A REVIEW OF RIPPLED MAGNETITE

DEPOSITS IN SUPERCRITICAL

ONCE-THROUGH BOILERS

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ABSTRACT

Rippled magnetite deposits occur in some supercritical once-through boilers and give rise to excessive pressure drop increases. For example, in 10,000 hours the pressure drop across the evaporator of a typical boiler increased by 70 percent. Heat transfer is impaired when the build-up of corrosion products exceeds 100 g/m . Average spacing and height of ripples are in the range 180-350 μm and 20-40 μm, respectively.

Rippled deposits are only formed when the fluid bulk velocity exceeds about 2 m/s. Heat flux increases the formation of corrosion product deposits but has no effect on ripple geometry. Ripple spacing decreases with velocity and the ripple spacing/height ratio decreases with tube diameter, at constant mass flux conditions. Corrosion product deposits consist of two distinct layers and their build-up follows the logarithmic time law.

A mechanism for the formation of rippled deposits is suggested.

CONTENTS

NOMENCLATURE

d	Tube diameter (mm)
e	Ripple height (μm)
f	Friction factor $(= \tau w / \frac{1}{2}\rho u)$
$\dfrac{\Delta p}{\Delta p_o}$	Relative pressure drop
r	Tube radius (mm)
Re	Reynolds number
t	Time (h)
u	Fluid bulk velocity (m/s)
w	Amount of deposit (g/m^2)
w*	Amount of deposit at asymptetic conditions (g/m^2)
x	Ripple spacing (μm)
λ	Ripple ratio (= x/e)
φ	Friction function
τ	Time constant (h)
τ_w	Shear stress at wall ($^N/_{m^2}$)

1. INTRODUCTION

The corrosion of boilers may lead to changes in their heat transfer and pressure drop characteristics. These changes are ususally detrimental to the operation of the boilers and invariably result in shut-down and chemical cleaning. In most cases boiler corrosion has to be lived with.

Experience with some supercritical once-through boilers has shown that unacceptably high pressure drop increases occur in the evaporators such that frequent chemical cleaning is required. Observations of tubes removed from these boilers have shown that transversely rippled corrosion products on the walls are responsible for these increases. An understanding of how these rippled surfaces are formed should be useful in an attempt to reduce the problem.

Schoch (1) was the first to report excessive pressure drop increases in a supercritical once-through boiler. Subsequent papers by Schoch et al (2,3,4,7), Schuster (5), Richter et al (6) and Köhle and Richter (8) report on the problem in more detail. Haller et al (9,10) have also reported on rippled surfaces in supercritical once-through boilers. Foster and Garnsey (11) and Garnsey et al (12) have discussed the above work and presented some experimental results.

2. DESCRIPTION

The phenomena of rippled surfaces of corrosion products has only been observed in evaporator tubes carrying water in the liquid phase. In economiser tubes and tubes carrying steam all corrosion products films are evenly distributed with no evidence of ripples. Since the rippled structure in responsible for the excessive increases in pressure drop the nature of these films and of the variables giving rise to them will be considered.

2.1 Structure

All corrosion product films in supercritical once-through boilers are in two layers. The inner layer corresponds to the thickness of the tube material that has corroded. The layer is dense and protects the tube metal from rapid corrosion. The outer layer is more porous and is rippled in evaporator tubes carrying liquid water (1-13).

The inner layer is 5-15 μm thick (6,9). The magnetite crystals are 0.1 - 0.2 μm (5,6) and the pore sizes are < 0.01 μm (6). The crystals in the outer layer, where the surface is rippled, consist of coarse single crystals some of which are considerably rounded. The area between the ripples consists of fine crystals, closely adjacent to each other, and evidently flattened. On the up-stream side of the transverse ripples the crystals were strongly eroded while on the down-stream side the crystals were better formed and decreased in size from the crest to the flat area (4,5,6). Where suspended corrosion products deposited the particles were incorporated in the outer magnetite layer (5).

Haller et al (9,10) observed that the structure of the corrosion product films was transversely rippled. Schock et al (3,4) and

Richter et al (6) stated, however, that the structure ranged from a transversely rippled form to a crater-like form where the transverse ripples were connected by longitudinal ripples. Schuster (5) stated that the crater-like structure was more likely at high Reynolds numbers.

The average spacing between transverse ripples has been reported as 200-350 µm (4), and 180-300 µm (6), with the respective ripple heights 25-40 µm and 20-40 µm. Several measurements of ripple spacing x and height e are given in Table 1 where the ripple ratio $\lambda = x/e$, and tube diameter are also given.

