coefficient for transfer by convection dropped from about 6·4 to 5·8 B.T.U. per sq. ft. per hour per ° F. The resistance offered by this scale can be obtained from the equation:—

$$\frac{1}{5{\cdot}8} = \frac{1}{6{\cdot}4} + \frac{1}{h_c}$$

where h_c = transfer coefficient for scale.

From this it will be seen that the resistance offered by the scale is 1/10th that of the total resistance of hot gases to water, and since drop of temperature is proportional to resistance the temperature drop through scale will be of the order of 100° F., and neglecting any effect due to the presence of a water film the temperature of metal will be at least 100° F. in excess of the mean water temperature. Bearing this in mind, the importance of the freedom of superheater tubes from scale need hardly be emphasised. The reduction in heat transfer due to scale will be more marked in the case of tubes subjected to radiant heat since the gas film on the outside of the tube offers practically no resistance to radiation. The presence of scale will also affect the circulation with consequent increase of water film. It is, however, evident that if the water-tube boiler, whether for high or low pressure, is to be a success in marine practice, absolutely pure feed water is essential. Experience has shown, however, that at high pressures distilled water is liable to set up corrosion, and it has been necessary to make the water slightly alkaline.

Brief mention might be made here of the effect of increase of pressure on the circulation. Münzinger and other authorities agree that the size of bubbles decreases with the rise of pressure, and that circulation slows down. Smaller steam bubbles, however, mean more solid water and less overheating of tube metal, so that any reduction in circulation is counteracted to a certain extent. Hartmann has experimented on a coil of small tubing 140ft. long in which the coils were close against each other, and found that at a pressure of 1,470 lb. per sq. in., water circulation took place under a small supply head without any overheating of the tube. In the case of the Benson boiler it is claimed that the best results are obtained at the critical pressure, viz., 3,200 lb. per sq. in., at which point the steam and water have the same density and the change from water to steam takes place instantaneously without the formation of bubbles. Moultrop and Engle

(I. of E. & S.S., 11/2/1930) state that their experience with 1,400 lb. per sq. in. boilers and water-cooled furnace walls does not indicate that forced circulation is necessary or desirable. Loeffler, however, considers that forced circulation is desirable for pressures about 1,500 lb. per sq. in. It would, therefore, appear that provided the design of boiler is satisfactory as regards feed arrangements, water circulation should be satisfactorily maintained at very high pressures. It is claimed, however, by some boiler-makers that as a result of tests carried out, tubes of comparatively small diameters are preferable, as when using tubes of large diameters the water circulation has been stopped due to several steam bubbles forming together and completely blocking the tube.

In the case of superheaters there should be no possibility of scale formation due to impurities carried over with the steam, *e.g.*, due to frothing or priming. The formation of oxidised scale is a different matter, and will be mentioned again later.

To ensure a satisfactory temperature of metal in superheaters the position and design is of the greatest importance. The exigencies of the service do not permit of radiant superheaters in marine work, and even with the convection type of superheater special care should be taken to prevent radiant heat from the fire reaching the tubes, particularly in the case of coal-fired boilers, as owing to reduced flow of steam during manœuvring, working at low output and after stoppage the tube temperature will become uniform and tend towards the gas temperature with ultimate failure of the tubes. One special point might be mentioned in regard to steam flow in superheaters. In all calculations that are made it is assumed that the velocity is the same in all the tubes. This cannot be the case in practice with the usual type of headers fitted. The flow through some tubes will be much greater than in others with consequent overheating of those tubes with reduced flow as has been evidenced in some cases by superheater tubes being at a dull red heat. Correct flow can only be obtained with equal distribution, and this is a point which will need special attention with the high superheat temperatures now being adopted. Correct steam distribution can be obtained with a multiple loop, single pass design of superheater, the inlet to the saturated header being on the end opposite to the outlet superheater header. With this construction the length of steam travel is the same for all sections of the superheater, each unit drawing its proper share of steam.

It might be of interest to mention that Moultrop and Engle (loc. cit.) in the discussion to their paper state that in the third design of high pressure boiler (1,400 lb. per sq. in.) the arrangement of the superheater on the multiple loop single pass principle made the use of the expensive alloy tubes used in the second design (1,400 lb. per sq. in.) unnecessary. It should also be borne in mind that the final steam temperature is a mean temperature, and it is quite possible that owing to variations in gas flow and temperature the steam delivered by certain tubes may be considerably in excess of the mean exit temperature. This particularly applies to those cases in which it is not possible to arrange the superheater with the hottest steam in the coolest gas zone, that is, with the entering saturated steam passing through the hottest gas zone. Special care should be taken that the gas distribution and velocity are uniform across the superheater in order to prevent any possibility of variation of heat transmission and hot spots.

SECTION III.

MATERIALS FOR TUBES.

The ultimate success of the high pressure water-tube boiler depends largely upon the quality of the material used for the tubes, and an assurance of homogeneous material is particularly desirable Soft mild steel tubes have been used largely on account of their relative cheapness and ease of manufacture, but with the high pressures and high temperatures now being adopted, attention is being drawn to alloy steels which are more suitable.

So far, for water-tube boilers, there appears to be no necessity for departing from the use of low carbon steels but undoubtedly there is a call for the soundness of steel used in the manufacture of tubes and reliability against segregation, and the troubles that arise from it, most prominent amongst which is corrosion.

Tubes for water-tube boilers are usually specified to be cold drawn under 1½ ins. diameter and weldless, and manufactured from steel made by the Siemens-Martin open hearth process, the percentage of sulphur and phosphorus being stipulated not to exceed say ·035 and ·03 respectively. The tests specified by most authorities consist of tensile, flattening, crushing and bulging or expanding tests, together with hydraulic pressure tests. In regard to the tensile tests some authorities quote a maximum strength without a minimum, others a minimum strength or a range of strength, the limits being for ambient temperatures. The tubes are also required to be free from surface defects which incidently may be inherent in the material or caused in the process of manufacture. Frequently the material is required to comply with a chemical specification, but this may be no guarantee that certain of the constituents are evenly distributed throughout the material, and it is this lack of homogeneity which causes corrosion. The most easily detected segregates are those due to the presence of sulphur in steel which occurs as sulphide of manganese or the double sulphide of manganese and iron, and these sulphides show up best by sulphur printing. When acted upon by acid, sulphides and phosphides of iron decompose with local evolution of sulphuretted and phosphoretted hydrogen, which may be made to discolour a suitably sensitised surface. Reprinting is done by means of silver bromide paper wetted by immersion in dilute sulphuric acid, the sensitised surface being brought into contact with the polished face of the specimen to be examined. The paper is left in contact for say two minutes, and on its removal there is found an image of varying intensity outlining the sulphide areas by the local production of sulphide of silver. Recent experiments have shown that the quantity of hydrogen phosphide evolved is much too small to give visible markings of any kind on the bromide paper. Three sulphur prints are illustrated in Fig. 15, in which "A" represents section of thin tube made from thick skin segregate class steel, "B" a heavy tube made from a thin skin segregate steel, and "C" a tube made from fully "killed" steel.

To ensure satisfactory material it is essential that, as any segregation present in the tubes must necessarily have been present in the original ingot, an examination by sulphur printing should be made at the earliest stages of manufacture, either in the original ingot or in the billets made from it. The association of corrosion and pitting in tubes with the presence of segregates has been convincingly dealt with by G. R. Woodvine and A. L. Roberts in a paper entitled "The Influence of Segregation in the Corrosion of Boiler Tubes and Superheaters" (Iron and Steel Inst., Vol. CXIII).

These authors made sulphur prints from a number of new tubes taken at random from various consignments, and found them badly segregated on the inner surface, the sulphur con-

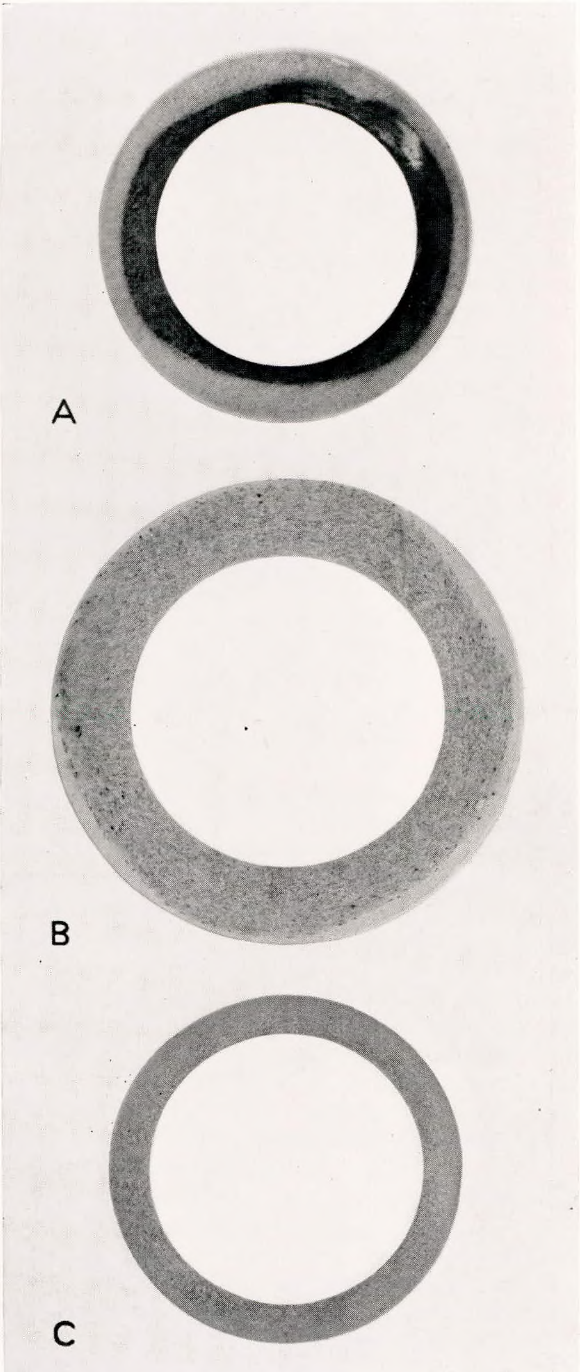


Fig. 15.

Collingham has stated (See discussion on "High Pressure Steam," I. Mech. Eng., 1927, p. 180.) that The British Thomson-Houston Company had considered the problem and did not expect dissociation to be sufficient to cause any trouble in boilers at pressures and temperatures considered suitable in the light of present knowledge. American investigations have also proved that for mild steel dissociation occurs at temperatures above 500° C. It will, however, be shown later that considerations of strength limit the use of mild steel to temperatures not greater than 900° F., so that with proper design and care to prevent excessive temperatures serious trouble due to oxidation should not be experienced. For land work the latest developments include a superheated steam temperature of 1000° F., which necessitates the employment of some alloying element such as nickel and chromium, which will make the material more resistant to oxidation.

Some interesting particulars of experiments carried out to determine the resistance to oxidisation of heat-resisting steels are given in a paper entitled "Tubes in Steam Engineering," by R. Waddell and L. Johnson (Liverpool Engineering Soc., Vol. LI). According to these authors high chromium irons and nickel chromium austenitic steels were unattacked by steam at 550° C. and by furnace gases at 850° C.

The approximate temperatures at which oxidation may start having been determined for any particular steels, it becomes necessary to consider the strength of the materials at these high temperatures. As the temperature of a metal is increased it is found that there is a limit at which the physical properties of the material change, and in recent years much attention has been given to ascertaining a suitable criterion of strength at elevated temperature. It has been found that at a certain temperature materials behave in a manner resembling a viscous fluid and under stress deformation continues for various periods depending on the intensity of stress. As a result much research work has been and still is being carried out to ascertain whether there is a definite stress for each material and temperature at which deformation or creep ceases. The methods adopted in determining the rate of creep and some particulars of the results for certain materials have recently been given in a paper read before this Institute in April last by S. L. Archbutt, and it is not proposed to go into any further details here. Attention has more recently been given to the determination of the stress at which the rate of creep will not exceed a permissible amount, thus allowing for a known extension to take place for a given life, and the strength of the material is thus expressed in terms of temperature and time. In this manner it is found possible to use ordinary carbon steel at higher temperatures than has previously been thought desirable. The working stresses are however based on considerations of plastic distortion, as any attempt to consider the applicability of the elastic theory for temperatures above say 750° F. must be questioned, as will be apparent from Fig. 2. H. L. Guy has shown in his paper "Tendencies in Steam Turbine Development," read before the North Western Branch of the Institution of Mechanical Engineers at Manchester, January, 1929, how ordinary carbon steels may be used at temperature of 900° F. with the same factor of safety; that is, with the same creep rate, as at 700° F., provided the working stress is reduced by 60%.

In order to ensure greater safety at high temperatures than is possible with ordinary mild steel, steel manufacturers have investigated the alloying of certain elements such as chromium, nickel, molybdenum. tungsten, vanadium, manganese and silicon with low carbon steels so that increased strength will be attained. For boiler tubes it is essential that the addition of any of these elements should not interfere with the mechanical properties of the material at ambient temperatures, that is, the material must be capable of being bent and expanded cold, and for certain types of superheater tubes it must be possible to weld the material. So far there is little available information of the behaviour of alloy steel tubes under service conditions, though there is a fair amount of information regarding their properties. The chief reason their use has as yet not become more general is on account of the highly increased cost. In some cases where it is necessary to use special alloy steels the cost can be reduced by dividing the superheater into two sections, consisting of mild steel tubes in which steam can be raised to a temperature of say 750° to 850° F., and the final superheating section consisting of the special alloy tubing in which the steam temperature is further increased to the required amount. Thus in the 1,420 lb. pressure boilers at Mannheim Power Station 3% nickel tubes have been used in the hottest parts. The advantages of the addition of small quantities of nickel, however, seem rather uncertain as regards superheater tubes. In this respect it may be mentioned that recent research indicates that the addition of low percentages of nickel has an adverse effect on the creep properties compared with ordinary mild steels. An alloy steel known as Enduro metal containing about ·09 C, ·34 Mn, ·84 Si, ·014 S, ·021 P, 16·7 Cr. ·19 Ni has been tried for the last pass in certain superheaters in America, but according to A. E. White (Trans. A.S.M.E., Vol. 51-1) this material appears to develop brittleness when held around 1000° F. for a long time and accordingly, owing to this property, its use has been discontinued in some cases. The demand for a material which is strong at high temperatures and does not scale, has led to the development of high nickel, high chromium steels which are austenitic in structure, and consequently can only be hardened by cold work. Most prominence has been given to an alloy of 19-18% chromium and 8% nickel. This material can be welded and machined, and tubes made from it will withstand the specified expanding, crushing and flattening tests. It has about twice the strength of low carbon steel at elevated temperatures, and in addition has a high resistance to oxidation. J. R. G. Monypenny, however, in Metallurgia, June, 1930, considers that further investigation is needed before austenitic chromium nickel steels can be recommended for use at 600° C., as at this temperature the steels are particularly liable to intergranular attack by many corrosive media which have little or no action on them when they are in correctly treated condition. This seems to be borne out in practice, and the writer has been informed that while high chrome nickel alloy steel appeared at first to justify its use for high temperature service, failures have recently been experienced with this metal due to intercrystalline breakdown which gradually went on without giving any warning. In all cases no bulging or splitting of the tubes occurred, but failure was caused by a sudden breakdown of a large piece of metal from the tube.

It appears that the addition of small quantities of other elements gives improved properties, an alloy containing 18% Cr, and 8% Ni and 0·3 to 1·5% W being considered the most satisfactory composition for withstanding high temperatures or chemical attack. Tests made by J. R. G. Monypenny, however, have shown that the addition of about 1% tungsten may retard the intergranular breakdown, but under certain conditions of chemical attack the steel is not immune from this defect. Unfortunately the price at present is almost prohibitive, being not less than 12 times that of low carbon steels. Further, there is the likelihood of trouble in the fitting of these austenitic steels on account of the difference of the coefficient of expansion from that of other materials, *e.g.*, expanding the tubes into headers. In certain cases in order to prevent hardening or re-crystallisation due to being expanded into headers, short lengths of ordinary mild steel have been welded to the ends of the superheater elements, thus preventing failure at the expanded joints.

The Foster Wheeler Corporation of New York have been carrying out experiments with a chrome vanadium steel, of which the following is an approximate analysis: Cr 0·85 to 1·05, Mn 0·6 to 0·8, Va 0·15 to 0·2, Si 0·1 to 0·15, C 0·17 to 0·22. This amount of vanadium is not sufficient to produce any vanadium characteristics in the metal, but acts as a scavenger and gives a very close grained metal which is exceedingly tough. Up to the present it is understood that tubes made from this steel have proved satisfactory in service, and have a much greater resistance to higher temperatures than have the ordinary carbon steel tubes.

In order to reduce cost and still have a greater factor of safety at high temperatures than that given by mild steels, attention has been devoted to the effect of small quantities of molybdenum and copper to low carbon steels. Two tube materials which have become more prominent recently on the Continent and the price of which is stated to be about 50% higher than that of ordinary steel tubes, are manufactured at the Thyssen Works and are known as Th 30 and Th 31. The approximate chemical analyses of these steels are, for Th 30: Mo 0·2 to 0·3%, Cu 0·2 to 0·3%, C 0·08 to 0·12%, Mn 0.5%, Si 0.12%, with P and S as low as possible; for Th 31 steel the carbon content varies from 0·16 to 0·18%. The tubes are capable of withstanding the same mechanical tests as ordinary tubes. Th 30 can be welded, but for Th 31 the welding should be done by the oxy-acetylene process. Creep tests are not available at present, but the results of some comparative tests supplied by the makers are given in the accompanying table:—

MATERIAL.	Stretch Limit Tons per sq. inch.		Ultimate Tensile Tons per sq. inch.	
	400°C	500°C	400°C.	500°C.
Th 31	17·8	15·1	32·6	24
Th 30	11·9	10·8	25·8	19·2
3% Ni.	14·7	9·5	26·9	15·9
Mild Steel	8·1	5·5	20·5	11·7

The yield stresses stated in this table are not the stresses at definite yield points. Professor Korber has shown that for soft steels the yield point ceases at about 300° C so that it becomes necessary to adopt some criterion of minimum plastic strain. For practical reasons he adopts a 0·2% limit and the yield stresses given in the table correspond to what is known as 0·2% proof stress.

It is a little early to judge with any certainty how this tube material is behaving in boilers. Messrs. Vereenigte Kessel Works at Dusseldorf have built a water-tube boiler fitted with superheater tubes of this material, the working pressure of which is 52 kgs per sq. cm. (740 lb. per sq. in.), the tubes being exposed to a temperature of 450° C (842° F). The time of guarantee has already lapsed and it is stated that the firm intend to use these tubes in future for their boilers. Similar tubes have also been fitted in a Benson boiler which has recently been installed by Messrs. Blohm and Voss for experimental purposes in a cargo vessel owned by the Hamburg Amerika Line.

A somewhat higher alloy carbon steel has recently been introduced in this country by Messrs. Hadfield, Ltd., and is known as "Era 131." The writer is indebted to Messrs. Hadfield, Ltd., for the following information. Stated briefly, Era 131 steel, while maintaining a high strength in the range of advanced steam temperatures, 750° F. to 1100° F., has practically the same mechanically properties as mild steel at ordinary temperatures, and cold drawn seamless tubes fully comply with the tests specified in B.E.S.A. Spec. No. 53. It is claimed that the resistance to heat scaling is about half the rate of ordinary steel for equal temperatures, and that under long continued heating (200 hours) at a temperature of 840° F. it suffered no deterioration in its properties. Another advantage is that the coefficient of expansion is practically the same as that of ordinary steel.

The high resistance to creep of Era 131 steel compared with mild steel (·25 C. ·75 Mn) is indicated in Figs. 16 (*a*) and (*b*).

SECTION IV.

SUGGESTED FORMULÆ FOR DETERMINING THE THICKNESS OF TUBES FOR HIGH PRESSURE WATER-TUBE BOILERS.

In the three preceding sections the stresses in boiler and superheater tubes and some considerations regarding their factors of safety have been dealt with.

It will be evident that any formulæ for ascertaining the suitable thickness of tubes which will at the same time provide direct evidence of the actual stresses arising in service conditions will be of a very complicated nature, and so it becomes necessary, in order to be able to calculate readily a suitable thickness for a given diameter of tube and working pressure, to formulate a simple rule. In most cases this can be done by means of a modification of the formula for calculating the thickness of thin tubes. The stress adopted in such a formula is not, of course, the actual stress in the tube, but represents the mean circumferential stress.

Referring back to Figs. 5 to 8, it will be obvious that the most suitable formula will be that in which the thickness so calculated will give values of k which will coincide with the optimum values. There are, however, one or two special points which have to be considered when dealing with boiler tubes. In the first place it is necessary to make some allowance for irregularities in the process of manufacture, which may or may not be detected in the inspection. Secondly, allowance must be made for wear, corrosion and pitting. It will, however, be obvious that any increased thickness due to these two causes will have less effect as the thickness of tube for the same diameter, increases; that is, the higher the working pressure and consequently the thicker the tube, the less will be the effect of any reduction in strength on account of wear, etc., compared with a thinner tube for a lower working pressure. For this reason tubes for low working pressures have a much lower mean circumferential stress than is permissible for high pressure work.

It might also be pointed out that the tubes of marine boilers may be affected by movements in the hull structure, thus causing additional stresses.

An addition to the factor of safety might also be considered necessary in marine boilers on account of the greater inconvenience due to failure of a tube or explosion. In many respects therefore it appears reasonable that the thickness of tubes for marine water-tube boilers should be, if anything, slightly heavier than is considered satisfactory for land boilers. Up to the present no authority in this country has issued rules for determining the thicknes of tubes for high pressure land or marine water-tube boilers. In the United States the American Society of Mechanical Engineers has issued rules, while rules are already in force for land boilers in Germany.

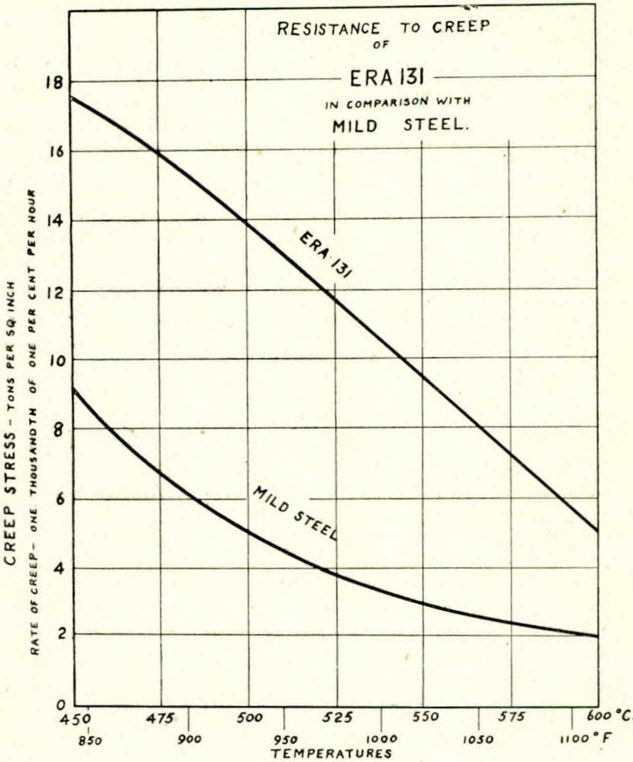


FIG. 16.A.

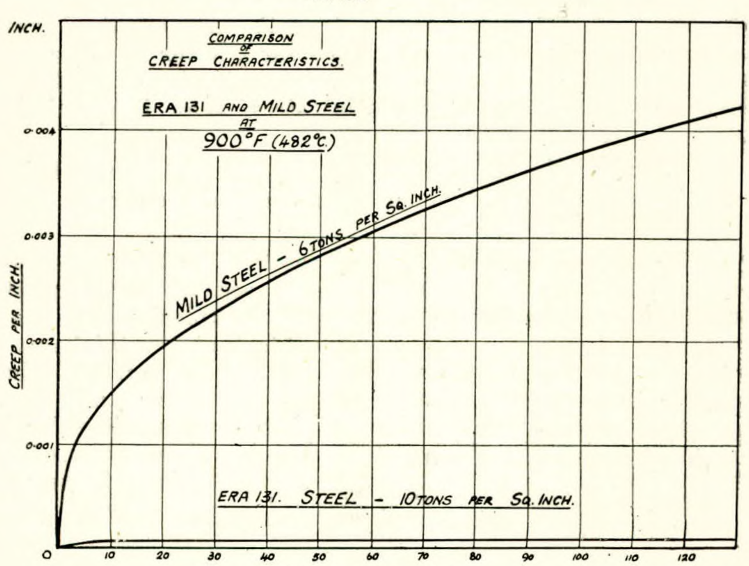


FIG. 16. B

For most high pressure work in this country it appears that the thicknesses of tubes have been calculated in accordance with the A.S.M.E. Rules.

After a careful study of the problem and considering the thicknesses of tubes which have been used with satisfactory results in high pressure boilers in this country and elsewhere, the writer suggests that the following formula might be used to ascertain the thickness of tubes for high pressure water-tube boilers for marine purposes, viz.:—

$$t = \frac{W.P. \times d}{100} + x$$

where t = thickness of tube in 1/100th's of an inch.
W.P. = working pressure in lb. per sq. in.
d = internal diameter of tube in inches.
x = factor depending on the position of the tube in the boiler.

For tubes not in the fire or subjected to the radiant heat from the fire:—

$$x = \frac{2000}{W.P.} \text{ but not greater than 7}$$

For fire rows of tubes or tubes subjected to radiant heat from the fire the value of x as given above to be increased by $\frac{2000}{W.P.}$ but not greater than 4.

For superheater tubes:—

$$x = \frac{2000}{W.P.} \text{ but not greater than 5}$$

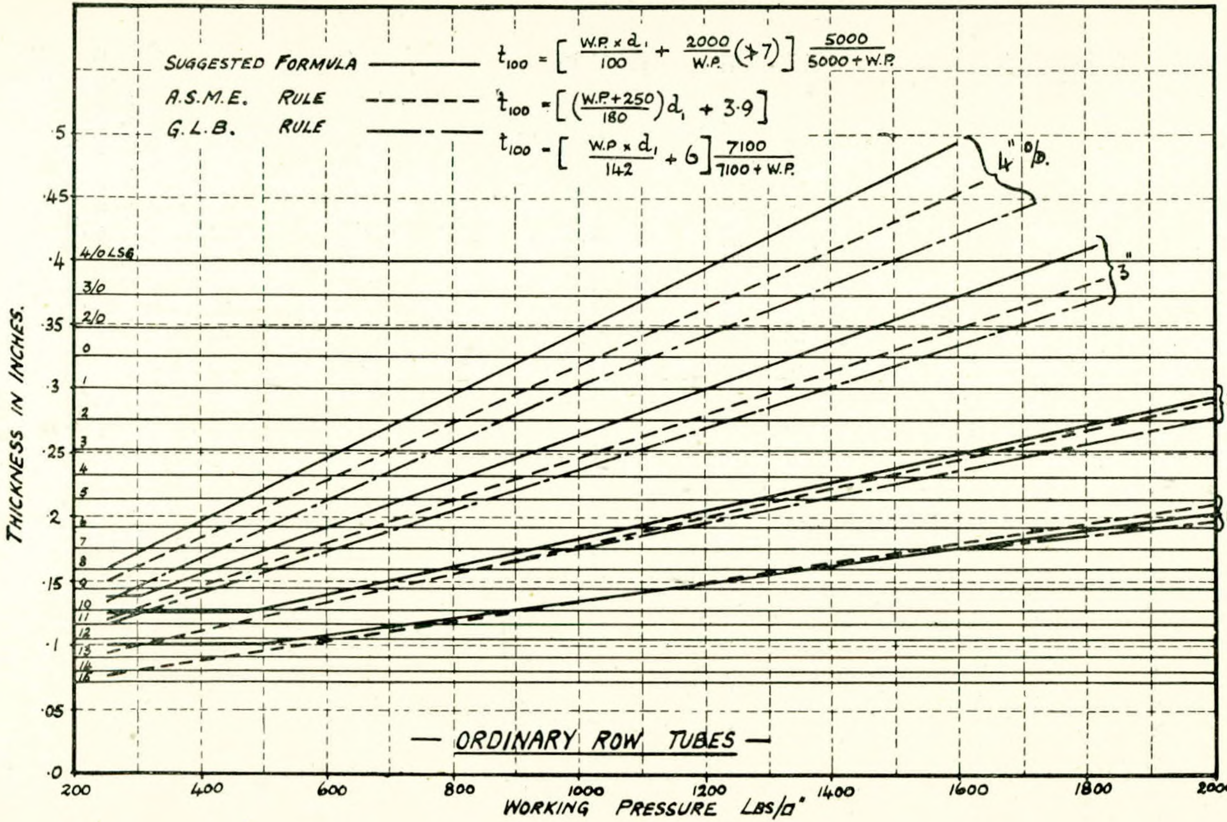
for steam temperatures not exceeding 850° F. The usual practice is to specify outside diameters for tubes, in which case the formula becomes:—

$$t = \frac{5000}{W.P. + 5000}\left(\frac{W.P. \times d_1}{100} + x\right)$$

where d_1 = external diameter of tubes in inches.

It will be observed that for any particular diameter of tube the value of the factor x decreases as the working pressure rises, that is, with increase in thickness. This is as it should be, since any reduction in strength due to wear and corrosion is proportionately less with thick than with thin tubes.

Fig. 17 shows the thicknesses of tubes of various outside diameters plotted against the working pressure in lb. per sq.


SUGGESTED FORMULA
A.S.M.E. RULE
G.L.B. RULE
$t_{100} = \left[\frac{W.P. \times d_1}{100} + \frac{2000}{W.P.}(\mp 7) \right] \frac{5000}{5000 + W.P.}$
$t_{100} = \left[\left(\frac{W.P. + 250}{180}\right) d_1 + 3.9 \right]$
$t_{100} = \left[\frac{W.P. \times d_1}{142} + 6 \right] \frac{7100}{7100 + W.P.}$
4" O/D.
3"
2"
$1\frac{3}{8}$"
THICKNESS IN INCHES.
4/0 LSG
3/0
2/0
— ORDINARY ROW TUBES —
WORKING PRESSURE LBS/□"

Fig, 17.

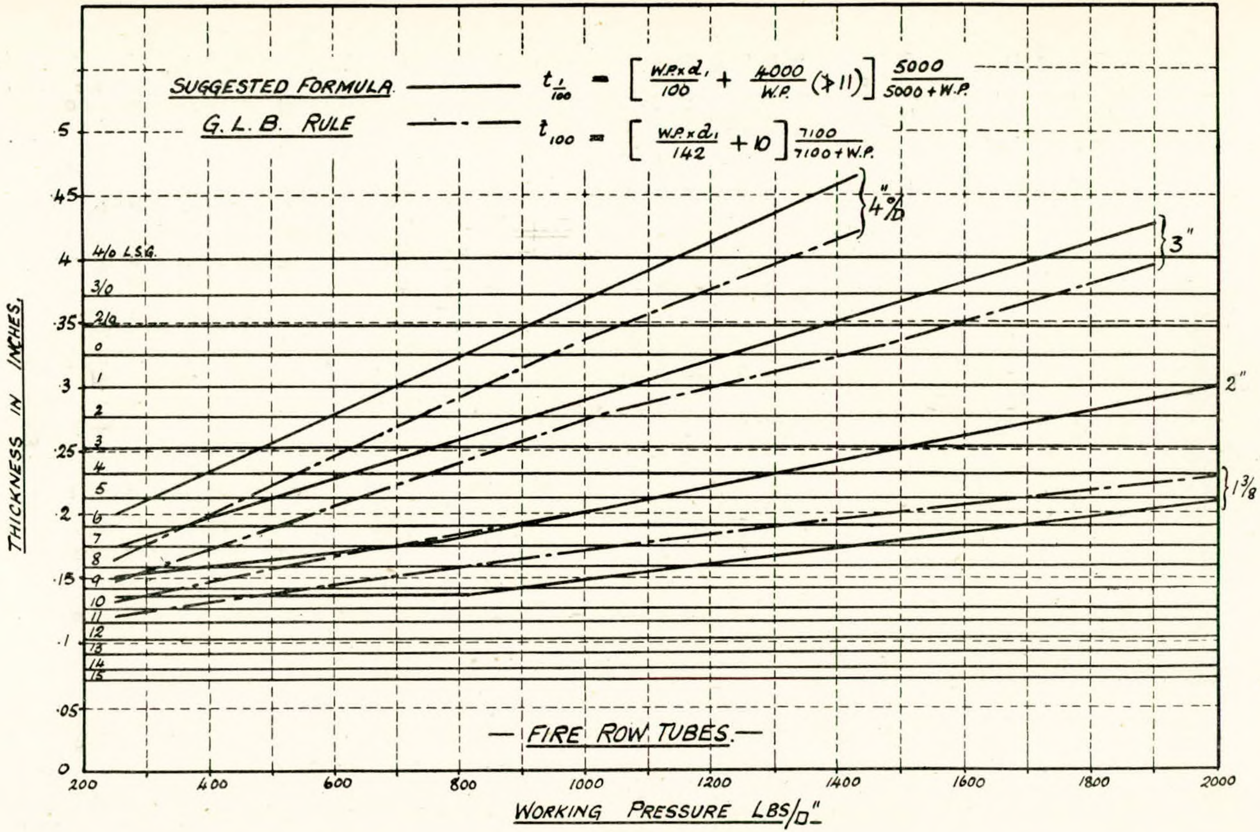


Fig. 18.

NOTE.—Value of $\frac{4000}{\text{W.P.}} \ngtr 11$ given in suggested formula is $\frac{2000}{\text{W.P.}} (\ngtr 7) + \frac{2000}{\text{W.P.}} (\ngtr 4)$

in. The corresponding L.S.G. sizes have been added and generally the thickness of tube should be made to the nearest gauge above the calculated thickness. This figure also gives a comparison between the calculated thicknesses of tubes of $1\frac{3}{8}$in., 2in., 3in., and 4in. o/d ascertained by using the A.S.M.E. rule, the German land boiler rule and the suggested formula, for tubes not in the fire, while Fig. 18 gives a comparison for tubes in the fire or subjected to radiant heat. In the latter case comparison has only been made with the German land boiler rule.

The curves marked XX in Figs. 5, 6 and 8 show how the values of k obtained by using the suggested formula compare with the optimum values.

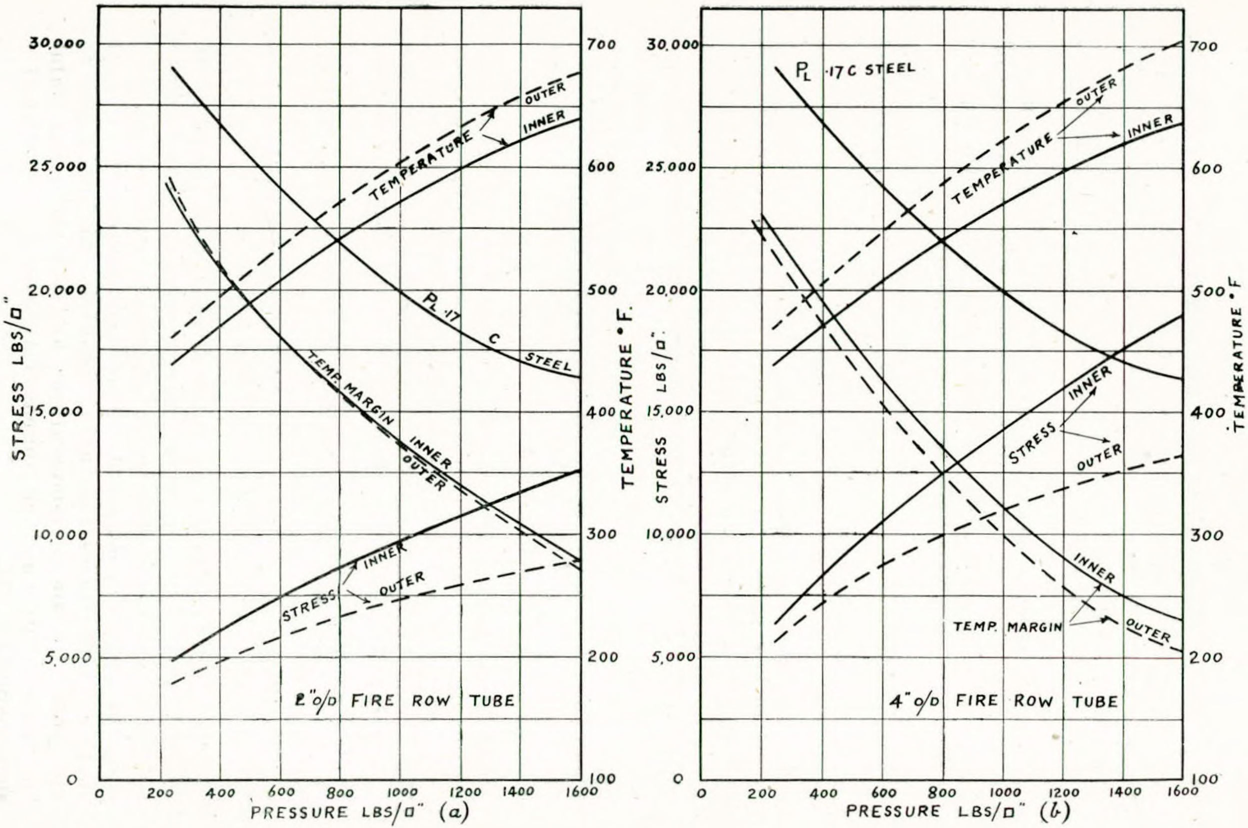
It will be observed that with the high transmission rates in the fire rows an appreciable reduction in thickness, due to irregularities in manufacture, wear or corrosion may be permitted without increasing the maximum stress in the tubes. For ordinary rows the maximum stress is slightly increased with reduction in thickness below that given by the suggested rule, but the stresses are still considerably less than those in fire row tubes.

SECTION V.

FACTORS OF SAFETY WITH TUBE THICKNESSES IN ACCORDANCE WITH SUGGESTED FORMULÆ.

The factors of safety for boiler and superheater tubes may be considered in two ways: (i) on a stress basis, that is, margin of strength based on elastic limit, ultimate tensile strength or creep limit and (ii) on a temperature basis, that is, margin of temperature above which failure will take place due to the working stresses in the tube.

Boiler Tubes. As an example of these two methods the stresses for various pressures in 2in. o/d and 4in. o/d fire row tubes having thicknesses in accordance with the suggested formula will be considered. The temperatures of the inner surface of the tubes has been taken as 25° F. above the corresponding steam temperature, and for the outer suface the temperature has been increased an amount determined by using equation (3).



30,000
25,000
20,000
15,000
10,000
5,000
0
700
600
500
400
300
200
100
STRESS LBS/□"
TEMPERATURE °F.
TEMPERATURE
OUTER
INNER
P_L ·17 C STEEL
TEMP. MARGIN
INNER
OUTER
STRESS
INNER
OUTER
2" o/D FIRE ROW TUBE
0 200 400 600 800 1000 1200 1400 1600
PRESSURE LBS/□" (a)
30,000
25,000
20,000
15,000
10,000
5,000
0
700
600
500
400
300
200
100
STRESS LBS/□"
TEMPERATURE °F
P_L ·17 C STEEL
TEMPERATURE
OUTER
INNER
STRESS
INNER
OUTER
TEMP. MARGIN
INNER
OUTER
4" o/D FIRE ROW TUBE
0 200 400 600 800 1000 1200 1400 1600
PRESSURE LBS/□" (b)

Fig. 19.

Figs. 19 (*a*) and (*b*) show the calculated stresses at the inside and outside surfaces of 2in. and 4in. tubes respectively, plotted to a base of working pressure. The corresponding values of the limit of proportionality (P_L) for 0·17 carbon steel, taken from D.S.I.R. Reports Nos. 1 and 14, have been added, and the differences between the P_L curves and curves of tube stresses indicate the factors of safety, if P_L be taken as the criterion of strength. It will be observed that in the case of the 4in. o/d tube the stress at a pressure of 1,360 lb. per sq. in. coincides with the limit of proportionality.

The temperatures of the inner and outer surfaces of the tubes are also shown together with curves of temperature margin. The temperature margins indicated are the difference between the temperatures of the tubes and the temperatures corresponding to the creep limits represented by the stresses in the tubes. It will be noted that even at the highest pressure shown there is a margin greater than 200° F. This would be slightly reduced with tubes made of 0·10 carbon steel and also with higher heat transmission rates.

Superheater Tubes. The foregoing methods may also be applied to superheater tubes where the temperature does not exceed 750° F. Above this temperature, for low carbon steels, it is necessary to consider plasticity rather than elasticity, and this will be dealt with later.

Fig. 20 shows the stresses, stress margins, and temperature margins for a 2in. o/d superheater tube which is probably the largest superheater tube that would be fitted. With low heat transmission rates in convection superheaters the temperature of both inner and outer surfaces of the tube may be taken as the same, and in this example are equal to 750° F. In this case only the stresses at the inner surface need be considered. Temperature margins are shown for 0·10 C. and 0·17 C. steel, and it will be noted that at the highest pressures there is a margin of safety of about 200° F. which is satisfactory.

When dealing with temperatures higher than 750° F., for low carbon steels it is now becoming recognised that in order to get the most from the material the stress distribution must be considered in accordance with plastic distortion, and in this connection much important and useful work has been done by R. W. Bailey, of Messrs. Metropolitan Vickers Electrical Co., Ltd. The results of his investigations have been recently published in Engineering, June, 1930, under the title of "Thick-Walled Tubes and Cylinders under High Pressure and Temperature," and it is now proposed to consider the case of superheater tubes subjected to high temperatures in the light of Bailey's treatment of the subject. Briefly, Bailey's experiments on thin walled steel and lead tubes, subjected to compound stresses, and on a thick walled lead pipe subjected to internal fluid pressure, gave no evidence of axial creep,

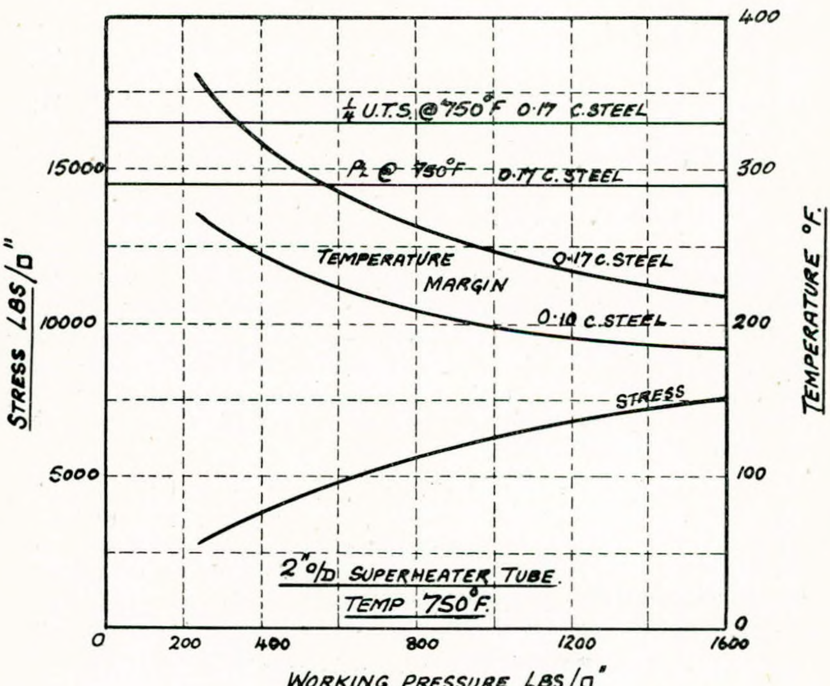


Fig. 20.

from which it was deduced that creep was due to shear and hence was uninfluenced by normal stress on the plane of shear. The experiments also indicated that the torsional creep test provided a very ready means of deducing the creep behaviour of a tube under internal fluid pressure, and if ψ = creep rate in shear (radians per hour) and C = circumferential or diametral creep rate (strain per hour) then

$$\psi = 2\,C.$$

Owing to the small amount of data available regarding torsion creep tests, the variation of creep rate with temperature was considered to be similar to that found in tensile tests. The relations between stress and rate of creep as determined by tensile tests can be represented by the following two linear equations, in which (19) may be considered suitable for temperatures up to 500° C. and (20) for higher temperatures:

$$f^1 = a^1 + b^1 \log_{10} \psi \dots\dots\dots\dots\dots\dots (19)$$

$$\log f = a + b \log_{10} \psi \dots\dots\dots\dots\dots\dots (20)$$

Prof. Norton has employed the double logarithmic method of plotting the results of his tensile tests and Figs. 21 (a) and (b) give some of his creep tests at 900° F. and 1000° F. which are taken from his book "The Creep of Steel at High Temperatures."

Tests carried out by Bailey have shown the diametral creep rate to be about one-half the rate given by tensile tests due to the influence of the axial load on the tube. Accordingly the diametral creep rates indicated in the following have been taken as one half the values given by Norton's tensile results.

Bailey then deduces expressions connecting the equations (19) and (20) with the stress in a thick walled tube of internal and external radii r_1 and r_2 respectively, due to internal pressure p, which in the special case of a superheater tube is approximately given thus:—

$$\log_{10} \frac{r_2}{r_1} = \frac{0{\cdot}2171p}{f} \dots\dots\dots\dots\dots\dots\dots\dots (21)$$

where f is the shear stress at the outside of the tube which, under plastic conditions, may be considered to be the same as the stress at the inside surface of the tube.

By means of equation (21) an approximate determination may be made of the value $\frac{r_2}{r_1}$ for any given condition of working pressure temperature and permissible creep rate. The value of the stress f for a rate of creep ψ equal in magnitude to twice the permissible diametral creep rate C can be obtained from the results of torsion creep tests at the service temperature.

In the case of a convection superheater tube the heat transmission rate is such that the temperature may for all practical purposes be considered as uniform across the wall thickness. Now values of $\frac{r_2}{r_1}$ for a superheater tube can be obtained by use of the suggested formula for the thickness of tubes, and since the working pressure and temperature are known for any particular case, use may be made of equation (21) to obtain the creep rate for the calculated stress f at any service temperature and the approximate life of the tube for a permissible deformation can be determined.

As an example, consider a tube 2in. o/d with internal working pressures of 250, 500, 1,000 and 1,600 lb. per sq. in. and superheated steam at temperatures of 850° F. and 950° F. With correct ratio of steam flow to gas flow the temperature of metal will be not more than 25° F. above steam temperature, but for the purpose of this investigation the metal temperatures will be taken as 900° F. and 1,000° F. The rule thicknesses of the tube for the various pressures are such that the values for $\frac{r_2}{r_1}$ are 1·11, 1·145, 1·225 and 1·336 respectively; substituting in equation (21) the values of f will be found to be as follows:—

Working pressure lbs per sq. in.	250	500	1000	1600
$f = \dfrac{0{\cdot}2171p}{\log_{10}\frac{r_2}{r_1}}$ lb. per sq. in.	1200	1850	2460	2760

It may be mentioned here that using the elastic theory the maximum combined stresses at the inner surface with heat transmission rate of about 8,000 B.T.U. per sq. ft. per hour will be found to be 2,800, 4,400, 6,300 and 7,500 lb. per sq. in. respectively; or expressed as shear stresses 1,400, 2,200, 3,150 and 3,750 lb. per sq. in., which are greater than the values of f given above.