TABLE 1

Ripple ratio at different tube diameters

Distance Between Ripples x	Ripple Height e	Ripple Ratio $\lambda = x/e$	Tube Diameter d	Reference
µm	µm		mm	
450	90	5	148	4
350	45	7.8	38	12
201	16.5	12.2	16.8	10
193	14.2	13.6	15.7	10

2.2 Variables

The main variables reported as affecting the amount and structure of two-layered films are heat flux and flow velocity. Schoch

et al (4) and Richter et al (6) observed that a variation in circumferential heat flux had no measurable effect on the amount of corrosion products formed.

Schuster (5) observed that heat flux only increased the amount of material on evaporator tubes when deposition of suspended solids contributed to the build-up of corrosion products on the wall. On a typical evaporator tube the amount of corrosion products on the fired side could be 50% greater than on the unfired side. The cross-section of the ripples was also wider on the fired side.

Haller et al (9,10) reported that the amount of corrosion products removed from evaporator tubes by pickling depended on the local heat flux. The amount of corrosion products on the fired side of evaporator tubes could be 2-3 times greater than on the unfired side. The amount of corrosion products determined by Haller et al (10) after 18 months of operation ranged from 13-312 g/m^2.

An important conclusion reached by Schoch et al (3,4) and Richter et al (6) was that both the inner and outer magnetite layers grow with time and contain equal amounts of corrosion products. The reason for this was that magnetite has about twice the volume of the iron from which it is formed. Haller et al (9) stated, however, that the thickness of the inner layer was independent of the fluid conditions, heat flux and time.

Heat flux has no apparent effect on the surface structure of the rippled magnetite films (4,6,9,10).

While rippled surfaces are only formed in evaporator tubes carrying liquid water, the fluid velocity must also be greater than 1.6-2.9 m/s (4,5) or 1.6-2.0 m/s (6). There appears to be

to be a critical fluid velocity of $\sim$ 2 m/s that must be reached before ripples are formed. This observation has been supported by data presented by Foster and Garnsey (11).

Schoch et al (4) reported that changing the fluid velocity from 2.5 m/s to 8.6 m/s the ripple spacing descreased from 310 μm to 190 μm, respectively. The ripple spacing x was considered inversely proportional to the fluid velocity. An increase in tube diameter at a constant fluid velocity was observed to decrease the ripple ratio λ. For a 145 mm ID tube Schoch et al (4) measured x = 450 μm and e = 90 μm at the flow velocity of 6.6 m/s, while Garnsey et al (12) measured x = 350 μm and e = 45 μm at a flow velocity of 6.75 m/s.

Schoch et al (4) reported that a reduction in flow velocity from 6.3 m/s to 3.6 m/s changed the surface of the corossion products from a crater structure to a more transversely rippled structure. Schuster (5) also stated that a decrease in Reynolds number changed the structure from crater form to a pattern of transverse ripples.

3. CONSEQUENCES

The formation of corrosion products in boiler tubes may change the heat transfer and pressure drop characteristics. The corrosion film presents an added heat transfer resistance while the greater surface roughness increases the pressure drop and enhances the convective heat transfer. It is well known that repeated-rib roughness enhances heat transfer. The overall effect on heat transfer is therefore made up on two competing factors. When the heat transfer performance of a boiler tube is reduced the metal temperature may rise and lead to tube failure.

3.1 Pressure Drop

Schock et al (3) noted that during the first 11,500 hours of operation of a supercritical once-through boiler the pressure drop across the economiser and evaporator had increased by 55%. Following acid cleaning the pressure drop across the whole boiler increased by 18% in 2200 hours while the evaporator pressure drop increased by 54%. More typically the pressure drop across the evaporator increased by about 70% in 10,000 hours (6). At clean conditions the evaporator contributes 33% of the boiler total pressure drop. The pressure drop increases were therefore almost exclusively due to the high increases in the evaporator. It was estimated that the reduction in flow area due to corrosion product formation could only be responsible for < 1% of the increased pressure drop (6). In the first 6 years of operation a supercritical once-through boiler had to be chemically cleaned every 18 months to restore the pressure drop to acceptable levels (8).