With metal temperatures of 900° F. and 1,000° F. and the torsion rates of creep C corresponding to one half the creep rate ascertained from Norton's diagrams for tensile tests on (i) 0·08 C steel, (ii) 0·20 C steel, and (iii) 0·42 C steel the following results are obtained:—

Pressure lbs. per sq. in.		250	500	1000	1600
2f lbs. per sq. in.		2400	3700	4920	5520
C_{900}	(i)	$<10^{-7}$	$<10^{-7}$	$<10^{-7}$	$1{\cdot}3\times10^{-7}$
	(ii)	$<10^{-7}$	$<10^{-7}$	$<10^{-7}$	$<10^{-7}$
C_{1000}	(i)	$<10^{-7}$	$3{\cdot}5\times10^{-6}$	$>10^{-5}$	$>10^{-5}$
	(ii)	$<10^{-7}$	$2{\cdot}5\times10^{-7}$	6×10^{-6}	$>10^{-5}$
	(iii)	$<10^{-7}$	$1{\cdot}3\times10^{-7}$	3×10^{-6}	9×10^{-6}
$2f_c$ lbs. per sq. in.		2270	3450	4440	4770

$2f_c$ shown above is the mean circumferential stress calculated by the thin tube formula, and it will be noted that the stresses so determined are somewhat less than the values of 2 f.

Suppose now that the stress $2f_c$ be increased by 50% to allow a satisfactory margin of safety, then the creep rates are as follows:—

		250	500	1000	1600
Pressure lb. per sq. in.		250	500	1000	1600
$3f_c$ lb. per sq. in.		3400	5200	6660	7150
C_{900}	(i)	$<10^{-7}$	$<10^{-7}$	8×10^{-7}	2×10^{-5}
	(ii)	$<10^{-7}$	$<10^{-7}$	$<10^{-7}$	$<10^{-7}$
C_{1000}	(i)	8×10^{-7}	$>10^{-5}$	$>10^{-5}$	$>10^{-5}$
	(ii)	$<10^{-7}$	9×10^{-6}	$>10^{-5}$	$>10^{-5}$
	(iii)	$<10^{-7}$	5×10^{-6}	$>10^{-5}$	$>10^{-5}$

It will, however, be observed from Figs. 21 (a) and (b) that the chrome nickel steel would be suitable so far as strength is concerned for all pressures, in fact at a tensile stress of 7,600 lb. per sq. in. the diametral creep rate C_{1100} is less than 10^7.

A slightly greater security would be afforded at high temperatures and pressures by the use of a smaller superheater tube Thus for a $1\frac{3}{8}$in. o/d. tube at 1,000° F. the diametral creep rates would be:—

W.P.		500 lb. per sq. in.	1000 lb. per sq. in.
C_{1000}	(i)	3×10^{-7}	$>10^{-5}$
	(ii)	$<10^{-7}$	3×10^{-6}
	(iii)	$<10^{-7}$	10^{-6}

From the foregoing the life of the tubes can be approximately ascertained, and it will be apparent that if high superheated temperatures are to be used with the ordinary carbon steels available the working pressures must be reasonable. A diametral strain rate of creep of 10^{-6} per hour, equivalent to ψ rate of 2×10^{-6} would result in a 2 in. diameter tube becoming 2·02in. after 10,000 hours (417 days) which might be considered a satisfactory figure where high temperatures are considered desirable. With this rate of creep as a basis the limiting pressures or temperatures for a metal can be deduced by the aid of equation (21) and creep test results. Thus consider metal temperatures of 900° F. and 1,000° F., and material

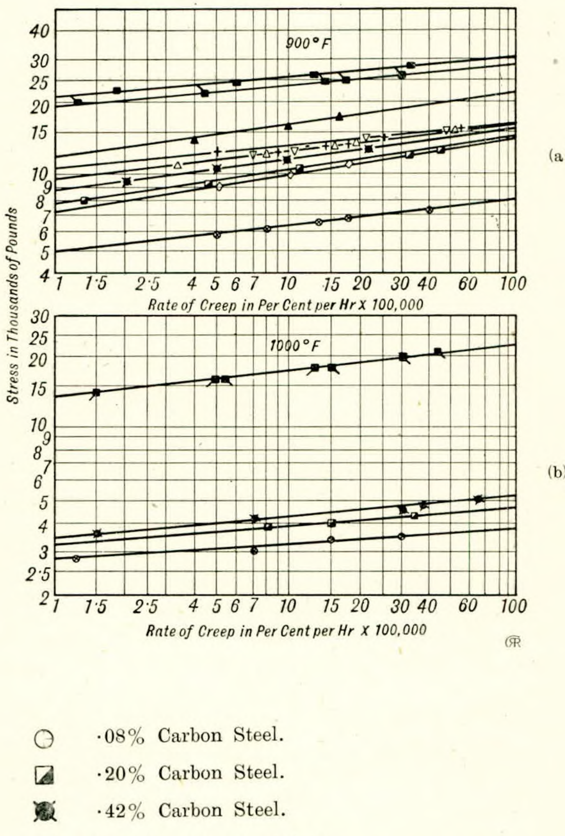
(i) 0·08 C, (ii) 0·20 C, and (iii) 0·4 C steel. For a permissible diametral creep rate C of 10^{-6} strain per hour, corresponding to a tensile creep rate of 2×10^{-6} strain per hour, the creep stresses can be obtained from Figs. 21. Consider a 2in. tube suitable for working pressures of 500 and 800 lb. per sq. in., with $\frac{r_2}{r_1} = 1{\cdot}145$ and 1·16 respectively; the following limiting pressures are obtained:—

TEMPERATURE		900°F		1000°F	
f lb. per sq. in.	(i)	3400		1700	
	(ii)	6000		2050	
	(iii)	6500		2250	
$\frac{r_2}{r_1}$		1·145	1·16	1·145	1·16
Limiting Working pressures p by eqn. (21) lb. per sq. in.	(i)	921	1010	460	505
	(ii)	1630	1780	550	610
	(iii)	1760	1930	610	670
Working Pressure by formula for superheater tubes lb. per sq in.		500	800	500	800

The additional factor of safety afforded by tubes of a higher carbon content than is usual in superheater tubes is apparent, as also is the need for special heat resisting alloy steels if high temperatures are to be used in conjunction with high pressures.

The correct thickness for 1000°F can, however, be obtained from the formula $\log_{10} \frac{r_2}{r_1} = \frac{\cdot 2171p}{f}$ since p is known, f is given for 1000°F and r_2 is 2″. At this temperature, however, the influence of oxidation and spheroidisation will be more marked and it is not considered advisable to use these steels at 1000°F.

It might be as well to mention that the stresses given in Fig. 21 (*a*) and (*b*) for an extension of 1 or 10% in 100,000 hours refers to a creep rate and not a measured extension for this period, the stresses corresponding with 1% elongation in 10,000 and 100,000 hours being interpolated and extrapolated from the results of short period tests. The results of all short time tests are always open to some criticism in the absence of really prolonged tests, but in the meantime they serve some useful purpose in offering a guide to the behaviour of metals over very long periods at elevated temperatures.



○ ·08% Carbon Steel.

◪ ·20% Carbon Steel.

✱ ·42% Carbon Steel.

■ 18% Cr. 8% Ni ·5% Si.

◇ ·39% C 3·51% Si ·22% Ni 2·25% Cr.

△ ·34% C ·74% W.

▽ ·4% C 2·22% Mn.

\+ ·4% C 1·3% Ni ·66 Cr.

▲ ·1% C ·86% Si ·23% Ni 17·6 Cr.

Fig. 21.

SECTION VI.

TUBES IN SERVICE.

Defects common in medium pressure water-tube boilers might naturally be expected, and to a greater extent, in high pressure boilers. As regards their frequency they occur in the following order: internal corrosion, external corrosion, distortion, cracking or splitting, overheating due to presence of scale or to blow-pipe action of the flames. Some interesting particulars of experience with water tubes in a boiler operating at 1,300 lb. per sq. in. at the Lakeside Station, Milwaukee, U.S.A., were given by John Anderson in a paper read before the Institute of Fuel in November, 1927. Trouble was first experienced due to scale, tubes becoming overheated, causing bulges about $1\frac{1}{2}$in. diameter and $\frac{1}{2}$in. high. These bulges were ultimately perforated, a small hole less than 1/10th in. in diameter opening up and allowing steam to blow into the furnace, but no splitting of the tube with consequent explosive rupture occurred. In other cases blisters were formed on the tubes due to localised overheating. Having prevented further failures of this nature trouble occurred due to rapid corrosion in fire row tubes, heavy internal deposits being built up in a short time, but with correct feed water treatment these difficulties were ultimately overcome. From information available it appears that in high pressure boilers split tubes or bulges which open do not generally lead to explosions, and frequently have only been traced by loss of efficiency or extinction of part of the fire.

Further information respecting operating experience with boilers having working pressures of 1,200 and 1,400 lb. per sq. in. installed at the Edgar Station of the Edison Electric Illuminating Co. of Boston is given in a paper by R. E. Dillon (A.S.M.E., 1929). See also "Electrical World," April, 1929. During the early stages of operation several superheater tubes were ruptured through faulty steam distribution, which was rectified by altering the baffling arrangements and fitting ferrules in the first pass of the superheater. Bulging of several 2in. boiler tubes in the upper bank was found on investigation to be caused by concentration of flame close to the uptake headers, extending to the top of the first pass. This concentration was largely due to heavy accumulation of slag in the bottom of the boiler. To prevent further occurrence feed water was diverted from the lower to upper bank.

A. Spyer, in the discussion on his paper "The Modern Development of the Water-Tube Boiler for Marine Purposes" (Trans. I.N.A., 1929) states that when the Langebrugge boilers (W.P. 796 lb. per sq. in. steam temp. 840° F.), which are fitted with ordinary mild steel superheater tubes, were first started up, owing to a mistake a temperature of 842° F. to 932° F. was obtained in the superheater, and the tubes failed at this higher temperature. This higher steam temperature would probably result in metal temperatures appreciably in excess of 1,000° F.

In the case of the original boilers of the *King George V.* a fire row tube burnt through, the tube becoming overheated, due to incrustation arising from the feed water, and superheater tubes gave out owing to excessive gas temperatures; as regards the existing boilers a fire row tube burst, due to loss of water in the boiler.

Failures such as those mentioned above occur in medium pressure boilers, and with the much smaller water content of the high pressure boiler less serious damage due to explosion is likely to result. In this connexion it may be noted that the vessel in which the Benson boiler, previously referred to, was fitted has made a voyage to Canada. Some tubes have burnt, but owing to the small water content, viz., not more than ½ ton, only the burners went out and nothing serious has happened.

An interesting point which needs consideration in dealing with high temperatures is the degree in which the structure of the metal remains permanent, and if any change of structure takes place, its effect on the durability of the metal. The writer has only been able to make a few tests dealing with this point, but in the first place it might be well to refer to the change of structure that takes place when carbon steels are subjected to high temperatures such as might arise in superheaters.

It is well known that the pearlite grains in carbon steels are made up of distinct parallel plates or lamellæ alternatively of ferrite and cementite, and if the metal be kept for a sufficiently long time at a temperature just below its critical range, say 600° to 700° C., the cementite tends to collect in the form of rounded particles which is known as "spheroidisation" of the cementite or "balling" of the pearlite. The effect of spheroidising is to decrease the strength and elastic limit of the steel and to increase its ductility and softness, the degree being more marked in high than in low carbon steels. An example of the change of structure in an 0·16 C steel superheater tube is given by R. W. Bailey in a paper entitled "Creep of Steel under Simple and Compound Stresses and the Use of High Initial Temperature in Steam Power Plant" (World Power Conference, Tokyo, 1929). Micro-photographs of the structure of the tube taken over various parts in its length indicated distinct signs of spheroidisation of the cementite at certain sections in the hottest part of the gases, showing that the temperature of the metal had been in excess of the steam temperature though general overheating was not suspected. The tube had been in actual service for 16,000 hours, the working pressure being 195 lb. per sq. in. with normal steam temperature 644° F., considerably lower operating conditions than are now in vogue. An increase in temperature would cause a more rapid change in structure, but the actual influence of spheroidisation of cementite on the creep rate has not yet been investigated. Its effect would appear to be comparatively small for low carbon steels, and would be retarded by satisfactory annealing of the tubes subsequent to manufacture.

In order to ascertain the extent of any change in structure or alteration of the physical properties of ordinary mild steel superheater tubes, the writer has obtained a number of specimens of tubes which have been in service, and as it is thought that some of the results of the investigation up to the present time might be of interest they are given below. In all cases, sulphur prints were taken, hardness tests (Vickers pyramid) made on the inner and outer surfaces, photo-micrographs of both surfaces obtained, and a few tensile tests made. Owing to pressure of work in other directions the tests are not yet completed.

Sample A.

$1\frac{1}{8}$in. o/d superheater tube, used and unused, supplied by Messrs. Yarrow and Co., Ltd. Used tube in service about 12 months, working pressure 375 lb. per sq. in., steam temperature 750° F. Examination of micro-structure showed little difference between the inside and outside of tube. Carbon content of unused tube 0·12%, the used tube being slightly in excess of this. Sulphur prints were good, the amount of segregates being quite small. It will be noticed that the internal surface is slightly harder than the external, which might be expected, having regard to the method of manufacture.

Sample B.

$1\frac{1}{2}$in. o/d tube supplied through the courtesy of Mr. C. Murdoch, and taken from the 2nd pass, 2nd, row of superheater in after boiler of s.s. *King George V.* Working pressure 550 lb. per sq. in., steam temperature 700° F., tube in use the whole of 1929 season. Analysis of specimen gave 0·14 C, 0·58 Mn, 0·18 Si, 0·025 S, 0·013 P. Sulphur prints were good. The direction of work can be seen in the photo-micro, but there is no undue distortion from cold work, while distribution of carbide areas is satisfactory. The steel is clean and shows little evidence of segregation, slag or other inclusions. There was no evidence of spheroidisation at high magnification.

Sample C.

$1\frac{1}{8}$in. o/d used and unused superheater tube supplied through the courtesy of Mr. J. Johnson, chief superintendent engineer for the Canadian Pacific Steamships, Ltd. Used tube in operation about six months. Working pressure 340 lbs. per sq. in., steam temperature 680° F.

The used tube was in excellent condition, the internal surfaces being as clean as in the case of the unused tube. The photo-micros show typical structures of low carbon steel. The used tube showed nothing to suggest spheroidisation or other deterioration, the structure being as good as the unused sample.

Sample D.

$1\frac{7}{8}$in. o/d superheater tube supplied by Messrs. Superheater Co., Ltd. The spear-head portion of this tube was known to have been considerably overheated, as at one time no steam whatever could pass owing to accumulation of deposit. The straight portion of tube was coated with an internal deposit $\frac{1}{4}$in. thick. Working pressure 250 lb. per sq. in., steam temperature 650° F. Specimens were taken from (A) the straight portion of tube containing heavy internal deposits and (A.B.) from burnt spear-head.

"A."—The structure consisted of ferrite with small straggling areas of sorbitic pearlite. The steel was clean and no appreciable decarbonisation was visible along the outer surface, but at the bore to a depth of 0·01in. a distinct decarbonised layer was detected. The internal surface was very irregular, showed adhering scale, with underlying oxide rootlets, running inwards to a depth of about 0·002in.

"A.B."—The specimen was thickly coated with scale and showed a distinct oxide network persisting to a depth of 0·006in., but the centre of the section appeared to be very little affected. The steel is very mild and probably the burnt surface was produced very rapidly and acted as a blanket to the material at the centre of the tube. The structure consists of ferrite with small scattered etching areas which stood up in relief during polishing, were obviously hard and apparently consisted of martensite.

Sample E.

$1\frac{7}{8}$in. o/d superheater tube supplied by Messrs. Superheater Co., Ltd., and stated to have been in use for about 12 months. Working pressure 750 lb. per sq. in., steam temperature about 840° F.

The structure of the tube specimen consisted of ferrite with small sorbitic pearlite areas. No evidence of any appreciable decarbonisation was visible at the bore or the outside. The steel appeared to be reasonably clean. There was no evidence of spheroidisation at high magnification.

The photo-micros for the structures of the samples are illustrated in Fig. 22, and the physical tests are shown tabulated in Table II. I am indebted to Mr. A. F. Simpson, of

TABLE II.

SAMPLE		Ult. Tensile Strength. Tons. per sq. in.	Elongn. %	Vickers Pyramid Hardness Numeral		Mean Circumferential Stress Lb. per sq. in.
				Inner Surface	Outer Surface	
A	UNUSED	21·25	42 on 6″	129 131 132	115 115 123	1,525
	USED ...	20·9	42 on 6″	115 126 131	109 115	
B USED ...		24·8	30 on 6″	150 150 155	123 140 142	1,680
C	UNUSED	27·6	17·5 on 8″	136	136	1,190
	USED ...	26·9	18·5 on 8″	145	150	
D USED ...		—	—	135	130	1,000
E USED ...		24·0	32·5 on 8″	128 136 140	130 136 140	2,460

the English Steel Corporation, Ltd., Sheffield and my colleague, Mr. L. Ripley, for the results of these tests and photomicros.

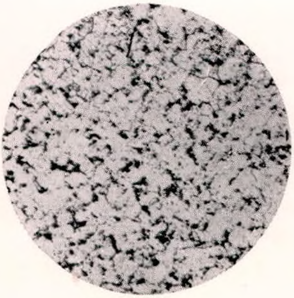
It must not be inferred from the results of these tests that spheroidisation will not ultimately take place in the material of the tubes in service but that, so far, insufficient time has elapsed for this structural change to progress. Thus, in addition to Bailey, Norton has shown that in his tests on pearlitic steels the only change in structure after heating for periods not greater than 1700 hours at 1000°, 1100° or 1200° F. was a thorough spheroidisation of the pearlite.

CONCLUSIONS.

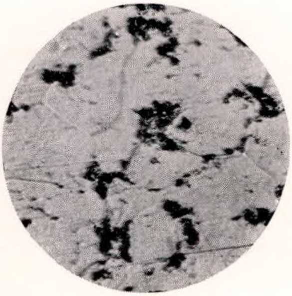
An endeavour has been made in this paper to show that the stresses, temperatures and factors of safety of tubes for high pressure water-tube boilers can be ascertained with a reasonable degree of accuracy, and, given satisfactory material, there appears to be every indication that the reliability of tubes for high pressure boilers should be equal to that obtained in moderate pressure boilers.

Undoubtedly the successful operation of the high pressure water-tube boiler depends largely upon the use of the most suitable material for the tubes. The special selection of material and the need for care during the process of manufacture and inspection cannot be too greatly emphasised. It is therefore considered desirable that in the first instance, Steel Makers and Tube Makers should confer with one another with a view to drawing up a suitable specification for the billets from which the tubes are made. Later, Engineers, Boiler Makers and Tube Makers might come together in order to formulate regulations for the thickness, testing and inspection of tubes suitable for high pressure boilers and high degrees of superheat.

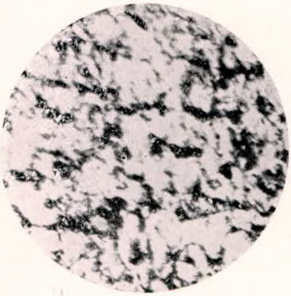
The writer wishes to thank Mr. J. Johnson, Mr. C. Murdoch, Messrs. Babcock and Wilcox, Ltd., Messrs. Yarrow and Co., Ltd., Messrs. The Superheater Co., Ltd., and Messrs. Sulzer Bros., who have kindly furnished specimens for examination or have given information which has been of assistance in the preparing of this paper. Thanks are also due to Mr. A. E. Laslett, I.S.O., and to the writer's colleagues Messrs. L. Ripley (Middlesbrough), J. Pringle (Sheffield), J. S. Heck



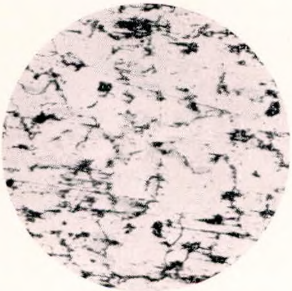
Sample "A"
Unused × 100.



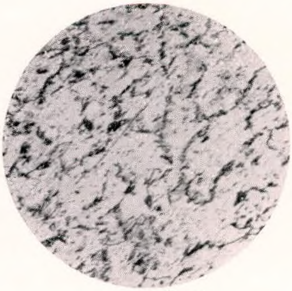
Sample "A"
Used × 250.



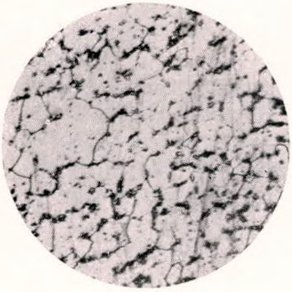
Sample "B"
Used × 250.



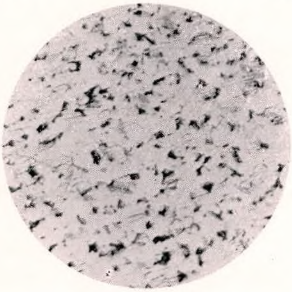
Sample "C"
Used × 100.



Sample "C"
Unused × 100.



Sample "D"
(Burnt) × 100.



Sample "E"
Used × 100.

Fig. 22.

slot, and then hydraulic pressure was applied to burst the tube. The bursting pressure was about 1,400 lb. per 1/64 in. thickness of metal left at the bottom of the slot.

Secondly, the tube was thinned down over a length of 6 ins. to various thicknesses and again burst by hydraulic pressure. A tube thinned down to 1/64 in. thick burst at 1,100 lb. water pressure.

Thirdly, as the results of the above experiments always showed a very small rupture, due to the hydraulic pressure being released immediately the fracture occurred, some tubes were tested under steam pressure, so as to get the result of the explosive force of the steam, and they found that it took a pressure of 1,250 lb. per sq. in. to burst a 1·33 in. ($1\frac{1}{3}$ in.) dia. tube, the walls of which were ·017 in. (1/64 in.) thick.

Fourthly, a tube in which there was a steady steam pressure of 375 lb. was heated in a furnace and they found it was necessary to make the tube almost white hot, as measured by a radiation thermo-couple 2,000° F., before they could rupture an ordinary $1\frac{3}{4}$ in. tube, the walls of which were ·128 in. ($\frac{1}{8}$ in.) thick.

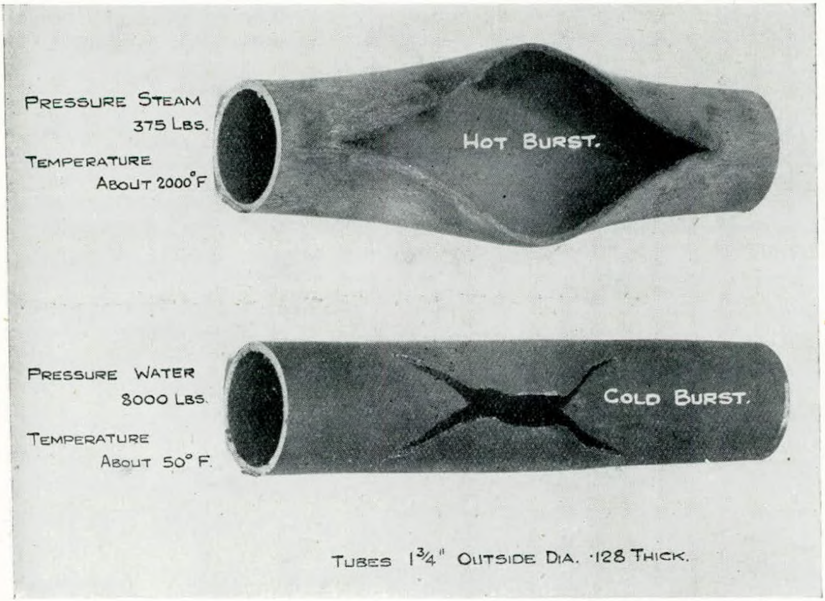
Fifthly, a tube $1\frac{3}{4}$ in. diameter, thickness ·128 in. ($\frac{1}{8}$ in.) was burst with a hydraulic pressure of 8,000 lb. per sq. in. This tube had expanded from 1·759 ($1\frac{3}{4}$ in.) diameter to 1·984 in. (2 in.) diameter before bursting.

The characteristics of the bursts are shown in the accompanying photographs.

These experiments showed that the material of a tube could be relied upon to stand the calculated stress, and as long as the stress was kept well below what might be called the creep limit, the tube would be quite safe for a long period with a fixed allowance for corrosion.

There had been such great progress in condenser design and material that the evil effects of impure feed had been greatly reduced and, at the same time, as Mr. Dorey pointed out in his paper, the result of segregation of sulphur and phosphorus was more clearly understood than formerly, so that to-day the fear of failure through wasting of the material was not so great as it was a few years ago, and with present day knowledge it was reasonable to suggest that the thickness allowance for corrosion could be reduced.

Mr. Dorey, when speaking of heat transmission rates, assumed ratings varying between 20,000 B.T.U's. per hour for the ordinary row tubes for marine boilers up to 80,000 B.T.U's. per hour in the fire rows of highly forced Naval boilers. It was very difficult to form a reliable estimate of the amount of work done by the various rows of tubes in a boiler. One difficulty was to obtain the correct measure of the temperature of the furnace gases at any particular point. If a thermocouple was used, it was affected not only by the temperature of the gases, but also by the radiation from the surrounding



material, which might be either hotter or colder than the gases. The error arising in these measurements might amount to 20% or even 25%.

With the help of Dr. Muir, of the Royal Technical College, Glasgow, Yarrow and Co. had made many investigations on this question of heat transmission, and as far as present knowledge went, the following figures were suggested:—

In an ordinary boiler evaporating 6/8 lb. of steam per sq. ft. of heating surface, the heat transfer in the fire rows was something between 40,000/60,000 B.T.U's. per hour, and the heat transfer in the outer rows of tubes was something between 1,000/3,000 B.T.U's. per hour.

In a destroyer boiler at full power evaporating 16/18 lb. of steam per sq. ft. of generating surface, the heat transfer in the fire rows was something between 100,000/120,000 B.T.U's. per hour, and the heat transfer in the outer rows was something between 2,000/8,000 B.T.U's.

The relation between the heat transfer in the fire rows and in the outer rows of any nest of tubes was dependent on many conditions, amongst them being the number of tubes in the path of the gases, the temperature of the preheated air supply to the furnace, and the percentage of CO_2 in the flue gases.

It would be interesting to hear Mr. Dorey's opinion as to the nature of the failure which would take place if a boiler tube was made too thick for the corresponding pressure and rating. One might imagine that the tube would swell and become thinner, thereby correcting the original mistake of making the tube too thick, but they had no evidence of this compromise being arrived at in practice, and one would hesitate to leave tubes in a boiler which showed signs of swelling, although perhaps the swollen tubes were safer than the original tubes. One question arose as regards this stress due to rating and temperature, and that was—did a high stress increase the liability to corrosion?

The question of creep over a long period had been fully brought out in Mr. Dorey's paper. There was, however, another effect of high temperature, namely, that of annealing the material which, even if it lasted for only a short period, ought to be avoided, and one property of a tube for which there was a demand was that of having a high annealing temperature. The tightness of superheater joints generally depended on the internal stress in the material, and if the material was raised to above a certain temperature, this internal stress was relieved. If, therefore, a superheater tube which had been expanded into a tube plate was at any time raised to this annealing temperature in the tube plate, the joint between the tube and the tube plate would not remain tight. There were ways of getting over this difficulty, viz., by welding the tube into a flange or header, but even in these partly welded constructions the tightness of the joints at some place depended on the internal stress which had been produced in a bolt or stud by the act of screwing it up, and in this case also, if at any time the temperature should rise much above the designed temperature, the joint failed.

On account of the varying conditions which existed in marine installations, it was not advocated to work at the highest possible superheat, so as to allow for variations in the steam pressure, in the temperature of the feed, and in rate of working which occurred at sea, all of which affected the degree of superheat.

Mr. Dorey had drawn attention to the blow pipe action of the flames. This was a most important consideration, and at an earlier part of the paper he explained why a blow pipe action was so serious, viz., because it removed the gas film from the surface of the tube and exposed the tube to the full temperature of the gases.

In all boilers which were fitted with baffles near the fire, whether these baffles were formed of refractory screens or by bending the tubes so that they lay close together, there was a probability that the portions of the tubes where the baffles ended were exposed to a blow pipe action. To put it another way, if the fire rows of a boiler were so designed that the gases could only escape over a part of the area exposed to the fire, it was at the edges of this opening that the velocity of the gases was much higher than it was over the rest of the opening, because the gases always tried to take the shortest path. This effect might not be felt at very low ratings, but this concentration of heat should be avoided as it might have serious results.

Referring again to the importance of this paper, it was to be sincerely hoped that the Institute of Marine Engineers would draw the attention of the Board of Trade and the registration societies to the facts which had been so ably put forward by Mr. Dorey, so that rules might be drawn up to meet the requirements of up-to-date British practice.

Mr. C. HUMPHREY DAVY (Messrs. Babcock and Wilcox, Ltd.) remarked that Mr. Dorey was to be complimented on the exceedingly interesting paper which he had prepared wherein he dealt with the subject which was receiving particular consideration at the present day by both the designers and users of tubular boilers. The whole subject was dealt with to a very detailed extent and in view of the restricted amount of time available for discussion, it was proposed to make mention of those points which had appeared to be of greatest interest at present.

With regard to tube wall temperatures, it would be appreciated by all who had concerned themselves with the design of high pressure boilers that one of the biggest difficulties in connection with tube wall thickness was the ascertaining of the actual internal and external wall temperature of the tube. As Mr. Dorey had said, there was not much difficulty in regard to the internal temperature, but it was exceedingly difficult to ascertain the external wall temperature under actual boiler service conditions. It was almost an impossibility to arrange the means for temperature recording so as to cut out other local effects which might exist due to stratification of gases and so on in the boiler.

Since temperature was a necessary function in a formula for tube thicknesses which really took into account the conditions under which the tubes were to exist, it naturally followed that as the actual temperature was the most difficult factor on which to obtain really true evidence, one could only turn to empirical formulæ based on the results of observation and long practical experience.

In the case of tubes for comparatively low pressures, the actual mechanical stress in the tube played only a small part in the determination of the tube thickness because if a low pressure tube thickness were determined only from the point of view of stress, it was doubtful whether there would be sufficient wall thickness to provide for a satisfactory expanded joint. Furthermore, as Mr. Dorey had pointed out, the corrosion factor became far more important in the case of low pressure boilers because pitting of a thin tube wall naturally resulted in a far greater percentage reduction in the strength of the tube than would be the case with a thick wall high pressure tube. On the other hand, when dealing with thick tubes for high pressures, the questions of possibility of expanding, ratio of internal diameter to length, and stresses set up in the internal wall of the tube became of greater importance than the mere bursting stress in the tube itself.

Under the heading of tube materials, Mr. Dorey had given a good deal of food for thought. The suggested specification of a maximum percentage of sulphur or phosphorus of ·035 and ·03 respectively, whilst ideal, might prove rather difficult to work to in practice as a certain amount of margin was naturally desired by the maker of the tube steel, and from a practical point of view a maximum content of ·04% in each case was considered to be very good practice at the present day. In this connection it will be remembered that the figure of the British Engineering Standards Association was ·05% and this specification formed the basis for the majority of requirements in this country, at the present day. The foregoing remarks naturally applied to mild steel only, as special alloy steels naturally required different specifications. In this country one of the best known specifications for tube material gave only a maximum tensility of the tube billet, this being 28 tons per square inch, and it was common practice to call for tensile tests on the tube material only, seeing that the satisfactory condition of the tubes themselves could best be checked by mechanical tests such as expanding, flattening and crushing tests.

In the majority of cases the tubes for water-tube boilers were expanded into tube plates having a tensility of 28 to 32 tons or into sectional headers manufactured from billets having a tensility of 26 to 30 tons, and seeing that in the knowledge and practice of boiler making it was desirable to retain a margin of at least a ton between the tensility of the tube and the tensility of the plate into which it was expanded, it would appear that in some cases a rather lower maximum tensility for the tube billet would be desirable. In most cases the matter was automatically regulated by the tube maker who, having no minimum tensile limit specified, naturally chose a good ductile steel, which in the majority of cases gave a finished tube having a tensility of between 23 and 25 tons per square inch. These tubes gave a very satisfactory expanded joint, and it would appear, therefore, that a maximum tensility rather lower than at present specified would safeguard the position and prevent the possibility of less ductile tubes being acceptable.

Some interesting remarks had been made by Mr. Dorey on the possibility of using steels having a higher carbon content than that which had been widely used at the present day, namely, about ·1% to ·15% carbon content. Such steels had already been tried out to some extent, but it was to be regretted that they had not up to the present proved very satisfactory and there was a good deal of information available to show that steels having carbon contents ranging from, say ·2% to ·4% were very much more subject to the effect of creep than lower carbon steels, due presumably to the spheroidisation of the carbide in the crystal structure. In addition, the experiments which the speaker's firm had carried out in a special experimental superheater over a period of 18 months showed that increase in carbon percentage gave rise to very rapid oxidisation of the internal surface of the tubes, and their experience was that tube failure due to scaling, that is to say internal oxidisation, was of almost greater moment than failure due to low creep values at high temperatures.

The same remark applied to a number of steels tested in their experimental superheater, and in many cases tubes had been found to contain several layers of oxide on their internal surfaces, showing that the first oxide scale formed was not a definite protection against further oxidisation as had often been thought to be the case.

Reference had been made to an alloy steel known as "Enduro," in which the chromium and nickel contents were given as 16·7% and ·19% respectively. It might be of interest to know that the original "Enduro" which was known as "Enduro Metal A" had been entirely superseded by what was known as "Enduro S.188," in which the percentages of chromium and nickel were increased to 18% and 8% respectively. The special superheater working at a steam temperature of 1,000° F., which was installed experimentally at the Delray Station of the Detroit Edison Company in America, was manufactured from this "Enduro S.188" and the condition of the material was being very carefully watched by the Babcock Company of New York, who were responsible for the design and manufacture of the superheater.

Already a considerable amount of experimental work had been done in the direction of finding materials suitable for superheater tubes to withstand temperatures in excess of, say, 840° F. It was definitely considered by certain of the superheater manufacturers in this country that for steam temperatures in excess of 840° F., special steels were a necessity.

Dr. J. W. JENKIN (Director of Research, Tube Investments, Ltd.) (Visitor) remarked that the most impressive feature of Mr. Dorey's paper was the vast amount of ground which he had covered, a point which had been emphasised by previous speakers, and it was not easy to deal with the subject adequately within the ordinary limits of verbal discussion. The paper was of especial value when read in conjunction with a paper presented to the North Western Branch of the Institution of Mechanical Engineers in Manchester on the preceding Thursday by Mr. K. Baumann. Both authors rightly emphasised the importance of creep as a basis of design, and it seemed to him that Mr. Marriner's point about the loosening of expanded joints was similar to the loosening of flange bolts dealt with by Mr. Baumann, and attributable to relief of stresses by creep, as distinct from a function of annealing temperature. The tube maker was most closely concerned with materials, which indeed formed the basis of the ultimate success of high pressure boilers, as Mr. Dorey stated in his conclusions. He would like therefore to confine his remarks to Sections 3 and 6 of the paper, although each division provided ample scope for thought and discussion.

Mr. Dorey said that there was undoubtedly a call for soundness of steel and reliability against segregation. It should be pointed out, however, that a very large percentage of tubes made to-day were manufactured from fully killed steel, and were therefore free from segregation. His appeal for examination of billets by sulphur printing was also somewhat late in that this method of inspection had been standard practice amongst tube makers for years. They would probably all agree that a non-segregate steel was more serviceable from the corrosion point of view, but a word of warning was desirable. Engineers owed one important property to the existence of the sulphur-free outside skin shown in the Author's Fig. 15 A, namely, ability to expand well into the tube plate. When the non-metallic matter was uniformly distributed in fully killed steels, the outer skin necessarily contained inclusions, which might give rise to external fissures in roller expanding. It was also a fact that the inclusions in non-segregate steels were not all of the same type as in mild steels, and there was one particular kind of inclusion which was very brittle, and gave rise to the splits referred to. The mean, one might say, was the thin-skinned material illustrated in Fig. 15 B, but in this case there was grave risk during tube manufacture of the segregate corresponding to the corners of the original square ingot shape coming to the surface and causing breaks in the skin. As steel makers would know, fully killed steels often possessed relatively dirty skins on account of the quiet rising of the metal in the mould, and the purpose of machining was to remove that skin and any surface blow-holes. He rather doubted whether Mr. Dorey was correct in suggesting that turning of the billet eliminated hair cracks in the finished tube.

The author did a great service in emphasising the importance of resistance to oxidation at the service temperature, a point which other writers had tended to under-rate. Instances of the type illustrated in the accompanying photographs were all too frequent. Fig. A showed a burst in a superheater tube which formed part of a relatively low pressure and low temperature system. The cross-section Fig. B would indicate the extent to which a scale had formed on the inside of the tube. This scale consisted of magnetic iron oxide formed by the action of steam on the steel. The resulting overheating led to the formation of a similar scale on the outside, by the action of the flue gases, so that one had the state of affairs

Fig. A.

shown in Fig. C, where it was found that the wall thickness, originally 3/16th in., was reduced to 3/32nd in. Another result was the almost complete loss of carbon (Fig. D x 150) and excessive grain growth, as might be seen on comparing Fig. D with the structure of the tube as manufactured, Fig. E, at the same magnification. The outside diameter of the tube had increased from $1\frac{1}{2}$ in. to 1 21/32nd in. The reason for this failure was probably connected with operating conditions rather than design, but the tendency towards increased temperatures would involve increased risk of such occurrences. The tube material at the time of failure was no longer a fine-grained steel, but a coarse-grained pure iron, with different mechanical characteristics, and the thinning of the wall resulted in the tube being subjected to greatly increased stress.

This naturally led to the applicability of alloy steels designed to give improved service as regards strength at high temperatures, with or without resistance to oxidation. Mr. Dorey said that it was essential that the addition of any alloying elements should not interfere with the mechanical properties of the material. Was it not more logical to suggest that if a material could be found which would adequately

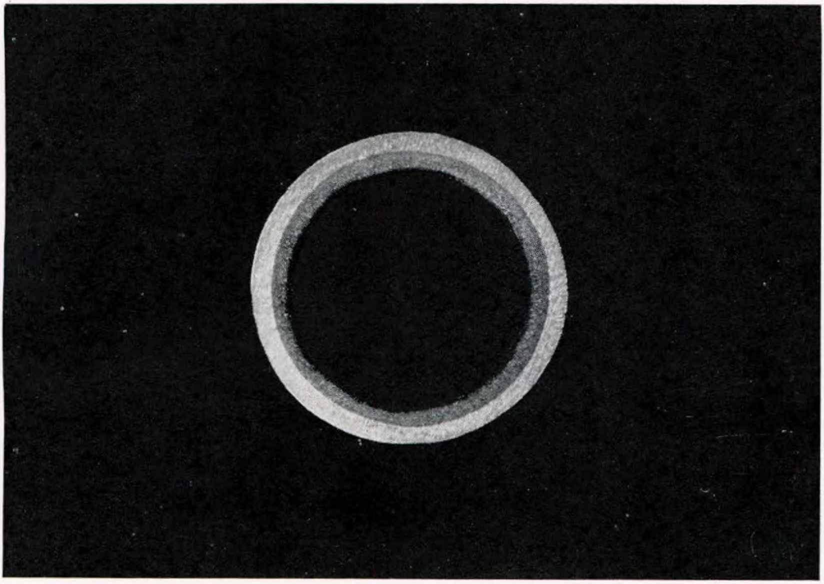


Fig. B. End view, actual size.

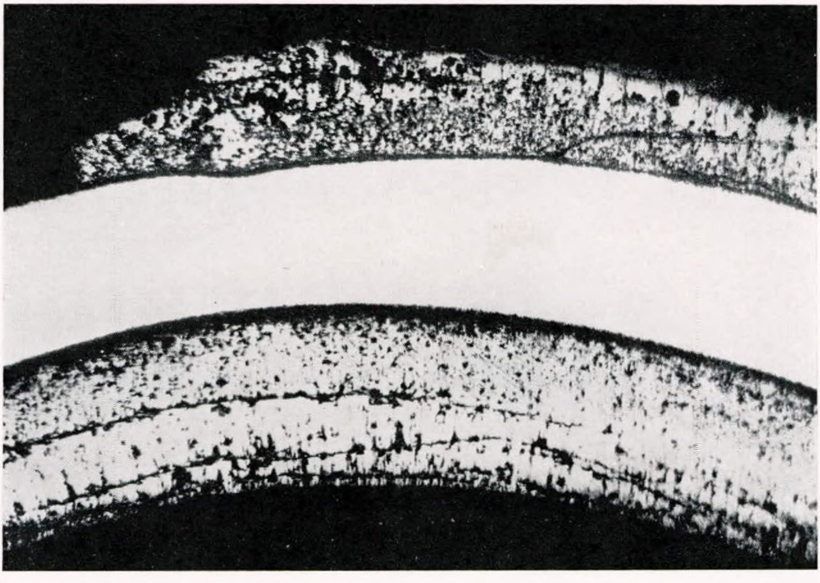


Fig. C. Transverse section, X 10.

of manufacture. He would be interested to know what was the basis for this statement. He (Mr. Dorey) stated that in the photomicrograph of sample B, the direction of work could be seen; he was afraid that he had failed to find this, and as to there being no undue distortion from cold work, the photomicrograph did not reveal the grain boundaries in the material. It was stated that sample C showed no spheroidisation, but he would be inclined to think that the photomicrographs did indicate a tendency in that direction. Indeed, with all possible respect, he found the photomicrographs extremely difficult to interpret; making every allowance for the effect of reproduction, the micros appeared to be out of focus, and to give an inadequate representation of the structures of the materials. In sample D, the Author referred to sorbitic pearlite, and even martensite: he failed to see how these structures could occur in material after having had the service stated.

Mr. Dorey had covered so much ground that to suggest that he had omitted an important phase would seem almost unfair, but he did. The major part of his paper was of particular value to designers, and a smaller portion to the makers of steel and of tubes, but he omitted the operating engineer. A wide experience indicated that the majority of tube failures were due to bad operating conditions, and he thought that if Mr. Dorey suggested getting together first steel makers and tube makers and later tube makers, engineers, and boilermakers with a view to formulating a basis for materials and design, he should also include operating engineers so that some code might be laid down for the conditions under which the plant was to work. A first class tube in a well-designed boiler would fail if starved of steam, or if the operation was otherwise faulty, as the accompanying illustrations showed.

He hoped Mr. Dorey would take what he had said in the kindest possible way, for he was sure that tube makers would agree with engineers that the paper was a most important contribution to the end they all had in view. He shared very cordially in the enthusiasm with which it had been received.

Mr. F. S. MARSH (The Chesterfield Tube Co., Ltd.) (Visitor), congratulated the Author on his most excellent paper. He mentioned the element of doubt for temperatures above 400° C. and pointed out the importance of ensuring that the tubes should be suitable for the practical conditions they were to be subjected to. The Author had mentioned that soft mild steel tubes had been used on account of their relative cheapness and ease of manufacture, but he could safely say that many steels with important qualities were now available, although the question of cost must receive serious consideration. It was hardly to be expected that tubes in special materials could be produced relatively cheaply. The question of sulphur prints was discussed, and a warning issued as to the interpretation of these prints.

He questioned the advisability of limiting the sulphur and phosphorus to ·03, and mentioned that excellent materials were available for tube-making with sulphur and phosphorus up to ·05.

Yield point tests at high temperatures would give valuable information, but creep stress tests necessary involved considerable time being taken for the test. It was important that uniformity of material should be insisted upon, as the rate of corrosion would be increased where different materials were in contact. He pointed out that the tube makers and the steel makers were giving this problem most careful attention, and he asked for the assistance of marine engineers in communicating the results obtained after periods of time when special tubes had been under trial. The advantages of cold drawn tubes over hot finished tubes had not been mentioned in the paper, although this subject was one which could readily form a topic for discussion.

Mr. W. J. TALBOT (Talbot-Stead Tube Co., Ltd., Walsall) (Visitor), said that most of the points he had intended to discuss had been taken up by previous speakers. He wished to associate himself with the thanks of others for Mr. Dorey's valuable and definite contribution towards the efficiency of the steam engine, for marine work particularly. He thought that some of Mr. Dorey's figures were on the safe side; for example, in Fig. 18, for 1,800 lb. pressure he gave a thickness of 3 gauge. There had been working in a German locomotive under these conditions, tubes of 7 gauge thickness, which suggested that Mr. Dorey's figure was on the safe side. The diagrams he gave in Figs. 17 and 18 were extremely valuable. He would, however, require to check the figures given, as he had been taught to be cautious in these things. Mr. Dorey's reference to alloys was absolutely up to the minute, but he was afraid that as regards the manufacture of superheater tubes they would have to modify their methods, because materials which were proving to be of any good at all for high temperatures and high creep and resistance to oxidation, would not machine well. The chromium nickel tungsten alloy to which Mr. Dorey referred was most prohibitive in cost (incidentally the tungsten content was generally ·6%). There was one installation in London of superheaters with tubes made of this material, which took 66 tons of steel for a start. It was said that this material was not considered safe. In a superheater which had been working for more than 18 months, microphotographs taken before and after operation had shown no difference in structure resulting from a temperature in the tubes which at times reached nearly 1000° C.

With regard to sulphur prints, he had been asked by a high Admiralty official some time ago what he thought of sulphur prints. He had replied that he doubted their value because the bulk of the tubes in the British Navy had been made from segregated steel. Other steels did not expand nearly as well as the segregated steel, and the outside rim of the latter made a better finished job.

Mr. H. E. GEER (The Superheater Co., Ltd.) (Visitor) referred to the many eulogistic tributes to the work the Author had done in preparing his paper, and desired to add his quota to those of other speakers. The Author had made mention of various alloy tubes which had been suggested and tried for superheaters for high pressures and high temperature steam. The firm he represented had for a considerable time, been urging the steel makers to produce a steel which, whilst possessing the ductile properties of ordinary mild steel, had superior heat-resisting properties at temperatures of between 400 and 500° C. A letter had come to hand yesterday from one of the English steel makers, who wrote :—

" We have gone ahead and made a small charge of special steel for superheater tubes along the lines which I indicated, and we have now determined the creep stress by our standard quick time method. The values are very satisfactory, as you will see from the following results :—

Temperature.	Ordinary Tube Quality. Tons per square inch.	Special Superheater Quality. Tons per square inch.
400° C.	3·8	7·5
450° C.	2·4	5·1
500° C.	1·0	3·0

" This material can also satisfactorily weld so far as we have been able to try it by ordinary smithy method so that it would appear to meet the specification that we discussed at our last meeting."

It was admitted that the creep test results were obtained by the quick time method, and some might dispute their accuracy. At the same time, the results were comparative, and showed the superiority of the new steel at higher temperatures.

From experience, it had been found that steels containing chromium could not be forge welded, and as this had been previously pointed out to the steel maker, it was obvious that the steel evolved was without chromium and was probably of a ductile nature. The particulars were very brief, but the manufacturers had been asked to carry out tests to determine the temperature at which oxidation commenced in comparison with mild steel, and also the comparative rates of oxidation at temperatures up to 500° C. If this material proved satisfactory, it would enable the superheater designer to provide for increased steam temperatures and also to retain a higher factor of safety on the material should there be short periods of local overheating during service.

The Author had referred to dissociation of steam in superheater pipes, and reference should be made to a report recently presented by Mr. C. H. Fellows of the Detroit Edison Company at the Annual Convention of the American Water Works Association held in Toronto, entitled "Dissociation of Water in Steel Tubes at High Temperatures and Pressures." In his summary of the report, particular emphasis was made on the question of steam velocity in the tests. When the steam speed was 25 ft. per minute considerable internal corrosion took place; at velocities of about 850 ft. per minute the scaling was much less, and at a velocity of 3,000 ft. per minute oxidation could not be detected. This speed of 3,000 ft. per minute was quite a normal speed in present-day superheater practice. The tests were carried out at steam pressures of 100, 200, 300 and 400 lb. per sq. in. The tubes were electrically heated to about 1,200° F., and steam passed through them at varying pressures, speeds, and superheats.