Richter et al (6) measured the friction factor of individual boiler tubes over a period of 3200 hours. The friction factor of evaporator tubes with different initial surface conditions

all tended to the same value of $f = 6.25 \cdot 10^{-3}$ (Fanning friction factor) at Re $\sim 1.6 \cdot 10^6$. A typical evaporator tube (34.5 mm ID and e $\sim$ 25 µm) was removed after 3550 hours and the friction factor at different Reynolds numbers determined. At Re $\sim 1 \cdot 10^6$ the friction factor of a rippled tube was 77% higher than a commercial tube and 43% higher than expected from sand grain roughness.

Haller et al (9,10) give no pressure drop data on boilers, but present friction factor measurements on a typical evaporator tube. The tube was 15.7 mm ID, x = 193 µm, e = 14.2 µm with 55 g/m^2 of magnetite on the fired side and 15 g/m^2 on the unfired side after 18 months of operation. At Re $\sim 1 \cdot 10^6$ the friction factor exceeded that of a clean commercial tube by about 75%. Haller et al also measured friction factors in 8 tubes with in-service generated films. There were able to correlate the friction factor data to the friction similarity function (19).

$$\phi \quad \sqrt{\frac{2}{f}} + 2.5 \ln \left(\frac{e}{r}\right) + 3.75 \qquad (1)$$

where ¢ = 8.5 as for sand grain roughness but e the ripple height was taken as 4e. When 4e has been substituted into Equation (1) with ϕ = 8.5 it can be re-arranged such that the factor 4 is taken outside the natural logarithm and the friction function becomes $\phi \sim 5$.

They found that there was an average deviation of 6% and maximum deviation of 10% between the measured and predicted friction factors.

Foster and Garnsey (11) have given the relative pressure drop increases across the economiser and evaporator in seven subcritical boilers following chemical cleaning. Figure 1 shows that the data follows an asymptotic curve with values slightly lower than those mentioned above. Foster and Garnsey (11)

suggested that the problem of rippled corrosion product surfaces might also be present in subcritical boilers, although this had not been reported.

Garnsey et al (12) assumed that the corrosion product films in supercritical once-through boilers formed according to the parabolic time law. Using the ripple height e = 45 μm in a typical evaporator tube removed after 6199 hours of operation they derived:

$$e = 2.45\sqrt{t} \qquad\qquad (2)$$

where time t is in hours and e in μm. The time dependent ripple height was then used in the friction similarity function to calculate the minimum pressure drop expected across the evaporator.

3.2   Heat transfer and wall temperature

Haller et al (9,10) removed four tubes from a supercritical once-through boiler after 18 months of operation and performed heat transfer tests simulating boiler conditions. In one of the tubes with deposits of 13-66 g/m^2 no impairment of heat transfer was observed. In fact, higher heat transfer coefficients were measured than in a clean commercial tube. Haller et al (9,10) concluded from their studies that corrosion films with rippled surfaces and moderate weights of magnetite 50-100 g/m^2 shown no impairment of heat transfer. When w > 100 g/m^2 heat transfer is, however, impaired under any operating conditions.

Schuster (5) has stated that after 10 months of operation of a supercritical once through boiler no increases in tube wall temperature in the evaporator could be detected. The weight of magnetite after 10 months was about 88 g/m^2 (8) which is

below the limit of 100 g/m^2 set above for the impairment of heat transfer. Since tube wall temperature increases when the heat transfer has been impaired the above observations (5,9,10) agree. Schuster (5) states that in supercritical boilers heat transfer is improved by rippled magnetite and in subcritical boilers the departure from nucleate boiling is moved to a higher steam quality so that the danger of burn-out is reduced. Heitmann and Thomas (13) studied the influence of corrosion products on tube wall temperatures in once-through boilers.

4. GROWTH WITH TIME

Schoch et al (4) and Richter et al (6) removed several evaporator
tubes from a supercritical once-through boiler at different times
and location and determined by pickling the amount of corrosion.
They found that new tubes had greater corrosion (twice as much
in 600 hours) than tubes that had been chemically cleaned several
times. By assuming that the growth of magnetite in the
evaporator followed the logarithmic time law they derived the
expression:

$$w = 25 \ln (1 + 0.01 t) \qquad\qquad (3)$$

where $w (g/m^2)$ is the amount of corrosion products formed per
unit area and t is the time in hours. Data for new tubes was
excluded from the derivation. The expression is valid for
service periods not exceeding 18 months.