With regard to sulphur content, there were various opinions, but for high duty superheater work they had always insisted that the sulphur content should be kept as low as possible. They had recently been obtaining steel with a sulphur content not exceeding ·02. This was a mild steel of 22—26 tons tensile, non-segregated, clean and homogeneous, and the tubes made from it were the best they had yet been able to obtain.

The Author had mentioned transmission rates in superheaters up to 8,000 B.T.U's. per sq. ft. per hour, but it could be definitely stated that these rates were very much exceeded in practice. In superheaters where heat transmission to the steam was effected by both radiation and convection, the rates were much higher. On the superheaters at the plant of Synthetic Ammonia and Nitrates, Ltd., which worked at a pressure of 750 lb., delivering steam at a final temperature of 840° F., the transmission to those portions of the elements exposed to both radiation and convection was 25,000 B.T.U's. per sq. ft. per hour, and even more when the boiler was being forced.

They had had some interesting remarks from Mr. Marsh of the Chesterfield Tube Co., and he would like to mention that this particular Company had recently supplied them with low carbon steel tubing containing small percentages of copper and molybdenum, somewhat on the lines of those mentioned by the Author as being made by Messrs. Thyssen in Germany. Experiments had been carried out on this tubing in an endeavour to forge weld it to ordinary mild steel tubing, and this had been successfully carried out, as was evidenced in the sample he showed. As a test of the strength of the weld, the tubing had been hammered over and the condition of the two kinds of tubing showed little or no difference, the ductility of the two portions appearing similar. This was a very satisfactory result, as in the past it had not been possible to forge weld alloy steels to mild steels by the special process used. If this new type of steel possessed superior heat resisting and creep limit qualities to mild steel, it would allow of complete superheater elements being manufactured in which the low temperature portion was made of ordinary mild steel and the high temperature portion of alloy steel without having to revert to separate sections with intermediate joints.

Finally, he would again thank the Author for his most instructive paper and the trouble he had gone to in the preparation of diagrams. It was probable that this paper would, in the future, be looked upon as a standard work of reference and, no doubt, designing engineers would make use of the way in which the various formulæ and information had been embodied in graph form.

The CHAIRMAN expressed, to the visitors particularly, the Council's pleasure in having had Mr. Dorey, who was a Member of the Institute, present to give his paper that evening. Referring to the subject of the paper, he could sympathise with the manufacturer and he could also understand the inspector's point of view. When one considered the high standard of quality of the steel required for present day purposes such as those dealt with by Mr. Dorey in his paper, and when one visited a steel works, one wondered how they produced material of such quality as they did. The need of co-operation between all concerned if they were to reach and maintain the desired quality of steel was quite clear, as Mr. Dorey had suggested. He would like to criticise Mr. Dorey's diagram, Fig. 9, in which, amongst various optimi, he gave one which went up to 3,000 lb. working pressure and a creep limit stress of 9,000 lb. He thought it would be of interest if Mr. Dorey would complete the curves and give the " creep limit " of the junior engineer when he joined a vessel working at that figure! He had been pleased to note when reading a paper given quite recently by Mr. Nithsdale on the 600 lb. boiler, that the Author was looking forward to this paper by Mr. Dorey. He thought that the paper would give them the help and information which they were seeking.

BY CORRESPONDENCE.

Mr. T. H. BURNHAM, B.Sc. (Messrs. Hadfields, Ltd.) (Member), in a written communication, said that he would like to congratulate Mr. Dorey on the exhaustive way in which he had dealt with this important subject. He was specially interested in the sections dealing with materials, as there was no doubt that with higher temperatures and pressures in steam raising, the design and reliability of the plant depended on the materials employed.

With regard to mild steel tubes, Mr. Dorey's remarks on the necessity for soundness and homogeneity of the steel were to be supported. In the firm whom he represented Sir Robert Hadfield had spent many years in developing means of ensuring soundness of steel, and it might be noted that they were at the present time making special tube steel of high purity and homogeneity for high duty superheater tubes subject to the most rigid inspection for homogeneity, and in which the slightest flaw on either the inside or outside surface would lead to rejection.

Where special steels were employed for high temperature use, they were required to have the same reliability over long periods as mild steel had at ordinary operating temperatures and pressures, the additional capital expenditure being justified by the increased overall efficiency. A number of materials were now available for high temperature service, including the steel referred to in Fig. 16, together with a certain amount of data on creep strength, in the light of which calculations of tube thickness had to be made. He would suggest that the requirements of these special steels were very exacting. They had to meet specifications regarding bulging, expanding, flattening, etc., in the cold, as well as possess special properties at elevated temperatures. Whilst the " Era " steel referred to possessed a good resistance to creep—above that of so-called 18 x 8 corrosion resisting steel in the temperature range 400-500° C. (750-1000° F.) combined with improved resistance to oxidation and corrosion both by exhaust gases and condensed sulphurous liquors, and a coefficient of dilatation which was the same as that of ordinary steel, it might be noticed that its maximum retention of strength might be jeopardised in retaining such a degree of mildness and ductility as to enable it successfully to withstand certain cold working operations, such as machine made hairpin return bends.

Now everyone knew that practice was a compromise. He submitted that Mr. Dorey's suggestion of co-operation of steel makers and tube makers was a valuable one for the solution of the problem in connection with special tubes. It might be found practicable to permit a modification in the tests at ordinary temperature in the interests of the retention of mechanical strength at operating temperatures. Co-operation between engineers and steel makers was equally essential, and the requirements of engineers as regards permissible rate of creep for the components of steam piping systems—bolts, tubes and tube flanges—were being set forth in papers like that of Mr. Baumann before the Institution of Mechanical Engineers and the present one. This information enabled the steel maker to indicate from which steels the choice must be made so that their other properties might receive due consideration.

He submitted that Mr. Dorey's paper had done a great deal to show when special piping was necessary, what its mechanical properties must be, and that materials were available for engineers who had such schemes under consideration.

Mr. W. DENNIS HECK, B.Sc. (Member), in a written communication stated that the Author had emphasized the necessity for care in the selection of steel billets intended for the manufacture of the tubes of high pressure water tube boilers; he further considered it to be desirable that steel makers and tube makers should confer with one another in order to draw up a suitable specification for the billets. It was to be hoped that if such a specification be evolved by these parties it would include requirements ensuring above all things that a high degree of mechanical soundness would be consistently obtained. Where steel was to be drawn it was, in his opinion, not sufficient that the chemical composition and particulars of the mechanical tests should be specified, but the limiting portions of the ingot from which the billets might be derived should also be defined with precision.

During the discussion on this paper one had heard that segregate steel had been used with success in the manufacture of tubes, but while slight local excesses of such elements as phosphorus and sulphur might be present without harm, it appeared to be essential that sufficient discard should be taken from the ingot to ensure that piping and blow holes would be definitely eliminated. If asked, steel makers could no doubt make many useful suggestions as to the best practice regarding the conditions of pouring, the shape of the ingot and the percentage of top and bottom discard. These should be carefully defined in any specification designed to cover best quality billets.

It might be urged that such requirements would entail a very wide and rigid system of inspection, but it might be noted that a similar system was widely employed without difficulty in the manufacture of shell billets and it was surely possible to adapt it to the manufacture of billets intended for water tubes of high pressure boilers.

Major W. GREGSON (Messrs. Babcock and Wilcox, Ltd.) in a written communication, stated that apart from the high technical value of the paper, one greatly appreciated the enormous amount of time, thought and work put into the preparation thereof. The paper was of particular value at the present time when more and more attention was being focussed on the potentialities of high pressure high temperature steam in the Merchant Navy; in fact it was not going too far to state that the future of the British Merchant Navy hinged on the development of high pressure high temperature steam, as being the only system which gave the combination of high efficiency and flexibility of fuel.

To revert to one detailed point, the Author suggested that the radiant heated type of superheater was not likely to be favoured for marine work. Now in the application of modern steam boilers to high-powered ships much stress was laid on space limitations and the result was that the interdeck type of superheater tended to become more and more congested in design in order to conform with the available space. It would appear that superheater accessibility under such conditions might be enhanced by arranging two superheaters in series—a first stage interdeck type superheater of less crowded design followed by a modified form of radiant heated superheater for second stage heating. Such a superheater need not be in direct flame contact, but could be incorporated by suitable construction in one of the furnace walls and sufficiently shielded from direct furnace effect to avoid the objections normally raised against radiant heat superheaters for marine work. Furthermore, as it would receive already superheated steam from the primary unit, there would be no possibility of re-evaporation having to take place within it.

Major S. J. THOMPSON, D.S.O. (Governing Director, Messrs. John Thompson Water-Tube Boilers, Ltd., Wolverhampton) in a written communication, congratulated Mr. Dorey on his paper, which was full of most valuable information, and which he felt would be of help to everybody on the question of tubes for high pressure boilers, but particularly for tubes for high temperature superheaters.

This latter point was one that they were most interested in, and although they had not yet put in superheaters for such high temperatures, for some time they had been making investigations, as they felt that steam temperatures as high as this would certainly be demanded in the future. They had, of course, installed many superheaters for temperatures of 750° F., and they had had experience with superheaters for temperatures considerably in excess of this, and with ordinary mild steel tubes they had had no difficulties at these temperatures. Their experience led them to believe that with a suitably designed superheater temperatures of 900° F. could be obtained with a good margin of safety with mild steel tubes.

With regard to corrosion of superheater tubes, it would appear that at the temperatures named in the paper, taking in view the higher pressures, serious disassociation of the steam was unlikely, and one would expect that the steam would produce a thin tenuous protecting scale on the inside of the tubes. They believed that the corrosion of the tubes externally was likely to be more troublesome, as the tube externally was in contact with furnace gases of fluctuating composition containing some sulphur compounds. The attack from this cause with temperatures up to 650° could, as they knew, be prevented by aluminising. In this process they applied aluminising to the clean surface of the tubes by means of a metal spraying pistol. The aluminium coating was then heat treated at 1,300° F. for a few minutes, this aluminium covering being converted into aluminium iron alloy, which was resistant to oxidisation and sulphurous attack. The surface also became very hard and stood up well to erosion. The coating had no bad effect on the mechanical properties of the steel, or on the "creep," neither did it embrittle the tube or cause inter-crystalline break-down.

They had had considerable experience with the aluminising process, and they knew that it was of great assistance when both cast iron and steel were subjected to high temperatures. It might be known that already a number of superheater tubes were aluminised, and, as an instance, this process was used with success on the superheaters of the *Bremen*.

In the paper the bad effects of these segregated inclusions were mentioned, but there were also the inclusions of oxygen. During the process of making weldless steel tubes it was possible to roll in scale causing oxide inclusions, which were difficult to discover either by mechanical or chemical tests. Such tubes were, fortunately, not numerous, and ofter failed in service. This point was mentioned because it was interesting that such tubes could not be aluminised, as the presence of the oxide prevented the absorption of the aluminium into steel.

He would again like to thank the Author for his paper, which they appreciated as dealing so thoroughly with the subject, and which, incidentally, would be of assistance to them in their investigations.

Mr. ROBERT WADDELL (Messrs. Brown, Bayley's Steel Works, Ltd., Sheffield) in a written communication, said that the Author made a statement (p. 868, para. 3) that oxidation of the tubes was more likely to occur on the inner surface in contact with the high temperature steam, than on the outer surface in contact with furnace gases. This did not appear to be supported by any evidence, and to him seemed unlikely to be true for steam temperatures under 500° C., in view of the inevitable temperature gradient between the outer and inner surfaces. The furnace gases also were frequently additionally corrosive, due to the presence of oxides of sulphur.

Later in the paper (p. 870, para. 1), dealing with creep stresses, the Author quoted a conclusion of Mr. H. L. Guy, that "Ordinary carbon steels may be used at a temperature of 900° F., with the same factor of safety as at 700° F. (*i.e.*, with the same creep rate) provided the stress is reduced by 60%." He found this a very optimistic conclusion. The drop between 800° F. and 900° F. was probably of the order of 45%, and the difference, 15%, seemed very small to ascribe to the range 700° F. to 800° F. He would be glad to know whether the Author could produce any experimental evidence in support of the figure.

Referring to alloying elements in steel tubes, the Author stated that "recent researches indicate that the addition of low percentages of nickel has an adverse effect upon the creep properties as compared with ordinary mild steels." This statement was news to him, and he would be very much interested if the Author could quote the experimental evidence supporting it.

Again, the Author quoted the use of "Enduro" metal (a "stainless" iron of about 17% chromium and fairly high silicon) to which he gave a bad character on the score of brittleness, when held for long at temperatures of 1000° F. Such high chromium irons were known to be brittle even in the cold state, and it was not clear why the Author dismissed thus summarily the straight chromium group of materials on the behaviour of perhaps the least suitable of that group. For resistance to oxidation up to temperatures of 800° C. (a figure far beyond the present necessities) a much lower chromium than 17% would suffice, and materials containing 12/14% of chromium could be produced, having very good physical properties both cold and hot. So far as he knew, the experiments to determine the creep rate of these medium-chromium steels had not yet been carried through a sufficient range of temperatures, or for a sufficiently long time to enable an accurate figure to be quoted, which could be used as the basis of superheater tube design; but the preliminary investigations, results of which were read before the Liverpool Engineering Society by him on December 4th, 1929, seemed extremely encouraging, and ought to be followed up before resorting to the austenitic nickel-chromium steels with various additions of tungsten, molybdenum, etc. The danger of intergranular embrittlement in the austenitic steels was now so well known, and appeared so extremely difficult to guard against, that the virtues of the straight chromium materials should be thoroughly explored before such steels were discarded for superheater work. In his opinion these steels, while possessing a lower tensile strength at high temperatures than the austenitic steels, would be found to preserve their physical characteristics unimpaired for a very much longer time.

He would like in conclusion to congratulate the Author on his extremely able presentation of his case.

Mr. J. PRINGLE (Lloyd's Register of Shipping, Sheffield) in a written communication, said that he considered Mr. Dorey's paper most valuable and interesting. The Author had gone into the subject so thoroughly that he left little upon which to comment. However, he would like to add a word or two regarding the inspection side which, he thought was a very important matter.

He thought it was recognised that only non-segregated steel should be used for tubes of high temperatures. Under some methods of manufacture it was more difficult to make a first class tube, as non-segregated steel would not stand so much punishing as ordinary segregated steel. This applied particularly in the piercing by the rotary process.

In some cases it had been known that a tube broke in the middle of the walls of the tube, the defect being most difficult to detect either by external or internal inspection, unless the inspector knew the inherent defects for which to look. This certainly needed considerable experience with the various methods of manufacture as the defects to be found varied very considerably under different methods. The external examination could be assured by the electro zincing process which would indicate the most minute fracture.

With regard to the mechanical testing of tubes to B.S. 53 and the Admiralty Specification, these specifications were sufficient for ordinary tubes but did not appear to be sufficient for tubes for high pressures or temperatures. Might the writer suggest that instead of the flattening test at the end of each tube, an expanding test at each end of the tube should be adopted. This would show up any external or internal defects, whereas the flattening test only proved the two insides externally. The cost would not be any greater as the expanding could be done on the existing machinery used for bulging tubes. As an alternative test, a ring about 1 in. or $1\frac{1}{2}$ in. might be cut from the tube and this should be cut through on one side and bent round inside out to form a tube again of the original diameter, thus showing any likely internal defects.

Another point worthy of notice was that while the Author stated that the tube should be thoroughly clean inside it was equally important that the boiler should be carefully examined to see that there were no scale pits due to the swaging in of the ends during manufacture. It was understood that a new machine was now being adopted to machine the internal parts after swaging.

Mr. J. CALDERWOOD, M.Sc. (Messrs. Sulzer Bros., Ltd.) (Member), in a written communication, remarked that the problem of combined heat and mechanical stresses was one which had been tackled by many engineers in the past, but there was, he believed, no paper previously published in which it had been so thoroughly treated as in that which Mr. Dorey had presented to us. It was, further, a question which seemed to have been neglected in the design of boilers, and it was important that it should be realised that a design in which pressure only was considered became, with increasing pressures and high rates of evaporation, so inaccurate that it must lead to serious danger. In these circumstances, the existing rules of classification societies and other inspecting bodies became a danger rather than a safeguard. With the object of Mr. Dorey's paper and the general method in which he had tackled the problem, no one could disagree, but there were one or two small technical points on which he wished to comment, or on which further information would be of value.

In the evaluation of M in expression (4), it was made proportional to $(\theta_1 - \theta_2)$. Now this was correct for a flat plate where temperature drop was a straight line across the material, but for a tube the temperature drop was a curve and steeper at the inside than the outside, as could be seen from equation (3). If we were to carry out the stress calculation with the accuracy that Mr. Dorey attempted, this factor should be taken into consideration, as it would have a greater influence on stress distribution than some of the other factors introduced into his equations. He had not had time to examine the mathematics of the question carefully, but he believed that this correction would show the conditions to be somewhat better than were indicated by Mr. Dorey's equations, the maximum stresses in the tube being rather lower than those calculated.

Haigh's theory and Guest's law were both referred to in the paper, and an example worked out in which both gave much the same results. From Figs. 3 and 4, however, it was evident that such agreement would only be found within a very narrow range of conditions. It would be of value if Mr. Dorey could tell us whether this range would cover all cases likely to be met in practice, and if not, whether there was any experimental evidence available to show which method of calculation was more accurate. From the form of the expressions, Haigh's would appear to be the more rational theory.

To refer to Fig. (2), the curve for $\frac{E\alpha}{K}$ showed a sudden change at about 220°. Surely this could not be correct, as the curves of $E\alpha$ and of K both appeared to be smooth, and in any case there seemed no reason to expect a sudden change at this temperature. Mr. Dorey might, however, be able to offer an explanation. He noticed also that the values of E were mean from two different steels and for α from two further steels. Surely averaging of this kind could not be allowed unless these qualities were known to be constant over a wide range of mild steels, in which case there would be no need to take averages, as the true value of each for any steel within the range would be known.

In his calculations for the fire row of tubes, the Author had taken 40,000 B.T.U. per square foot, and his method of calculations assumed that the heat flow was even right round the tubes. Actually, any tubes exposed to direct radiation must have a much greater rate of heat flow on the side exposed than on the other, and it would be of great interest if in his reply Mr. Dorey could give some information as to the influence that this might have on the heat stresses. If the assumed average values were correct, then the heat flow on the first row of tubes must vary from 60,000 B.T.U. or more on one side to about 20,000 on the other.

In the fifth paragraph, under the heading "Tube Temperatures," Mr. Dorey referred to critical velocity as the velocity above which further increase did not lead to an increase of heat flow. This paragraph might cause some confusion, as in heat transfer problems the expression "critical velocity" was generally applied to the velocity at which the nature of flow of the fluid changed from steady to turbulent conditions, and at which there was a great increase in the co-efficient of heat transfer. Apart from this question of definition, Mr. Dorey's statement was misleading unless it was amplified. Actually there was no known velocity above which an increase in water or steam velocity would not increase the coefficient of heat transfer from metal to fluid, but with any given velocity of the hot gases outside the tubes, there was some point at which the heat transfer coefficient from the tube to the fluid inside became so great compared to the coefficient from the gas to the tube that further increase of the velocity of the steam or water had little measurable effect on the overall heat transfer coefficient. If, however, the gas velocity was increased, the velocity of the water or steam could with advantage be increased proportionally. Some years ago he carried out a number of experiments in heat transfer from air to water. The curves obtained when the velocity of either was altered, the other being kept constant, were of the form shown in Fig. F. With increased

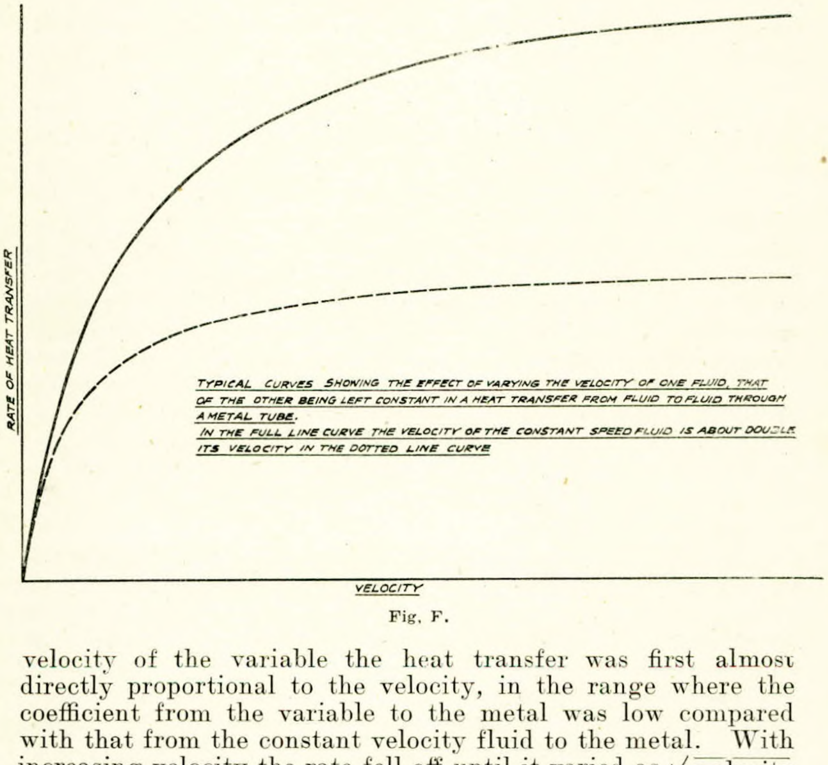


Fig. F.

velocity of the variable the heat transfer was first almost directly proportional to the velocity, in the range where the coefficient from the variable to the metal was low compared with that from the constant velocity fluid to the metal. With increasing velocity the rate fell off until it varied as $\sqrt{\text{velocity}}$ when both coefficients were equal. Finally, when the coefficient of the variable became very high compared with the constant, the rate of heat flow showed little further increase. When the water speed was varied the velocity at which this occurred was low, while with air speed as variable it was very high. If both water and air speed were varied at the same rate, the increase in the heat transfer was almost directly proportional to the velocity up to the highest velocities tested. This result was what would be expected from the expression given by Osborne Reynolds, $h = A + B \rho v$.

He could not understand why Mr. Dorey, after referring to the above expression, which was the outcome of the only thoroughly scientific and complete investigation of heat transfer that had been published, should then adopt a formula of the type $h = c \left(\frac{W}{a}\right)^{\frac{2}{3}}$. Formulæ of this type must have been derived from research covering a limited range of conditions, and could only be applied within that range, as they were a purely empirical expression of the form of the curve within that range. As the true form of the expression (i.e., that of Osborne Reynolds) covering any conditions was known, there could be no object in adopting a more limited expression. While Mr. Dorey might himself be conversant with the limitations of the equation that he used, it must be remembered that a paper such as his would, in future, be widely used as a work of reference, and others might be led to the belief that the expression which he favoured was unlimited in its application, and so might use it in cases where it would give results that were far from accurate.

In conclusion, he wished to again emphasise the great value of Mr. Dorey's paper, not only to boiler designers, but to all engineers who had to deal with problems involving heat transfer.

Eng. Rear-Admiral J. HOPE HARRISON (Member), in a written communication, said that the paper was a valuable contribution to the records of the Institute. To improve the efficiency of the steam engine, the pressures and temperatures of steam had been raised. In order to exceed pressures that were no longer considered economical, we generated steam in water-tube boilers. The vital feature of the water-tube boiler was the tubes. A very considerable amount of research had been carried out in order to obtain a tube that would satisfy certain tests. When we examined these tests, although it had to be admitted that material which would successfully stand up to them could not be of very inferior quality, still we found they were chiefly devised to ascertain whether the tube could be cheaply worked into a water-tube boiler and would stand a certain pressure when in place. An examination was seldom made of the material from which the tubes were manufactured, with a view to ascertaining whether the tube would give good service after it had become part of a boiler. Experience had shown that the life of a tube depended to some extent on the structure of the material from which it has been manufactured. In many cases the user specified nothing about the steel; very often basic steel was used.

Details of steel from which tubes were made had been specified only by the tube maker in the past, and he had been reluctant to use any steel, except that which experience had taught him he could fabricate into tubes cheaply, and would withstand certain physical tests and pass a visual examination.

In order to show up any marks on the outside of the tube, it was zinced; but the internal surface was not zinced and could only be cursorily examined visually. It was on this surface that rapid deterioration nearly always took place. If the water-tube boiler was to become standard for merchant ships, the life of tubes must be as great as possible. Apart from the cost of retubing, the time lost while a ship was being retubed was important. If boiler makers and tube manufacturers were wise, they would take every precaution that experience of water-tube boilers had shown to be necessary in order to avoid the criticism that must be levelled if the high costs of maintenance wiped out any gain in economy of fuel.

In setcions 1, 2, 4 and 5 of the paper, design questions were considered. The designer sat aloft and sneered at the inefficient operator (who was less articulate), when the fault was often the designer's, because he had been ignorant of the precise conditions under which his design would have to be operated. Although the designer might be able to say approximately what thickness of tube would withstand the heat and fluid stresses to which it was proposed to subject it when perfectly clean, no experienced operator forgot that tubes were never clean internally or externally, and over 90% of tubes were normally reduced 70% in thickness locally in the short space of 8 to 10 years, even with very careful operation, and in some cases in as many months. It was unwise, therefore, to speak of determining the thickness of tubes by calculating the stresses they would have to withstand clean, and adding what would (were there no such thing as corrosion, scaling, etc.) normally be a reasonable factor of safety.

The high pressure boiler had not been long enough in service to enable sufficient experience to be gained as to the best material to be used, but there appeared to be no reason to doubt that a steel containing ·1 to ·17% carbon would give satisfactory service at temperatures up to 800° F., if the steel was carefully made and inspected. The writer considered that a rigorous inspection of the steel from which tubes were to be made should be carried out by the ultimate user at the steel makers, and no inferior material allowed. He thought that the Author might have stressed the point more that experience had shown that cold-drawn steel was preferable to hot-drawn, and that the 'gun-barrel' finish (which a few final cold passes gave) was cheap in the long run.

There was a danger—if tube makers would not realise that water-tube boilers must not run up prohibitive costs for retubing—that the clock would be set back and the operating costs of high pressure plants would force users to look for something less costly to maintain.

Mr. E. G. RITCHIE (Chief Engineer, Boiler Inspection Dept., Manchester Steam Users' Association), in a written communication, stated that whatever the boiler engineer might think of present day rapid development to extreme conditions of temperature—pressure—duty, it was clearly his business to produce apparatus which would give the best combination of high pressure, high temperature, and high heat transmission, with continuity of operation, having regard also to the great driving requirements of the general design at least for power purposes, viz., overall economy in the broad sense, including first cost, running and maintenance costs, fuel and operating power.

Whether extended experience would justify extreme conditions of pressure, temperature and duty for commercial and power requirements was doubtful. He was of the opinion that for serious operation there should be a decidedly respectful margin between actual conditions and those shown to be possible in extreme experimental plants.

In the matter of superheater tube temperatures, Mr. Dorey's reference to "hot spots" was most important. In a large experience it had been often shown that superheater failures were almost invariably, accidents excepted, failures of individual tubes or of a small proportion of the tubes, caused by bad steam distribution, resulting in the starving of certain tubes, or to uneven flue gas temperature, or to both of these conditions.

It was the *average* steam temperature which counted in giving the desired steam quality, but it was the *maximum* tube temperature which caused trouble, and in reaching after maximum steam delivery temperatures, these two must be made to approximate as closely together as possible, either by suiting the steam flow to the local flue temperature or levelling out both the steam flow and the gas temperatures.

Both points seemed to call for special attention, and in connection with the second named, he would suggest that (as he believed had been shown) the gases flowing through a large combustion chamber to the stack tended very definitely to stratify according to temperature, and this stratification was persistent under steady conditions of operation. More precise information on this point than was possible from consideration of the mixed gases delivered to the chimney would possibly help in design for the elimination of "hot spots."

Again, the superheater might be subjected to accidental excess gas temperatures as well as to occasional steam starvation as in manœuvring, etc. For instance, improper furnace conditions with a leaky boiler setting admitting air might result in the burning of considerable volumes of carbon monoxide resulting in highly excessive temperatures beyond the combustion chamber, where it might do harm, *e.g.*, in the superheater chamber, or to generating tubes where circulation was feeble.

The best tube making was a very high expression of engineering skill, but even with the best intentions and equipment accidents occurred.

Small non-metallic masses or collections of impurities in the billet might be drawn out into long flaws in the finished tubes, perhaps visible but sometimes entirely concealed in the tube walls. A remarkable case of such a character came under his notice recently when a water-tube of the best make in a 600 lb. pressure boiler failed. On investigation they found that there had been a non-metallic streak precisely in the centre of the tube wall over the full length of the rupture some 9 ins. long. The edges of the fracture were both "V-notched" in section showing that only the thinned outer and inner skins of steel had been holding, and the stretch before failure was, of course, confined to these.

Cases like this in which the failure of a single tube might put the largest unit out of action, involving untold inconvenience, great loss, and perhaps danger, emphasised the need of extreme care in the manufacture of tubes, and for important plants and trying conditions the elaborate precautions referred to by Mr.

Dorey to ensure as far as possible the exclusion of impurities and to secure homogeneity, *e.g.*, generous cropping of billet ends, machining and sulphur printing, and free reduction of doubtful billets, were justified.

Inspection after completion, though necessary, was alone insufficient; it was impossible to see all defects, particularly in cold finished tubes, and occasionally rokes and fine cracks might develop in service or in expanding and belling, with the possible exception of tubes made under conditions of manufacture and material of the very highest class.

With reference to the spheroidisation of carbide in superheater tubes discussed by Mr. Dorey, the study of this was beset with difficulties, one of which was the uncertainty of data as to temperature, and in a less degree as to the time to which specimens had been exposed to such temperature. Steam temperature leaving the superheater was, of course, of little use as a guide to tube wall temperatures. They had noted the phenomenon of spheroidisation not only in superheater tubes, in which variation of its intensity seemed generally to keep step with the variation of temperature throughout the length of the tube, but also in steam equalising tubes of " Stirling " type boilers.

The effect of this on creep, as stated in the paper, was not known, but in low carbon steels was probably very small. From the investigator's point of view, the principal significance of spheroidisation seemed to be the indication of overheating which it provided. Unfortunately, the degree of spheroidisation was not necessarily an indication of the temperature to which the specimen had been subjected, on account of the time factor in the production of this characteristic formation.

The best tubes yet available, from the heat-resisting point of view, were unfortunately not suitable for attachment to headers, etc., by the ordinary simple process of expanding. The consequent need for the welding on of plain carbon steel ends was rather unfortunate and opened up the question of intergranular weakness which was apt to ensue when austenitic steels were heated as in welding. They might look to this small point of design for interesting developments as experience grew, and possibly a new design with mechanical attachments would be shown to be necessary. Simple expanding was perhaps not all that was desirable even for moderate duty conditions, and they had found a good deal of trouble from intense localised corrosion of superheater tubes at the flue side at the point of entry into the header; it was no doubt caused by leakage, which in a flue gas atmosphere containing sulphur compounds of course accounted for rapid localised wasting. Usually the leakage was not visible; the tube seat bearing surfaces showed no signs of leakage, and in no case had there been evidence of bad fitting. For the most satisfactory attachment by this method the header should, of course, be rigid and of rather higher tenacity than the tubes.

Mr. Dorey referred to dissociation of steam and the effect on the tubes. The usual first effect on superheater tubes seemed to be the formation of a hard protective oxide coating resistant to corrosion, but where air entered with the feed water the common effect was corrosion and pitting, chiefly about the expanded ends of the tubes.

The reference in the paper to tube diameters was appreciated; the relationship between wall thickness, diameters, pressure, heat transmission, and stress being treated very clearly. For extreme conditions of operation, diameter of tubes was of course strictly limited, and that carried with it the unfortunate limitation of the size of gas passages between tubes, other things being equal, including heating surface, cubic space and cost. These narrow passages were, of course, much more easily choked with ash than wider passages, and the tendency of such tubes to bend—further interfering with gas passages—was greater. Wide gas passages remote from the fire were, however, less important in the matter of ash than those near the fire.

With regard to "creep," we were still in need of data. Small differences of composition and of ordinary physical properties might or might not have corresponding effects in creep, but only comparatively small temperature differences near the practical limits now being approached were required to affect the creep rate very seriously; hence the need under "maximum" conditions, of effective control and knowledge of ambient temperatures and steam flow at all parts.

In the meantime we might perhaps hope for a range of steel specifications giving chemical and physical characteristics, including creep, over a suitable range of temperatures and stresses.

Mr. S. A. MAIN (Messrs. Hadfields, Ltd., Sheffield) in a written contribution, stated that he had been more specially interested in that portion of the paper dealing with the design of tubes for the higher working temperatures where the effects of creep have to be considered. For the reason that really successful design must be built up on experience, it was hardly to be expected that rules with any degree of finality could at present be drawn up for practice in this higher range of temperature, that is, above 750° F. The formulæ which in the past, that is for lower temperatures, had been most reliable, had been those in which the factors were based on satisfactory practical performance. This principle had in fact been used by the author (page 875) in his selection of a particular formula.

In the higher range of temperature such experience had yet to be obtained, but since practice had already advanced into those regions there must nevertheless be some basis of design, and working formulæ of however tentative a character were necessary. The author had applied himself to the problem in an admirable way, and provided formulæ and data which should lead engineers fairly safely for the present along this comparatively untrodden path. When the results of experience accumulated it would be no reproach upon his efforts if some revision was found to be necessary.

Much depended upon the reliability of carbon steels in their use at these higher temperatures. The evidence put forward in the paper, and in oral discussion, seemed somewhat conflicting on this point, that is, as to whether structural changes in the direction of spheroidisation must be expected. There were several cases, however, where carbon steel had been used apparently successfully at temperatures at any rate up to 850° F. The chief danger from their use seemed to be in the possibility of excessive temperatures occurring due to imperfect operating conditions. In such a case the steel might very soon be carried into the regions of temperature where its strength failed rapidly. This could occur, of course, more particularly with superheater tubes. In the range between 900° and 1000° F. the creep stress of carbon steel fell something like 50%, or for a particular stress, the rate of creep increased by more than a thousand times. This was readily seen in Fig. 21. Apart therefore, from their higher intrinsic strength, and the greater margin of safety so provided while temperatures remained normal, the special types of steel of comparatively low alloy content mentioned in pages 870 and 871 also offered greater safeguard against untoward operating conditions, since the temperature at which their strength fell to a dangerous point was higher.

The rapid fall in strength, and increase in rate of creep of carbon steel in the temperature range 850° to 1000° F. it would be seen necessitated special care in making covering allowances of temperature in design, as mentioned on page 880 that is, if an excessive factor of safety was to be avoided. The allowance of 25° made by the Author seemed, however, fairly reasonable in this respect.

Capt. P. T. BROWN, M.C., R.A.R.O. (Lloyd's Register of Shipping, Middlesbrough) in a written communication stated that the Institute would heartily welcome the thorough investigation made by Mr. Dorey on a subject so vital to present day steam engineering. His paper represented a great amount of work and he was certain that the members would be grateful to the Author for giving them the results of his labour.

Mr. Dorey's rules were developed from considerations of pressure and temperature stresses, but he introduced quite correctly, he thought, the mysterious x in his final formulæ under the heading "factor depending on the position of the tube in the boiler." He would go so far as to suggest re-writing this to read "factor depending on the type of boiler and position of the tube." Deflection of steam, or length of water drums and shape of tube each induced subsidiary stresses of an incalculable nature.

The Author's remarks on scale, alkalinity of feed, and circulation were opportune, and he particularly welcomed the attention he had drawn to the blocking of large tubes by the formation of steam pockets. Attention was drawn also to the trouble likely to arise with superheater tubes when manœuvring or working at low power. Did the Author not consider that it was the best course to change over to saturated steam under these conditions?

He would like to endorse the view expressed in the second paragraph of Section III. With proper care and effective cropping segregation could be reduced to a minimum and the well tried low carbon steels made quite effective for all but the very highest pressure and temperature. Where welding properties were requisite it did not appear to him desirable to introduce alloy steels.

The Author drew attention to the interior of Sample A giving greater hardness values than the external surface. Surely this was fundamental to the method of manufacture, although under certain conditions final heat treatment might reduce the difference. It was always rash to offer criticism of microphotographs as reproduced in the advance proof copies of the paper, but he had not the slightest doubt that the Author's remarks were correct.

Mr. J. JOHNSON (Chief Superintendent Engineer, Canadian Pacific Steamships, Ltd.) in a written communication, stated that the economic advantage of high pressure steam was now so definitely established that the use of water tube boilers in various classes of merchant ships might be expected to extend very rapidly within the next decade. An authoritative pronouncement concerning material, design, manufacture and preservation of the generator and superheater tubes for such boilers was particularly useful at the present juncture. Mr. Dorey's paper covered the range of these allied subjects most admirably. It was a valuable contribution to existing literature and would be of much help and guidance to present and prospective users of high pressure water tube boilers.

One found, in approaching this subject for the first time, that most tube manufacturers had two prevailing standards—Admiralty requirements and Mercantile requirements. This distinction, quite natural in earlier circumstances, needed some qualification to-day. The cost of tubes to Admiralty specification was almost prohibitive for merchant ships, even in the case of large express liners. At the same time, the quality of the tubes required for the boilers of such ships, or, in fact, for high pressure water tube boilers for any class of vessel, must reach a high standard, and the need for a specification suited to such tonnage was a very real one. Surplus weight or high first cost were both impediments in the way of the more general adoption of high pressure steam. It was to be hoped that Mr. Dorey's work would serve to promote some action in this direction.

The superheater tubes were the most vulnerable part of a mercantile boiler, for while the boiler proper would withstand a very high degree of forcing, as in naval practice, the superheater was the measure of the safety and endurance of the steam generator as a whole. As was well known, the manœuvring condition was the chief difference between marine practice and land practice. If the steam pressure was allowed to fall and navigating requirements demanded a heavy supply of steam, the fires, whether oil or coal, had to be forced, in which event gas temperatures mounted very rapidly, while the velocity of circulation through the superheater might not be correspondingly increased. A large proportion of excess air was more or less inevitable when manœuvring, and altogether conditions were more trying for the superheater than under stable steaming. It must not be forgotten that the effect of very high temperatures had to be considered in relation to the boiler stop valves, bulkhead and manœuvring valves, etc.; also, their effect upon the astern turbines, if such were employed, under alternating conditions of vacuum and full pressure. As the working pressure and temperature rose, these variations in the astern turbine naturally increased and were liable to cause some anxiety. Various measures had been considered in this connection: it was perhaps sufficient to point to the significance of these facts and keep them in view when considering the problem of boiler tube design. Having regard to the foregoing points, it was unlikely that appreciable advances in temperature would take place in marine practice, notwithstanding the availability of higher grade superheater tubes, which, incidentally, were expensive.

Although superheater elements might not fail by local overheating, due either to excessive gas temperature or starvation of steam circulation, they might depreciate as a consequence of sagging and general deformation. Their experience had been that superheater elements should be arranged almost vertically and be provided with proper supports, spacers or ferrules, to ensure that the pitching of the elements was maintained, and a uniform gas flow through all parts of the superheater assured. Vertical elements were practically self-cleaning on the fire side, which experience showed to be a useful feature in several respects. He would strongly endorse Mr. Dorey's view that an adequate and "uniform" circulation was greatly to be desired. Superheaters which were constructed on the principle that the steam would automatically and necessarily divide itself into equal quotas over a large nest, were liable to be found deficient in certain areas. 750° F. at the boilers seemed to be a safe working limit for marine work in the present state of their knowledge. With well lagged steam pipes, the drop between the stokehold and the engine room should not be more than 10°-15° F.

So far as generator tubes were concerned, the transmission rates on the fire rows in mercantile boilers were not appreciably greater than those which obtained in the first half of an oil-fired Scotch boiler with corrugated furnace. Nevertheless, fire rows, originally straight, did assume a slight curvature owing to the higher intensity of heating on the half circumference exposed to the furnace. Developments in water tube boiler design would be in the direction of greatly increasing the furnace capacity while lowering the maximum and average transmission rates on the tubes. So far as the durability of generator tubes might be influenced by continuous heat transmission, it was clearly only the fire rows and, possibly, one or two subsequent rows that were likely to be affected. Coming, however, to the more general question of tube depreciation as distinct from high transmission rates, it should be observed that a cold finished tube of stout scantlings, as used in a modern high pressure boiler, was a very robust article, and, given reasonable attention, ought to have a very long life indeed. If boilers were filled with hot water, fires lighted immediately and a closed feed system employed, good results might be expected. Even under these conditions, however, there was liable to be oxide formation in the form of a fine brown dust. A little judicious colloidal treatment was sufficient to deal with the small amount of free oxygen remaining and would practically eliminate this dust. It was difficult to convince those who had not had actual experience that boilers could be operated to-day without any scale formation whatever, whereas there was now ample experience to show that boilers could be run for six months without attention on the water side, and even then a purely nominal amount of brushing only was required.

There was a large amount of evidence now available to show that the high pressure water tube boiler was in every essential respect, superior to the earlier forms of steam generator, and that, given reasonable care in manufacture and operation great durability of the tubes might be confidently anticipated. Mr. Dorey's paper would stimulate interest in the various sections of the subject and do much towards promoting a fuller realisation of the conditions to be observed in order that a high standard of reliability and durability might be secured. The electro-zincing process added a little to the cost of the tubes but was a thoroughly reliable method of inspection, and quite worth while. The application of graphite or Apexior coatings was of some utility, and careful experiments had shown that the conductivity of the tubes was improved rather than diminished. The use of such protectives was, however, a matter for each engineer to decide, according to the routine under which the boilers were to be worked. Similar remarks applied to idle boilers or boilers emptied in port, and there was no doubt that a proper technique was necessary if the best results were to be obtained, and matters not left to the caprice of the individual engineer.

Dr. J. S. BROWN (Lloyd's Register of Shipping) wrote as follows: The maximum temperature of the steam which can be taken from a superheater is fixed by the practical consideration that tube failures will become unduly prevalent when a certain temperature is exceeded. These damaged tubes will provide their own evidence on the cause of failure, and it by no means follows that stress considerations are the only factors to be considered. It is necessary to emphasise that in 1924 it was shown by Prof. J. Muir, of Glasgow, that steam passed through a tube held at 850° F. led to the evolution of free hydrogen, due to the decomposition of the steam, and with a consequent oxidation of the tube material. When the tube temperature was raised to 1000° F. the evolution of hydrogen was quite rapid.

This laboratory experiment can be adjusted to practical conditions if it is assumed that the tube will be at 50° to 100° F. above the temperature of the superheated steam; and would then place the limiting safe steam temperature at about 800° F. The years which have passed since 1924 provide little to refute such a conclusion, and, on the other hand, evidence continues to accumulate in its support thus:—

(1) There is a process in chemical engineering using low pressure steam at the maximum attainable superheat, and the information available places the life of the superheater tubes at six months for a superheat temperature of 1050° F. When the tube bank is removed for renewal the tubes are as brittle as china, and appear to have become changed to a mass of oxide of iron. I look on this as a most important piece of evidence, as the chemical industry here concerned can only continue to exist by the acceptance of these somewhat rash conditions and in the more normal power plant the working temperatures must fall at some lower point on the scale of superheat.

(2) The successful development of the super-charged Diesel engine has led to the marketing of blowers driven by exhaust gas turbines, and it is relevant to notice that the makers of these units have found it necessary to fix a limit of 930° F. for the temperature of the exhaust gases entering the turbine.

Here the danger point would appear to lie in the turbine blading material.

These full scale applications each support a view in keeping with the deductions drawn from the original experiments of Prof. Muir, so that the limiting safe temperature for the tube continues to stand at about 900° F., and the issuing steam must be at a lower temperature, say at 800° F.

At the temperatures existing in the evaporating section of the boiler, and also in a normal superheater, the question of chemical failure may be excluded, and the proportioning of the tubes can then proceed from the consideration of the factors discussed in the body of Mr. Dorey's paper. There is an enormous amount of work hidden behind the preparation of the charts which he has provided, and the completeness of the examination is illustrated by the final comparisons with the standards used abroad.

THE AUTHOR'S REPLY TO THE DISCUSSION.

Mr. S. F. Dorey, in reply, stated that judging by the interesting discussion that had arisen, the paper had fulfilled a purpose for which it had been intended, namely, emphasizing the very great need of co-operation between steel makers, tube makers, boiler makers and engineers, in order to get some definite facts which would help them to draw up specifications and rules relative to tubes for high pressure boilers. It seemed to him a matter for regret that while the Americans and Germans had already settled these questions for themselves, a satisfactory basis had not yet been established in this country. Whether the conclusions reached in America and Germany were satisfactory remained to be seen, though so far the results in service appeared to indicate that they were. He had taken the trouble to write to the chief engineers of six large power stations in America having boilers operating at steam pressures from 1200 to 1400 lb. per sq. inch and steam temperatures of 700-750° F., and they had all stated that the tubes of the wall thicknesses specified in the A.S.M.E. Boiler Code were entirely satisfactory for the pressures stated. In some cases the walls of superheater tubes had been made somewhat thicker than called for by the A.S.M.E. Code in order to provide a sufficient margin for the falling off of the strength of the steel at the higher temperatures and for preventing the stress within the tube material from producing an excessive amount of creep.

Many interesting and valuable facts and views had been brought to light in the discussion, which would enhance materially the value of the paper.

Mr. Marriner, representing a firm who made both land and marine boilers, had called special attention to the urgent necessity for a definite ruling regarding tube thicknesses which, it was to be hoped, would be brought to the notice of competent authorities. The series of tests on tubes were of special value and indicated the good quality of the material. The particulars relating to heat transmission rates were useful to the designer in considering temperature stresses. Mr. Marriner's question regarding the probable nature of the failure of a boiler tube made too thick for the corresponding pressure and rating needed careful thought, since it depended upon the position of the tube in relation to the fire and the degree of thickness in excess of the optimum value. With a very thick fire row tube, bulging would take place due to overheating; this would interfere with local circulation, causing further overheating with formation of scale inside and final formation of blisters, with ultimate perforation. Undoubtedly high stresses increased liability to corrosion, due primarily to the impossibility of producing a perfect finish to the tube surface.

That there was a diversity of opinion regarding the maximum permissible percentages of sulphur and phosphorus was evident from the remarks of Messrs. Davy, Marsh and Geer, indicating the need for co-operation between the steel maker and tube maker. It would appear, however, that the percentages mentioned in the paper were not impracticable or unreasonable. He was inclined to agree with Mr. Davy that steel having a tensile strength of 23-25 tons per sq. inch was most suitable for ordinary work. The effect of increase of carbon content on both creep and oxidation characteristics of mild steel tubes mentioned by Mr. Humphrey Davy was of special interest to all concerned. It might be mentioned, however, that Messrs. Babcock and Wilcox, of New York, used tubes of a higher carbon content than specified in the A.S.M.E. Code (viz., ·08-·18 % C.), this being allowed by a recent decision of the Boiler Code Committee that seamless tubes for superheaters made of open hearth steel of any carbon content might be used, provided the physical characteristics required by the specifications were met. The higher carbon steel tubes were considered by that firm to be superior in having higher creep values than the lower carbon tubes.