Köhle and Richter (8) have extended the above reported data
up to service periods of about 60,000 hours, though no expression
is given. However, if the build-up of corrosion products is
assumed to be asymptotic it may be represented by:

$$w = w^* |1 - \exp(-t/\tau)| \qquad\qquad (4)$$

where w^* is the asymptotic value and τ the time constant. The
values for w^* and τ found most suitable were 190 (g/m^2) and
12,000 (h), respectively.

5. CORROSION PRODUCTS

The magnetite found in boiler tubes may originate from processes
other than local corrosion. Boiler waters usually contain both
dissolved and suspended products originating elsewhere in the
boiler. These products are transported to the wall by inertial,
turbulent and molecular diffusion. The dissolved species are
converted to solid products at the wall while the suspended
solids deposit due to adsorption. The adhesion of particles
to tube walls is probably firmer when crystallisation occurs
simultaneously.

5.1 Origin

A characteristic feature of supercritical once-through boilers
is the high purity water used in them. This applies both to
dissolved species and suspended solids.

Schoch et al (2,4) and Richter et al (6) have reported that the
dissolved iron content of water in the economiser and evaporator
was about 10 ppb during normal operation. The total dissolved
solids entering the boiler was less than 12 ppb, falling to
less than 4 ppb in passing through the evaporator. At start-up
the dissolved iron content of the water never exceeded 10 ppb
and that of the suspended solids was never greater than 50 ppb.
Haller et al (9) measured 7.1 ppb of suspended solids entering
the economiser of which 3.1 ppb was iron. On passing through
the boiler the concentration of the suspended solids decreased
considerably.

Schoch et al (2) investigated the iron content of water entering
a boiler and measured the amount of hydrogen formed during its
operation. The hydrogen formation corresponded well with the
total amount of magnetite removed by chemical cleaning at
shut-down. The corrosion products were therefore formed within

the boiler. A mass balance of the iron entering the boiler in the feed water and the amount of magnetite removed by chemical cleaning showed that only 4% of the corrosion products could have originated from the feed water.

Köhle and Richter (8) stated that the total iron content of the purified condensate was less than 2ppb. Analysis of water entering the economiser showed that 2-3 ppb dissolved iron and 3-4 ppb suspended solids (mainly magnetite) were picked up across the low and high pressure feed heaters. The total quantity of iron entering a typical boiler was therefore about 5-8 ppb. It was pointed out by Garnsey et al (12) that the 10 ppb of dissolved iron normally found in the economiser and evaporator sections (2,4) corresponded to the solubility of iron at the temperature of the boiler water as it entered the economiser. This suggests that the increase in iron content across the feed heaters measured by Köhle and Richter (8) resulted from iron going into solution.

5.2 Formation

The formation of corrosion products in boilers is usually governed by the parabolic time law as a result of diffusion of metal ions through the inner protective layer and a reaction with water at the solid-liquid interface (8,13). In one paper Schoch et al (3) suggested that the corrosion products in supercritical once-through boilers formed according to this mechanism. The corrosion mechanism in tubes carrying liquid water and steam was assumed the same. In a later paper (4), however, a separate mechanism was suggested for tubes carrying liquid water. The inner layer was assumed to grow as in the steam phase and represents the thickness of the corroded metal. The outer layer results from ferrous ions forming at the metal surface, diffusing by pore diffusion to the outside surface and

dissolving in the water. Ferrous hydroxide $Fe(OH)_2$ is formed and then crystallises according to the Schikorr reaction:

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + 2H_2O + H_2 \qquad (5)$$
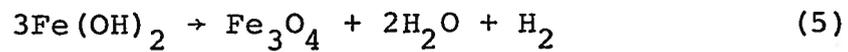
on the magnetite crystals already there. The main experimental fact supporting this mechanism is that the growth of magnetite layers in evaporators of supercritical once-through boilers follows the logarithmic time law which was derived for the case of diffusion in mutually blocked pores.

6. MECHANISMS

The starting point in any attempt to reduce or eliminate the problem of excessive pressure drop increases in supercritical once-through boilers, must be the mechanism that gives rise to the rippled corrosion product surfaces. Although the mechanisms put forward are dissimilar, they all suggest that the main factors giving rise to the ripples must be hydrodynamic in nature.

6.1 Erosion, deposition and precipitation

The first mechanism suggested by Schoch et al (3) was an erosion-deposition model. Magnetite crystals in the outer layer were removed from the surface by erosion and then fractionally deposited according to size in the more turbulent regions around the ripples. Subsequently Schoch et al (4) suggested the logarithmic growth law where ferrous hydroxide went into solution, partly to explain the formation of ripples (5). They argued that since precipitation depends on the transportation of dissolved species the turbulence and secondary flows at the surface must lead to preferential formation of magnetite crystals on the down-stream side of the ripples. At the same time the up-stream side of the ripples is continually being eroded resulting in a distinct ripple shape (4,6).