Dr. Jenkin had raised a special point in connection with the mechanical testing of special steels, which was worthy of careful consideration. Bearing in mind the improved properties under service conditions, it would be agreed that mechanical tests only slightly in excess of the work to which the material would be subjected during construction of a boiler, should suffice, and this would be satisfactorily met by cold bending and expanding tests. The comments made by Dr. Jenkin regarding segregations and oxidation were of special value from both the tube makers' and users' standpoint. The author was, however, inclined to the view that while "rimming" steel had its uses a superior quality of steel was required for high pressure work. That the internal surface of sample A —and also of other samples examined—was slightly harder than the outer surface was amply demonstrated by the hardness tests. The internal surfaces surely did tend to get rather more work-hardening due to the drawing operation, although in certain cases, this might be obliterated by the subsequent heat treatment. The direction of work was indicated in sample B, but would have been more definitely in evidence had a larger area been shown. The photomicrograph C was not quite as sharp as it might be, but gave no indication of spheroidisation. Referring to sample D and knowing the treatment this tube received, the conclusions made in the paper were adhered to.

The satisfactory annealing of the tubes, mentioned in the paper, to retard spheroidisation referred to proper normalising treatment, which though not ultimately preventing spheroidisation would retard its progress and, incidently, the creep rate of the material.

Mr. Dorey appreciated the remarks of Mr. Talbot and was glad to hear that nickel-chromium-tungsten steel tubes were proving satisfactory in service under the conditions stated. The comments made in the paper regarding intergranular breakdown of this material referred to special (acid) tests, and in this respect perhaps the criticism had been too severe. The cost of this material was not definitely prohibited if it was considered in the light of the subsequent saving in fuel due to increased steam temperature. He thought that in many cases first cost was allowed to influence the commercial man against the better judgment of the engineer, who often was not quite strong enough in backing his own convictions. Reference had been made to the behaviour of segregated steel tubes fitted in naval boilers. He thought it would be agreed that considering the extremely short period these tubes were under full working conditions and the comparatively short time even the boilers were in use per annum compared with the service requirements of the mercantile marine, it was extremely difficult to draw any direct conclusion from naval practice.

Mr. Marsh's comments regarding the respective merits of hot and cold drawn tubes were undoubtedly an interesting point for discussion, and the remarks made by Admiral Hope-Harrison were worthy of special note in this connection. In the author's opinion hot drawn tubes could not be considered altogether desirable for very high pressures.

Mr. Geer had referred to the creep limit of copper-molybdenum steels. Certainly too much reliance should not be placed on short time tests. The creep limit so determined might give some indication of the stresses the material might withstand satisfactorily for prolonged periods, but it gave no indication regarding rate of oxidation or permanence of structure.

The author thanked Mr. Geer for including particulars of the Fellows report, which he had inadvertently omitted. In regard to the heat transmission rates for superheater tubes, the author was aware of rates in excess of 35,000 B.T.U.'s per sq. ft. per hour in radiant superheaters, but confined his remarks to the ordinary convection superheater as applied to marine work. Referring to special alloy steels he thought it would be agreed that all analyses should be checked for the buyer, in order to show that the material was being consistently produced in accordance with the specification, to assure that the special properties claimed for any material might be realised in service.

Mr. Dorey was glad to receive the support of Mr. Burnham regarding the necessity for soundness and homogeneity in steel for tubes, a point to which Mr. Heck had also drawn particular attention. The question relating to the mechanical testing of special quality steels had already been referred to. The special test cited by Mr. Pringle should be carefully noted and was well worthy of consideration, particularly as an indication of the internal finish of the tube.

The arrangement of two stage superheater alluded to by Major Gregson was of special interest to the superintendent engineer and would appear to be a reasonable proposition. Mr. Dorey appreciated Major Thompson's contribution to the discussion and was interested to have confirmed that with a suitably designed superheater, temperatures of 900° F. could be satisfactorily maintained with ordinary mild steel tubes. This, of course, applied to land boilers with careful control of output. The satisfactory protection of the external surfaces of the tubes from corrosion by aluminising was also confirmed, and the details of this process given by Major Thompson were useful.

Mr. Waddell, like Major Thompson, had drawn particular attention to the effect of oxidation of the external surfaces of the tubes. The experience, drawn as it was from high pressure land work was valuable. With reference to the relative creep limits between 700° F. and 900° F., the following were the reductions for the 0·17 carbon steel (D.S.I.R. Report 1, page 43) mentioned, viz., 700:800:900::100:68:37·5. These experiments were carried out at the National Physical Laboratory and were more in accordance with the statement in the paper than with Mr. Waddell's figures; also Mellanby and Kerr's results for 0·35 carbon steel, viz., 700:800:900::100:65:40, and White's experiments on 0·14 carbon steel, viz., 700:800:900::100:72:50. Safe values would appear to be 100:65:35. The particulars of the experiments relating to the effect of small quantities of nickel in steel on the creep rate were not yet available for publication. Mr. Waddell's remarks regarding 12/14% chromium steels were of interest, but the author would be glad to be assured that the material could be produced consistently of good quality and with absence of surface defects in the finished tubes.

Mr. Calderwood had dealt with several points of technical interest. In the first place he was under a misapprehension regarding the temperature drop through the tube wall, viz., $\theta_1 - \theta_2$. There was nothing to infer that consideration had been given to heat flow through a flat plate, and no doubt when Mr. Calderwood had had time to look further into the matter he would see that all the equations referred to temperature difference in the walls of a thick tube. Reference to Figs. 3 and 4 showed that agreement between Haigh's strain energy theory and the maximum shear stress theory could only be within a narrow range, and this, incidentally, was in the vicinity of the optimum thicknesses. The author had plotted a large number of curves using both theories and was satisfied that so far as the optimum value was concerned the closeness of the results were such that the maximum shear stress theory could be satisfactorily applied.

Referring to Fig. 2, if the values of K had been plotted to as large a scale as $\frac{E\alpha}{K}$ the change of K at temperatures of about

210° C. would have been more noticeable. The change of the curve for $\frac{E\alpha}{K}$ was, however, probably made a little too abrupt at this temperature. In regard to the plotted values of E and α the author had intended to insert the actual spots for each material to show how closely they were in agreement, but perhaps this was unnecessary with the references quoted. The amount of tube surface exposed to radiant heat would of course, depend upon the spacing of the tubes, and with the spacing adopted in some boilers probably 270°-300° of circumference received the full heat value. Further, the velocity of the gases would be greater at the back of the tube than at the front. Temperature measurements had shown a drop of temperature in the gases of as much as 40° F. between front and back of tubes. The use of the word "critical" in regard to velocity of steam and water could probably have been better expressed. Mr. Calderwood's reference to his own tests were of interest. The formula for heat transmission coefficient, viz.: $h=A\left(\frac{w}{a}\right)^{\frac{2}{3}}$ was a national formula, and was also of the same form as Nusselt's equation, and the Reynold's equation could be shown to be approximately of the form $A_1\left(\frac{w}{a}\right)^{1-\beta}$, where β is of the order of 1/4 for smooth pipes.

The author thanked Admiral Hope-Harrison for his contribution to the discussion, which was of practical interest. He did not, however, agree with the criticism regarding methods employed in the determination of tube thicknesses, as the basis was similar to that used in ascertaining the strength of all engineering structures, being based on satisfactory stresses and experience. Admiral Hope-Harrison's remarks regarding the "gun-barrel" finish were fully concurred in. In the case of large boiler tubes for high pressure boilers hot drawn tubes might be permitted, provided they were subsequently subjected to a few cold passes.

The remarks of Mr. Ritchie, considering the invaluable experience he had had with land installations, also deserved special notice. It was remarkable how often reports on boiler explosions indicated that the root of the trouble was due to "hot spots," and showed the need for care in the arrangements of both steam and gas distribution during the whole time of operation of boilers. Mr. Ritchie's comments on spheroidisation, attachment of tubes, dissociation and creep enhanced the value of the discussion.

Mr. Main had done well in emphasizing the need for caution in formulating rules for the thicknesses of superheater tubes subjected to steam temperatures in excess of 750° F. A consideration of plastic flow showed that at high temperatures the limit of thickness of a tube on account of stresses calculated in the usual manner did not necessarily apply, and a thicker tube might be more serviceable. The increased margin of safety afforded by employing special alloy steels in preference to ordinary mild steel at temperatures in excess of 800° F. was well worth the extra expense involved in the first instance.

Capt. Brown referred to the superheater under conditions of manœuvring. In every case a flow of steam should be maintained through the superheater under all conditions to prevent overheating of the tube, but by a proper system of baffling the flow of hot gasses might be adequately reduced to meet all conditions of working.

Mr. Dorey appreciated very much Mr. Johnson's contribution to the discussion, and considering the large experience Mr. Johnson had had with moderately high pressure marine installations his remarks were of special import to all those concerned with economy of propulsion. The limitations of temperature —apart from pressure—in marine practice, in the light of experience undoubtedly pointed to the conclusion that 750° F. was the maximum temperature that should be maintained. The experience with superheater elements quoted by Mr. Johnson, and the results obtained by careful treatment in preventing scale formation were of much practical interest.

In a general survey of the contributions to the discussion the following prominent points had been revealed, viz. :—

(i) The necessity for definite regulations regarding the suitable thickness of tubes for high pressure water-tube boilers.

(ii) The need for homogeneous material which was being met, to a certain extent, by the steel maker.

(iii) The need for collaboration between the tube makers and steel makers regarding the cropping of ingots and maximum permissible sulphur and phosphorus contents.

(iv) The co-operation of steel makers, tube makers, boiler makers, and operating engineers in order that the materials to be used for high pressure boilers and high steam temperatures might be considered suitable to meet the demands of present day requirements.

(v) Mechanical tests to be specified having in view the special properties of the materials and the severity of working during fabrication.

(vi) The need for investigation regarding the respective merits of hot and cold drawn tubes.

(vii) The necessity for check analyses to be made on all special alloy steels in order to ensure that the steels contained the special constituents in the correct proportion.

The special cases of the effect of high temperatures on mild steel tubes quoted by Dr. Brown supported the evidence put forward by other authorities, and showed the limit to the usefulness of this material in superheaters.

In conclusion the Author desired to express his grateful thanks to all those who had come forward and given their views and experience in matters relating to tubes for water-tube boilers, thus not only stimulating interest in the water-tube boiler, but also contributing towards the success of the paper.

The following is a leading article from "The Engineer" of November 28th, 1930. In view of its special relevance to the foregoing paper and discussion it is reprinted in sequence therewith, instead of with the usual "Abstracts."

HIGH PRESSURE BOILER TUBES.

The paper read by Mr. Dorey, of which we conclude an abstract in our present issue, is of the greatest interest to designers of boilers and superheaters. Its object, we are given to understand, was to draw attention to the lack of any precise rule for determining the thickness of the tube walls of the generating and superheater tubes employed in modern high-pressure water-tube boilers. It was written by a principal engineer-surveyor of Lloyd's Register of Shipping and was addressed to members of the Institute of Marine Engineers, and its outlook is mainly marine; but, as the subsequent discussion showed, it has a much wider appeal, for the problem is the same for the land as well as the marine water-tube boiler. The present position with regard to the marine boiler may be stated in a very few words. The first rule fixing the thickness of tubes for water-tube boilers would appear to have been formulated in 1920, by the British Marine Engineering Design and Construction Committee, over which the late Mr.

A. E. Seaton so ably presided. That Committee comprised representatives of the Institution of Naval Architects, the Institute of Marine Engineers, the North-East Coast Institution of Engineers and Shipbuilders in Scotland, the Liverpool Engineering Society, and the three large classification societies, Lloyd's Register of British and Foreign Shipping, the British Corporation for Survey and Registry of Shipping, and the Bureau Veritas International Register of Shipping. The tube thickness in one-hundredths of an inch is given by the formula:—Working pressure multiplied by the external diameter of the tube and divided by a constant, which is sixty for the fire-tube rows and seventy-five for the other tubes. To this result a factor of eight is added. This result was approved by the Board of Trade and the classification societies in 1920. Practically the same formula appears to have been adopted by the Board of Trade authorities and it is given in the 1928 Instructions for the Survey of Passenger Ships. In this particular formula the factors for the fire-row and other tubes are slightly altered, being given as fifty-five and seventy-five respectively, while an addition of seven instead of eight is made. This formula, it is stated, may be used for tubes up to a working pressure of 250 lb. per square inch. By the adoption of suitable factors, the formula, it is true, may be adapted for higher working pressures, but at such pressures it gives a minimum thickness which is too great for practical purposes. At the present time working pressures up to 550 lb. per square inch are in use in British steamships, and land boilers are working at a pressure of 1,100 lb. per square inch, while there are under construction boilers designed to work at 1,400 lb. per square inch. On the Continent not only are similar pressures in use in several land installations, but there is more than one installation of Benson critical pressure boilers on land and an experimental installation in a cargo ship. British boilermakers rightly complain that whilst American and German authorities have legislated for these higher pressures, each design for a high-pressure installation put forward in Great Britain is dealt with by the Board of Trade on its own merits, a procedure which often leads to delay in the approval of plans and the ordering of tube material.

The problem presented, it seems to us, is to formulate without undue delay a specification and rules, which, while being acceptable to the Board of Trade and the classification societies, will cover a greatly increased range of working pressures. Such rules should take fully into account the newest information on the physical properties of mild steels, and the newer alloy steels now used in tube making, under high-temperature conditions. The important effects of creep and the change in structure of the cold-worked expanded ends of the tubes should not be overlooked. In any such investigation it will be most important to make some allowance for corrosion, both internally, and externally, but we believe that with the use of pure de-aerated feed water and oil fuel firing, coupled with the external cleaning of the tubes by scientifically designed steam blowers and the regular cleaning and polishing with graphite compound of the inside of the drums and tubes, the amount to be allowed for corrosion will be practically negligible. If we take, for a moment, the analogy of a chemical test tube, it will be remembered that in order to avoid heat stresses when boiling a liquid the thinnest glass is to be preferred. In the light of the Yarrow experiments on thin-walled tubes, we know that the bursting strength of such a tube is enormous. If, however, creep effects are to be allowed for effectively, a somewhat thicker tube must be employed, as, obviously, a too thin walled tube will fail earlier than one of greater thickness, owing to the higher mean stress resulting from the plastic flow of the material in the wall section. The question of the correct thickness for best working conditions, whilst important for generating tubes, assumes an even more serious aspect in the case of the tubes in a superheater. Other important questions bearing directly on tube strength are the homogeneity of the material supplied by the steel maker to the tube works, and its inherent suitability for the process of tube making, whether by hot or cold drawing. Again, appropriate mechanical tests and chemical analyses are required, bearing in mind the special heat-resisting qualities of some of the more recent alloy steels. With regard to mechanical tests, it may be necessary to modify some of the existing tests, having in view the very special and unusual properties which some of the new steels possess when exposed to very high temperatures. Again, the degree of finish and dimensional accuracy which is given respectively by the contrasted methods of hot and cold drawing would seem to open a valuable field for discussion and investigation. It will, we think, be generally admitted that for very high-pressure work tubes of superior quality to those generally supplied for moderate pressures are without doubt required when the very difficult service which these tubes are called upon to bear is taken into account.

The question remains as to how best the desired end may be accomplished. In considering possible ways, we cannot overlook the excellent work done by the late British Marine Engineering Design and Construction Committee, which was brought into being more than twelve years ago to co-ordinate the various rules then in existence for the construction of steam engines and boilers. Its main work was already done in 1918, but its activities were prolonged until 1927, when it was disbanded. The Board of Trade and the classification societies worked in closest connection with that Committee. The possibility of reconstituting such a body to deal with the question of tubes for high pressure water-tube boilers, and also probably different forms of high-pressure drums, must be taken into consideration. There already exists, however, a Consultative Committee of Shipbuilders and Marine Engineers appointed to confer with the Board of Trade, on which there are well-chosen representatives of the Institution of Naval Architects, the Institute of Marine Engineers, and shipbuilding interests on the Clyde and Tyne and at Belfast. Under the experienced chairmanship of Sir Charles Sanders, it is quite possible that the basis of this Committee might be broadened, in order to enable it to deal adequately with the question involved. One point cannot be overlooked. It is that land practice in high-pressure water-tube boilers has tended to advance more quickly than marine practice, and as the leading British constructors of boilers are interested in both land and marine boilers, it is very essential that any rules made should be equally applicable to both types of boiler. At the present time, both American and German boiler designers are guided, to a large extent, by the standard rules prepared by the Boiler Code Committee of the American Society of Mechanical Engineers, and by similar rules which have been drawn up and approved by the German authorities for the construction of land boilers. In our own country it might be possible, especially having in view the rapid advance towards higher pressures in land installations, to arrange for our own Institution of Mechanical Engineers to perform the very useful task of bringing together a panel of engineers who could deal effectively with the position we have outlined. The work would be done, we are sure, on the broadest possible basis, and in the closest co-operation with the other interested authorities, such as the Board of Trade and classification societies. If, at an early date, the wider rules, together with specifications for the different tube-making materials, were made available, they would, we are sure, greatly assist all the industries which are engaged, directly and indirectly, in the production of a scientifically designed high-pressure water-tube boiler.

A further contribution to the discussion on Mr. Dorey's paper by Mr. J. R. G. Monypenny, with the Author's reply, appears on page 945.

CORRESPONDENCE.

As set forth in the Bye-Laws, the Institute is not responsible for the views advanced by the Authors of Papers read, Contributions to the Discussions, or other Contributions, including Essays, published in the Transactions.

*THE EDUCATION OF ENGINEERS.

In forwarding the following contribution, the Principal of Sheerness Technical Institute extends an invitation to our Members to visit his school. Our Vice-Chairman of Council has done so on several occasions, and has been much impressed by seeing boys of 13 and 14 years of age engaged on what used to be regarded as higher mathematics, and thoroughly enjoying it.

Everything is given a practical turn so that the application of algebraical formulæ and geometry to concrete ends is a matter of natural daily routine.

It is very encouraging to watch these young lads using machine and hand tools in making useful articles from dimensioned drawings previously worked out in class, and to see their familiarity with various processes in steam, electricity, oil motors, chemistry, metallurgy, mining, plumbing, etc. One feels that here at any rate the foundations are being well and truly laid.

I confess to some hesitation in expressing my views on the education of apprentices because there are already so many views, quite sincerely held and expressed but biased according to the circumstances of the observers, that it is much easier to add to the general confusion than to reduce it.

There is much that is excellent in Mr. Wells' paper, but I would suggest that he is not well acquainted with present day primary schools and their methods—not that they are perfect by any means—but Mr. Wells' criticisms are out of date. I cannot, without unduly intruding on your space, deal with the paper in detail but should like to add that Mr. Wells has omitted to refer to a new type of school that should charm the heart of all engineers. I refer to the Junior Technical School, of which I shall again make mention before concluding. If he has not seen one I advise him to visit one at the earliest opportunity. There is, however, much truth in what is said

*See August issue, page 475.

about games. The fact is, school games are suffering from over-organisation and supervision.

Mr. Wells clearly under-estimates the work of technical schools and colleges. Perhaps he is unfamiliar with these institutions also, and in his section on University work, I notice that he is inclined to rule out all influence, even the good, that works requirements might have on the trend of research. There are not many who will go to such length as Mr. Wells.

In this matter of education of apprentices there are many important facts and circumstances to be borne in mind. A child, fortunately, does not at birth or in advanced infancy proclaim its future vocation. Early education must be of a general character, its aim being to develop mental alertness and to sharpen the senses—especially those of sight, hearing and touch. There are however, essentials required by all; a knowledge of the " mother tongue," two-fold in character—to understand it and to be able to express oneself in it; and the ability to compute. These are fundamental and are worth all the pains taken to acquire them. They set no easy task as the best of us will doubtless remember. And if the other subjects of the primary curriculum bear on these fundamentals as I believe is intended, there is not such a serious objection to them as Mr. Wells would have us think.

The vexed question is " When shall specialisation begin? " In attempting to answer this the critics of education overlook many factors, especially those critics who are interested in the particular industry. There are many occupations to follow, and many pupils and parents do not appreciate the requirements, mental and manual, of particular trades and professions. There is, for example, the common mistake that because a boy is fond of mechanical toys and wants to see the works he will make a good engineer. There is a lot of sifting to be done. Then again, important though it is to be able to earn one's livelihood, young people have, or should have, other interests in life. Education is a preparation for life in all its fulness, and any attempt to cramp it by too early specialisation will be detrimental to both apprentice and employer.

There is an aspect of the case however, that is worth some thought. Can engineering science be made a medium for a broad education? It has such a wonderful history, ranging as it does from the time of Aristotle and Archimedes, or even earlier throughout the ages, it is so entwined with human civilisation, so inseparable from mathematics, so rich in literature, so essential to progress, and with it are associated such outstanding personalities that the case seems already proved.

There is a type of Junior Technical School in existence working somewhat on these lines which seems eminently suitable for the pre-apprenticeship education of future engineers. In this school, although a day a week is devoted to workshop practice in wood and metal and great importance is attached to the applications of science, general education is by no means lost sight of. The age range is from 12 or 13 to 15 or 16 but might well begin at 11. It seems worthy of support and from the engineer's point of view looks ideal. At the age of 16 its pupils are ready to enter and to take full advantage of apprenticeship, but they should not be expected to be fully fledged engineers. Now the questions that are uppermost in my mind are "Are the engineering firms able and willing to give proper training to these youths?" "Do employers give these ex-pupils opportunity to apply their knowledge and ability?"

My experience suggests that the answers to these questions are in the negative. Is it not still the practice to leave apprentices to pick up what information and skill they can through haphazard chance of circumstances? Is there not a lamentable waste of time, energy and ability in this undirective treatment of apprentices? It is easy to be penny wise and pound foolish in this matter, and the temptation to exploit apprentice labour is very strong, indeed, in many cases irresistible. "Bench training" is an important part of an apprentice's education and should be considered as such.

The future of the nation depends so much on these young people that legislation may be necessary before apprenticeship is adequately provided for and regulated. Industrial firms may soon be called upon to decide whether they will make apprenticeship more directive and intensive or hand over the work to people qualified to undertake it. Continued school education during apprenticeship has much to commend it. Theory and practice should go hand in hand and much could be accomplished by closer co-operation between works and technical colleges; but why should Mr. Wells and your correspondents think only of school attendance in the evenings? Evening is the wrong end of the day for study, especially for people who have already done a day's work and are tired and sleepy. Have the works' authorities any obligations to apprentices to fulfil, do you think? Surely they can arrange, as is done in H.M. Dockyards, for their apprentices to spend two or three half-days a week at the local technical school. The firm that produces one great man does greater work than in turning out a hundred battleships and gigantic liners. It may do both. The technical schools and colleges are willing, and I believe, able to share in the training of apprentices, and master engineers could render valuable assistance to these educational institutions by showing active interest in their work and in seeing that they are well equipped for their purpose.

Heaven forbid that I should be unmindful of the benefits to be derived from the universities, but I am merely echoing the opinion of a prominent educationist at one time principal of a modern university and now master of one of the Oxford colleges, when I say that there is room for reform in university methods of teaching. I am convinced that the teaching in our technical schools is better than in many universities, not so much in the subject matter as in the method of presentation. A good many graduates leave the university with acute mental indigestion. Still, by all means let the best of our apprentices take a university course.

A. H. BELL, B.Sc.

In a written contribution to the discussion on Mr. Dorey's paper on "Tubes for High Pressure Water-Tube Boilers," see pages 893 *et seq.*,

Mr. J. R. G. MONYPENNY (Messrs. Brown, Bayley's Steel Works, Ltd., Sheffield) stated that the possible use, in the future, of steam temperatures over 950° F. raised the question of the strength of steels at such temperatures. Mr. Dorey had discussed this question in his extremely interesting and able paper, and indicated the deficiences of ordinary mild steel for superheater tubes working under such conditions. In suggesting possible alternatives, Mr. Dorey mentioned stainless irons and the austenitic nickel chromium steels, but his selection of "Enduro" metal, containing 0·09% carbon and 16·7% chromium, as typical of the former class was rather unfortunate. Material of this type was not only prone to develop a very undesirable degree of brittleness, as Mr. Dorey remarked, after prolonged heating at 1000° F., or thereabouts, but it was never also really tough after any form of heat-treatment. On the other hand, stainless irons containing 12/14% chromium were very tough and ductile, properties desirable in tube making material, and they were at least as strong as, probably stronger than, the higher chromium product at high steam temperatures. They also possessed adequate resistance to the attack of furnace gases and superheated steam. It was unfortunate, therefore, that Mr. Dorey did not mention stainless irons of this type; to many people, including the writer, they appeared at present to be the most promising form of material for tubes for high temperature steam.

The austenitic chromium-nickel alloys undoubtedly possessed higher creep stress values at high steam temperatures, but they suffered from the defect that, on being heated at such temperatures, their previously completely austenitic structure was not stable. A precipitation of carbide occurred between the austenite grains and there was evidence to show (as Mr. Dorey mentioned) that the membranes of carbide so formed might lead to sudden intercrystalline breakdown of the material. It might be also mentioned that additions of such metals as tungsten, titanium, and vanadium to these austenitic steels were of little, if any value, in preventing this intergranular weakness in material, such as a superheater tube, which was continuously exposed at 500° C. or 600° C. Additions of these metals might retard somewhat the first appearance of a carbide membrane, and thereby make certain heat treatment operations more easily carried out or more effective in their results, but this was of doubtful value in material employed under such conditions that there was ample time for carbide precipitation (with its accompanying liability for inter-granular weakness) to take place in any of these steels.

The austenitic steels had also the further disadvantage that their coefficient of expansion was some 50% greater than that of ordinary steel; this difference in expansion would undoubtedly cause trouble at points where the austenitic steel was connected up to mild steel. On the other hand, the stainless irons expanded at very nearly the same rate as mild steel.

In Fig. 16A Mr. Dorey gave some interesting comparisons between the creep strength of mild steel and of a lightly alloyed steel. The only point the writer would raise with regard to this diagram was that the stress values which were plotted referred to a relatively fast rate of creep. A value for extension of 0·001% per hour gave an illusive suggestion of minuteness which was, however, dispelled when translated into the corresponding figure of 8·7% per annum! The data recently published by Mr. Baumann (Engineering, November 11th, 1930, page 518) showed that when the rate of creep was reduced to figures, *e.g.*, 10^{-6} or 10^{-7} per hour, which gave a reasonable life for parts subjected to high temperatures, the permissible stress was reduced by about half.

In reply to the foregoing remarks, Mr. Dorey stated that Mr. Monypenny had confirmed the doubtful value of the nickel-chromium-tungsten steels at temperatures in excess of 932° F. (500° C.) and further emphasized the difficulty that would arise owing to the coefficient of expansion of these steels being appreciably greater than that of mild steel. In regard to his remarks on Fig. 16A it was appreciated that the creep rates were greater than could be considered satisfactory for use in any installation, but it did give some indication of the behaviour of "Era 131" steel compared with mild steel.

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ABSTRACT.

WASTE HEAT IN MOTORSHIPS. VARIOUS SYSTEMS FOR ITS RECOVERY.

"Journal of Commerce," 27th Nov., 1930.

No side of motorship technique has made greater progress during the past few years than has waste heat recovery. Not very long ago the provision of an exhaust gas boiler on a motorship was something of a novelty; to-day it is commonplace on four-stroke-cycle-engined ships, and it is making progress in the two-stroke world. The economies and technique of the subject have frequently been referred to in our motorshipping columns; they were admirably summed up in an interesting lantern lecture delivered by Mr. E. R. Hall before the Junior Section of the Institute of Marine Engineers.

The lecture was more than a descriptive survey of the marine waste heat boiler field, for its author offered a considerable amount of thoughtful comment on the various boiler designs that are available at the present time. Mr. Hall divided his lecture into two sections, dealing first with fire-tube boilers, and then with those, such as the Clarkson and Deutsche Werft, of the water-tube type. In the fire-tube boiler category he dealt with such designs as the Caledonia (horizontal and vertical types); the various designs of the Fried Krupp Germaniawerft, Kiel; the Ruston and Hornsby design; the Recovery boiler of Messrs. Daniel Adamson; the Cochran composite and full waste heat boilers; and the Spencer Bonecourt designs.

Two water-tube type waste heat boilers were discussed by Mr. Hall—namely, the Deutsche Werft Turbulo and the Clarkson types. The list is a comprehensive one which obviously must make an instructive study for all concerned with waste heat recovery at sea. A criticism that might be raised is that certain of the boilers dealt with have not yet been used at sea. In discussing the vertical boiler Mr. Hall pointed out that the water-level is in way of the tubes, a feature which he considered to be undesirable, because wasting is almost certain to occur at the water-level; the cleaning of the tubes of this boiler was also considered to be difficult.

A good point of the Krupp waste heat boiler designs is the manner in which the exhaust gas inlet branch is set so as to produce a strong turbulent whirling of the gases. Such an arrangement will doubtless assist heat transfer by promoting the very desirable scrubbing action on the heating surface which is essential to efficient heat transference. A very high proportion of the resistance to heat transfer across a tube is due to the relatively cold film of gas that adheres to the walls of the tube. A scrubbing action breaks down this film of inert gas, and this action is best accomplished by making the gases travel at right-angles to the heating surface.

It is worthy of note that this condition is satisfied in the well-known and successful waste heat boiler, the Clarkson, which has obviously been designed with very careful regard to the question of maximum attainable heat recovery from the exhaust gases.

A considerable amount of information was contained in the paper on different types of Clarkson boiler, including the duplex.

The ingenious Deutsche Werft Turbulo boiler, which combines a spark arrestor, was favourably commented upon by Mr. Hall. This is a water-tube boiler, and the entering gases are given a strong whirling motion, and are also cleaned by simple means. In this boiler also the gases impinge on the water-tubes at approximately right-angles, while a straightforward type of circulation is fitted to the boiler.

The paper concluded with some figures relating to the economics of waste heat recovery, and the author also discussed the questions of weight, ease of cleaning of the heating surfaces, facilities for ready inspection, and other points. A discussion followed the reading of the paper, which was an excellent one for the junior members of such a body as the Institute of Marine Engineers, combining as it did practical and theoretical matters.

*We are not aware whether these papers by junior members are to find their way into the Transactions—their reading is an innovation—but it would be an excellent form of encouragement to young members of the body if this were done. If the standard of Mr. Hall's paper is maintained, they definitely could be printed in the Proceedings as really useful contributions to technical literature.

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INSTITUTE NOTES.

JUNIOR SECTION.

Lecture: Waste Heat Recovery.

On Thursday, November 13th, a lecture was delivered at the Institute by Mr. E. R. Hall, B.Sc., Graduate, on "Waste Heat Recovery." The lecturer, who is associated with a well known firm specialising in this subject, presented a comprehensive survey of the various British and Continental systems of exhaust heat recovery which have proved commercially successful. His description was enhanced by numerous lantern slides, and at the conclusion of the lecture and discussion, the audience expressed their unanimous appreciation of the extremely lucid and concise manner in which Mr. Hall had treated his subject. The paper has since been approved by the Papers Committee for publication in the Transactions, and will appear in one of our issues next summer owing to

* See report below.

immediate pressure on our space. Meanwhile, a synopsis of the paper which appeared in the technical Press is reprinted on page 947.

The Committee desire to record their gratitude to Mr. George Adams, Vice-President, who very kindly occupied the Chair on this occasion and contributed some valuable remarks during the discussion, based on his first-hand knowledge of exhaust gas boilers as fitted in a number of ships of his Company.

Visit to the R.M.S. "Rangitiki."

On the afternoon of Sunday, November 16th, a party of 40 juniors visited the R.M.S. *Rangitiki* in the Royal Albert Dock, by courtesy of the New Zealand Shipping Co., Ltd. They were met and conducted over the vessel by Mr. Roberts, Assistant Superintendent Engineer, and Mr. Scott, the Fourth Engineer of the ship. The *Rangitiki* is one of the latest of the Company's high class motor ships, and is equipped with Sulzer engines of the most modern type. The party were given a thoroughly instructive description of the whole of the main and auxiliary machinery from the operating engineer's point of view, and as an additional privilege were shown over the luxurious passenger accommodation for which the *Rangitiki* and her sister ships are already famous. One feature which was specially noted and favourably commented upon by the visitors was the accommodation provided for the engineers, to which particular attention had evidently been given by the designers, presumably at the instance of the owners. Very hearty thanks were accorded to Messrs. Roberts and Scott on leaving, and subsequently by letter to the Company through Mr. A. H. Parker, the Superintendent Engineer, who had been personally instrumental in arranging the visit.

Visit to the Propeller Works of Messrs. J. Stone and Co., Ltd., Charlton.

We recorded in our October issue, on page 735, following the delivery of his lecture on "The Manufacture of Propellers," a kind offer on behalf of his Company by Mr. Wesley Lambert to arrange for a party of juniors to visit Messrs. Stone's Propeller Works at Charlton at an early date. The Committee having gratefully accepted this offer, the visit took place on the morning of Saturday, December 6th. The visitors were drawn from the leading ship-repairing firms on the Thames and several shipping companies who train their own apprentices, and it is felt that without exception they will have obtained through this visit information and knowledge of lasting value in their subsequent seagoing careers. We are indebted to Mr. Clavy, the Works Manager, and Messrs. Burgis and Hart, who received the party and conducted the tour of the Works, including the foundry, machine and finishing shops. To those familiar with the usual type of non-ferrous foundry attached to a general engineering works, the ordered arrangement and efficient working of Messrs. Stone's foundry and associated shops was a revelation. This is due to some extent, of course, to the fact that the foundry and works are engaged solely in the manufacture of bronze propellers of the highest class, for which the firm are famous, and the consistently high standard of their products was clearly evident in every department of their Works.

On leaving, the visitors expressed enthusiastic appreciation of all they had been shown, and the thanks of the Committee were subsequently conveyed to the Company.

BOOKS ADDED TO THE LIBRARY.

Purchased.

"Refrigeration Memoranda," by John Levey. 1930 edition. Price 5/- post free.

Presented by the Publishers.

"City Noise," published by the Noise Abatement Commission, Department of Health, City of New York, U.S.A., 1930.

This publication is a report of the Commission appointed by Dr. Shirley W. Wynne, Commissioner of Health, to study noise in New York City and to develop means of abating it. The present reviewer, writing from the heart of the City of London as one of the thousands of victims of the gowing curse of noise from street traffic, marvels at the apparent indifference of organised scientific bodies to such an obviously detrimental factor in our present day civilisation. Apart from intermittent articles in the popular Press, written by a few public spirited neurologists and medical authorities, no serious consideration of the problem appears to have been organised in this country, though we understand that the Institute of Industrial Psychology is giving the matter some attention in connection with the lowering of the efficiency of factory workers who are subject to excessive noise.

Consequently we accord generous acknowledgment and appreciation of the research carried out by a most widely representative commission regarding the noise problem of New York, whose findings constitute the report under review. If its value is in any way marred for British readers, it is due to the characteristic American style of presentation and wording, which is of the "popular" type, rather than the soberly technical to which we are more accustomed. This method of presentation may have been consciously intended in view of the interest which the subject should have for the public in general. When, as we hope, a similar co-ordinated study of the London noise problem is initiated the account of the American experiments described in this report will undoubtedly be closely considered and utilised. It must be admitted that most city noise is the indirect product of the activities of the engineer, and he must reasonably be called upon to take a responsible share in the efforts towards its abatement.—B.C.C.

"Diesel Engine Operation, Maintenance and Repair," by Charles H. Bushnell. Published by Chapman and Hall, Ltd., 1930. Price 17/6.

This book can be highly recommended to those mainly concerned with the practical operation and upkeep of oil engines, the later section comprising a most thorough treatment of the practical side of the author's subject. In this respect the book excels the majority of text books on oil engines, and should induce every seagoing motor engineer to add it to his library. Those who do so will make allowance for the essentially American point of view of the author, as it is based almost entirely on his personal experience; the phraseology employed is also characteristically American. In the practical sphere the book will be welcomed as a distinctly fresh and valuable treatment of its subject.—B.C.C.

"The Bolinder Book." Stockholm: J. and C. G. Bolinder Mekaniska Verkstads A.-G. $8\frac{3}{4}$ in. x $5\frac{1}{2}$ in. 180 pages. Price 21/- net.

The Transactions of the Institute have from time to time contained papers of absorbing interest dealing with the development of a particular design of heavy-oil engine. We can recall to mind, for instance, the excellent paper on the

Sulzer engine which Mr. Le Mesurier presented a few years ago, and the equally informative paper of Baron G. Steinheil on the Nobel engine. The book under review is an excellent attempt to give technical men interested in the historical side of oil engines something similar to the two papers referred to.

The Bolinder engine is, of course, a much smaller unit than the majority of Sulzer or Nobel engines, and it might be thought for that reason that a study of it would be less interesting and less informative than either of the papers mentioned. We have found its study of very great interest, however, and the illustrations are quite good.

The price asked for the book is high for a publication of this character, but as the volume is of rather a special type it can be considered worth the twenty-one shillings.— G.R.H.

"Questions and Answers on the Construction and Operation of Diesel and other Internal Combustion Engines," by John Lamb. London: Charles Griffin and Co., Ltd., 42, Drury Lane, W.C.2. $6\frac{1}{2}$ in. x $4\frac{3}{8}$ in. 340 pages. Price 10/- net.

As one of the oil engine experts of a well-known firm of tanker owners who operate a considerable number of motorships, Mr. Lamb is, of course, well qualified to produce a book such as the one under review. As might be expected from the title of the work, it is primarily intended as a guide to engineers studying for their Board of Trade certificate and endorsement. Bearing in mind the requirements of this class of reader, the book has wisely been made of handy pocket size, and of reasonable price; it is, moreover, written in straightforward language and is technically sound. It is thoroughly up-to-date, such features as supercharging, airless injection, double-acting engines, etc., being dealt with.

This is the third edition of the book, which has been carefully revised where necessary. It might be considered that the absence of illustrations would cramp the author's style and make the volume less useful than might otherwise be the case. For a book of the "questions and answers" type, however, illustrations are not really necessary, and in the reviewer's opinion the book does not suffer by their absence.

For the money we know of no better book for the junior motorship engineer than this excellent little *multum in parvo*. —G.R.H.

"British Railways—The Romance of their Achievement," by G. Gibbard Jackson. Published by Sampson Low, Marston and Co., Ltd. Price 6/- net. 244 pages. Numerous illustrations.

This volume is not exactly a romance of the iron road, but a technical history of our railway systems from their birth to the present day perfection, written in such a delightful manner that the reading thereof will appeal not only to the layman but also to the engineer. From before Stephenson's day to the present modern express locomotive the Author takes us step by step through the whole system of railway running, which includes every type of locomotive rolling stock and signalling.— A.J.

"Triumphs and Wonders of Modern Engineering," by G. Gibbard Jackson. Published by Sampson Low, Marston and Co., Ltd. Price 6/- net. 246 pages. Numerous illustrations.

If anything this book is more interesting than its companion volume previously mentioned. The Author is certainly not lacking in general engineering knowledge, for in this volume he gives us an account of the most interesting civil engineering as well as mechanical feats that have been executed since the first iron bridge was built over 150 years ago, which is still to be seen spanning the River Severn, although it was always my impression that the first iron bridge was that built by Stephenson, which until recently spanned the River Wear at Sunderland.

In this volume the Author is more versatile in that he includes what he calls mechanical marvels, which are nowadays without count. At the present rate of progress the Author, in the near future, may have greater scope for his pen.—A.J.

"Handbook on Nickel-Copper Alloy Condenser Tubes." Published by the Mond Nickel Co., Ltd., Imperial Chemical House, London, S.W.1.

As is well known, the Mond Nickel Company have recently devoted considerable attention to the question of condenser tube materials, and the present handbook deals with copper-nickel alloy tubes for this purpose. It presents in a condensed form the results of the Company's investigations and experiments on the difficult problem of condenser tube corrosion. The rather confident claim of the Company that the nature of the problem has now been fully appreciated and its solution found may be open to question, but it must be conceded that they have clearly and scientifically stated the aspects of the problem as affecting the marine engineer. Data obtained from the experimental use of nickel-copper alloys is presented in this handbook under the authority of several well known leading metallurgists and technical experts. We commend the book to the large number of our members who are directly concerned with the problems associated with modern condenser tubes.— B.C.C.

"Molybdenum in Steel and Iron." Published by High Speed Steel Alloys, Ltd., Widnes, Lancs. 37 pages.

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ELECTION OF MEMBERS.

List of those elected at Council meeting held on Monday, 1st December, 1930:—

Members.

James Linsdal Coates, 69, Ross Road, Wallington, Surrey.

Frederick Randolph Cecil Cookson, Engineers' Department, L.N.E.R. Dock Office, City Square, Hull.

Edgar George de la Mare, 49, Malvern Terrace, Brynmill, Swansea.

John Alexander Hamilton Heron, 10, Hollybank Road, Birkenhead.

William Cornelius Laws, 23, Battersea Park Road, S.W.8.

Windsor Colin McKenzie, 37, Greenheyes Drive, Snaresbrook, Essex.

William Nairn, Socony House, Cocanada, Madras Presidency.

Henry William Norman, 55, Inkerman Road, Woolston, Hants.

Arthur Hurle Robertson, 148, Beehive Lane, Ilford, Essex.

James Herbert Todd, 109, Maple Street, Brooklyn, N.Y.

Joseph Wilson, 11, Pitcairn Street, Dunfermline.

Robert Carss Youngs, Park House, Bromyard, Herefordshire.

Alfred Stockley, 15, Astor Avenue, Romford, Essex.

Companion.

Charles Edward Lee, 36, Keston Road, East Dulwich, S.E.15.

Associate Members.

Brinley Daniel Davies, 6, St. Peter Street, Carmarthen.

Alexander Stratton Imrie Donaldson, 2, Glenagnes Road, Dundee, Scotland.

Robert Campbell Thorne, 45, Khedive Road, Forest Gate, E.7.

James Malcolm Whitton, 30, Shandon Place, Edinburgh.

William Richard Woodman, Resident Chief Engineer, Ty-Bryn Institution, Tredegar, Mon.

Associates.

William Henry Horsfall, 55, Dundee Street, Hull.

Arthur Maude, Selby House, Elton Avenue, Alma Park, Levenshulme, Manchester.

Graduates.

Charles Richard Tomkins, 23, Woodhouse Road, Leytonstone, E.11.

George Alexander Wood, 6, Taylor Gardens, Leith, Scotland.

Transfered from Associate Member to Member.

Harry Marshall, Glenfield, Maidstone Road, Rochester.

Transferred from Associate to Member.

W. H. M. Parsons, Radford, Enstone, Oxford.

Transferred from Associate to Associate Member.

Arthur Eric Woodward, BM/WX34, London, W.C.1.

Transferred from Graduate to Associate.

John Taylor McIntyre, Burnside, Burlington Avenue, Slough.

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BOARD OF TRADE EXAMINATIONS.

List of Candidates who are reported as having passed examination for certificates of competency as Sea-going Engineers under the provisions of the Merchant Shipping Acts.

For week ended 8th November, 1930:—

NAME.	GRADE.	PORT OF EXAMINATION.
Inman, Frederick E.	1.C.	Sunderland
Wilson, Stanley	1.C.	,,
Robson, John	2.C.	Newcastle
Harrison, James W.	2.C.M.	,,
McCarraher, Alan J.	1.C.	London
Raine, William C.	1.C.M.E.	Sunderland
Cox, Albert T.	1.C.M.E.	London
Murdoch, Alexander	1.C.M.E.	Newcastle
Falvey, Charles L. G.	1.C.M.E.	London
Harvey, William S.	1.C.M.E.	,,
Minnis, Frederick C.	1.C.M.E.	,,
Webb, William S.	1.C.M.E.	Newcastle
Willens, Alexander T.	1.C.M.E.	London
Fairlem, George H.	1.C.M.E.	Liverpool
McFadzean, Hugh	1.C.M.E.	Glasgow
Ritchie, Herbert C.	2.C.M.E.	Liverpool
Grainger, Henry W.	1.C.	,,
Morris, William	1.C.	,,
Taylor, Herbert	1.C.	,,
Wilson, William N.	2.C.	,,
Shearer, Robert J.	1.C.M.	,,
Crawford, George	1.C.	Glasgow
Pattullo, Frank	1.C.	,,
Croucher, Alfred H.	2.C.	,,
Hornall, William	2.C.	,,
Cochrane, Alexander S. ...	1.C.M.	,,
Adams, Charles H.	1.C.	Hull
Buchanan, Robert G.	1.C.	,,
Graham, William	1.C.	,,
Rider, James G.	1.C.	,,
Ward, Walter E.	1.C.	,,
Waites, John H.	2.C.	,,
Wilson, George S.	2.C.	,,
Fieldhouse, Norman	2.C.M.E.	Glasgow
Green, John R.	1.C.M.E.	Newcastle

For week ended 15th November, 1930:—

Appleton, Eric T.	Ex.1.C.	Liverpool
Bullock, Samuel	Ex.1.C.	,,
Duff, Alexander	Ex.1.C.	,,
Evans, James C.	1.C.	Cardiff
Sayer, James M.	1.C.	,,
Spear, Philip L.	2.C.M.	,,
Scott, David H.	1.C.	Glasgow
Atkins, Robert G.	2.C.	,,
Roger, James S.	2.C.	,,
Somerville, John L.	2.C.	,,
Walker, Robert M.	2.C.	,,
Kerr, Colin F.	2.C.M.	,,

For week ended 15th November. 1930—*continued.*

NAME.	GRADE.	PORT OF EXAMINATION.
Harmer, Frank R.	2.C.	London
Clark, Aubrey P.	1.C.	Newcastle
Ellis, George R.	2.C.	,,
Bishop, Adrian J.	1.C.	Southampton
Coulthard, Hugh	1.C.	Liverpool
Dykes, Francis P.	1.C.	,,
Moore, William H.	1.C.	,,
Pringle, Robert C.	1.C.	,,
Salter, William J.	1.C.	,,
Wilson, Harold	1.C.	,,
Meredith, James H.	2.C.	,,
Wigglesworth, George	2.C.	,,
Sayle, John H. De N.	1.C.M.E.	,,
Brandie, William	1.C.	Leith
Kirkwood, Alexander V. ...	1.C.	,,
McPherson, Hugh	1.C.	,,
Muirhead, Andrew B.	1.C.	,,
Anderson, James B.	2.C.	,,
Duncan, Samuel G.	2.C.M.	,,
Triolo, Ethelbald W.	1.C.M.E.	London
Christian, Alexander A. ...	1.C.M.E.	,,
Macdonald, John E. C.	1.C.M.E.	,,
Bollons, Thomas T.	1.C.M.E.	Newcastle
Kipling, Arthur	1.C.M.E.	Cardiff

For week ended 22nd November, 1930:—

Simpson, Thomas E.	1.C.	Newcastle
Forster, Francis R.	2.C.	,,
Taylor, Henderson K.	2.C.	,,
Heron, William C.	2.C.M.	,,
Laws, Walter	2.C.M.	,,
Beech, Harold S.	1.C.	Sunderland
Waugh, Harold	1.C.	,,
Wilson, Oliver	1.C.	,,
Wilson, Allan	2.C.	,,
McDonald, Hector	2.C.M.	,,
Hutchinson, William	1.C.M.E.	,,
Jackson, Charles T.	2.C.	Glasgow
Phillips, Andrew	1.C.M.	,,
Cunningham, James B. ...	2.C.E.	,,
Wallace, William C.	1.C.M.E.	,,
Richardson, Leslie W.	1.C.	Liverpool
Jones, Herbert V.	1.C.	,,
Kempsey, William	1.C.	,,
Greenwood, Leslie	2.C.	,,
Cook, David	1.C.M.	,,
Edwards, Griffith	2.C.M.	,,
Taylor, Robert	2.C.M.E.	,,
McKnight, William J.	1.C.	London
Spray, James	1.C.	,,
Thomson, Alexander	1.C.	,,
Grant, Donald S.	2.C.	,,
Hayman, Thomas P.	2.C.	,,
Hind, Henry G. S.	2.C.	,,
Wadham, Rolla M.	2.C.M.	,,