6.2 Oscillations

Garnsey et al (12) have suggested that the formation of rippled surfaces resulted from deposition-erosion processes under high frequency pressure, temperature and flow oscillations. These oscillations would determine the distribution of dissolved and suspended solids impinging upon the corrosion products surface. The frequency of the oscillations generated would depend on the characteristics of the fluid and tube geometry. Garnsey et al (12)

argued that since it was unlikely that the oscillations could
be sustained for the time required to complete ripple growth,
the formation process must be self-sustaining. No evidence
correlating ripple formation with fluid oscillations was
presented.

6.3 Sublayer bursts

Thomas (14) observed that the distance between ripples formed
in supercritical once-through boilers was similar to length
scales reported by Kline et al (15) for organised motions in
the sublayer of turbulent flows. The sublayer is envisaged
as consisting of regions of fast and slow moving fluid elements
with a certain transverse spacing. The slow moving elements
break up periodically at a given longituidinal spacing giving
rise to a process called bursting.

Thomas (14) suggested that there might be a connection between
the sublayer bursts and ripple spacing and put forward a
hypothesis where magnetite crystals deposited at points of low
surface stresses but erosion occurred elsewhere. The apparent
existance of a critical velocity, above which rippled surfaces
formed, was explained by assuming that the bonds between the
inner and outer layers could not be overcome until a certain
flow velocity was reached. Thomas (14) emphasized that there
was no evidence for this mechanism and pointed out that the
phenomena of sublayer bursts might give rise to rippling by
influencing the precipitation of dissolved species in some way.

7. DISCUSSION

The observations reported above indicate that the formation of rippled surfaces in supercritical once-through boilers is a relatively unknown phenomena. The structure and effects of rippled surfaces have been measured but the mechanism of formation is still open to speculation. It should therefore be useful to discuss some of the factors involved in the problem.

7.1 Deposition processes

In principle, the material giving rise to the outer layer may originate from local or external sources. It has been postulated (4,6) that the excess metal ions formed at the corroding metal surface diffuse to the outside and go into solution rather than forming magnetite crystals directly. The formation of the outer layer thus becomes a problem of deposition.

In addition to dissolved species, boiler waters may also contain suspended solids. The outer layer may therefore be formed from precipitation of dissolved species and from particulate deposition. Because system variables will not effect the two deposition processes to the same extent, some of the observations reported above may be explained by assuming that deposition of dissolved or suspended products predominated.

7.2 Flow velocity

There appears to exist a critical flow velocity above which rippled surfaces are formed. In the evaporator tubes of supercritical boilers this critical velocity is about 2 m/s when the predominant deposition mechanism is that of precipitation from solution. The reason for this critical velocity is not

clear. It has been suggested that a certain velocity is required to overcome the bonding forces between magnetite crystals in the outer and inner layers to form the apparently eroded area between ripples. This might be the case if ripples were formed due to some periodic distribution of shear stresses at the wall.

It is of interest that for a system where 15 μm sand particles in water were deposited on a hot surface, there was a sudden reduction in deposition at flow velocities exceeding about 2.25 m/s (17).

The flow velocities above 2 m/s at which rippled surfaces occur in evaporator tubes, according to Schoch et al (7) have been expressed by Martynova (16) as mass flux in the range 2280-2660 (kg/m² s). Similarily, the mass flux in evaporator tubes where rippled surfaces were formed according to Haller et al (10) was in the range 2034-3391 (kg/m² s).

7.3 Ripple ratio

The ripple ratios $\lambda = x/e$ reported for rippled surfaces in supercritical once-through boilers are in the range 5-13.6. See Table 1. It is well-known that pressure drop and heat transfer at surfaces having repeated rib roughness are at maximum in that range. It seems logical to assume the existance of some relationship between the two.

Behind individual transverse roughness elements the flow separates and then reattaches at some distance downstream. This distance depends mainly on the height e of the roughness elements and has been estimated by Lewis (18) to be about 7.5e for typical surfaces.

It has been observed that an increase in tube diameter at

constant fluid velocity decreased the ripple ratio (4). In
Table 1 the available data for λ at different tube diameters
are given. The fluid velocity at ripple ratio 5 and 7.8 was
6.6 and 6.75 (m/s) respectively. These velocities probably
fall somewhere within the mass flux values range of 2280-2660
$(kg/m^2 s)$ as estimated by Martynova (16), and are reasonably
close to the range 2034-3391 $(kg/m^2 s)$ for which the ripple
ratios 12.2 and 13.6 were obtained. The fluid conditions for
the data points given in Table 1 are therefore similar. The
ripple ratio and tube diameter are plotted on log-log scales
in Figure 2 and shown to fall on a smooth curve. Note that
the tube diameter spans an order of magnitude. This strongly
suggests that there is some relationship between ripple ratio
and tube diameter.

7.4 Solubility

At 300 bar pressure the ppb solubility of iron in water decreases
with temperature and reaches a minimum at 390^0C (12) that
corresponds to the pseudo-phase change from water to steam at
supercritical conditions (6). If the solubility is expressed
as a function of enthalpy, it decreases continuously with no
minimum (16). It was pointed out by Garnsey et al (12) that
rippled surfaces in supercritical once-through boilers are
formed where the ppb solubility of iron is decreasing and
approaching a minimum. At higher temperatures where the
solubility has increased no rippling is observed. This strongly
suggests that the main criteria for the formation of rippled
surfaces is neither the phase of the water nor the fluid velocity
but the solubility of iron. Martynova (16) stated that the phase
of the water was not important in the formation of ripples.

Velocity may, however, have an indirect influence on the
formation of rippled surfaces. A change in velocity will result
in a different temperature profile across the boundary layer

such that the iron supersaturation will also change. It is postulated here that rippled surfaces are formed where the water is only slightly supersaturated with iron.

7.5 Mechanism

The mechanism by which rippled surfaces are formed in supercritical once-through boilers has still not been made clear. Some suggestions have however been put forward.

The ripples are probably made up of corrosion products that have deposited rather than formed locally. Most of the deposition is due to dissolved iron that precipitates according to a dehydration reaction. Suspended solids may also be deposited and appear to do so preferentially on hot surfaces. The adhesion of particulate matter may therefore depend on a reaction term that varies with temperature.

The surface structure of the ripples is however not affected by the circumferential heat flux. This suggests that the mechanism that gives rise to the ripples is a hydrodynamic phenomenon. Flow separation behind roughness elements is such a phenomenon. The enhanced heat and mass transfer rates of rough surfaces are mainly due to the elimination of the laminar layer at the reattachment point. In a situation where some material is depositing the build-up at the reattachment point would be more rapid than elsewhere. In follows that the formation of rippled surfaces might be due to a flow separation phenomenon.

The build-up of rippled surfaces consists probably of three periods: Initiation, propagation and termination. The flow separation model would apply in the propagation period where the growth of a roughness element has been initiated. A

roughness element that forms on a tube wall will project into the fluid and promote deposition at its tip. This element might be the natural roughness of the tube or have resulted from a bursting process in the sublayer. Once it has formed it will grow faster than the low-lying areas around it. The growth of a rippled surface may be initiated in this way. The above is probably only true for hard deposits such as magnetite that are not easily removed from the surface. The growth of the rippled surface will be terminated when all the surfaces in the boiler circuit have such a thick inner protective layer that the corrosion has been reduced considerably and only a limited amount of iron passes into solution. This occurs in an asymptotic fashion as shown above.

The main driving force for the deposition of iron from solution is the concentration difference. When the driving force is very large deposition will occur irrespective of any sites (reattachment points) on the surface that are more favourable than others. The material depositing will therefore be evenly distributed. When the driving force is very small, however, the deposition will occur selectively at the sites where the flow reattaches. The deposition will therefore be enhanced at certain distances downstream from elements or ripples. This distance is typically 7.5 times the ripple height and corresponds to the ripple ratio λ. As already shown in Figure 2 the ripple ratio depends on the tube diameter. This means that the distance of the reattachment point downstream from a roughness element is likely to decrease with tube diameter.

See Ref (20) for further details.

8. CONCLUSIONS

1. Rippled magnetite deposits may occur in the evaporator tubes of supercritical once-through boilers and give rise to excessive pressure losses.

2. The surface structure of rippled deposits depends on flow velocity but is apparently not affected by heat flux. The spacing between ripples decreases with velocity and the ripple ratio decreases with tube diameter at constant mass flux conditions.

3. Rippled deposits are probably formed due to flow separation and re attachment in situations where the depositing material is at saturation and strongly adherent.
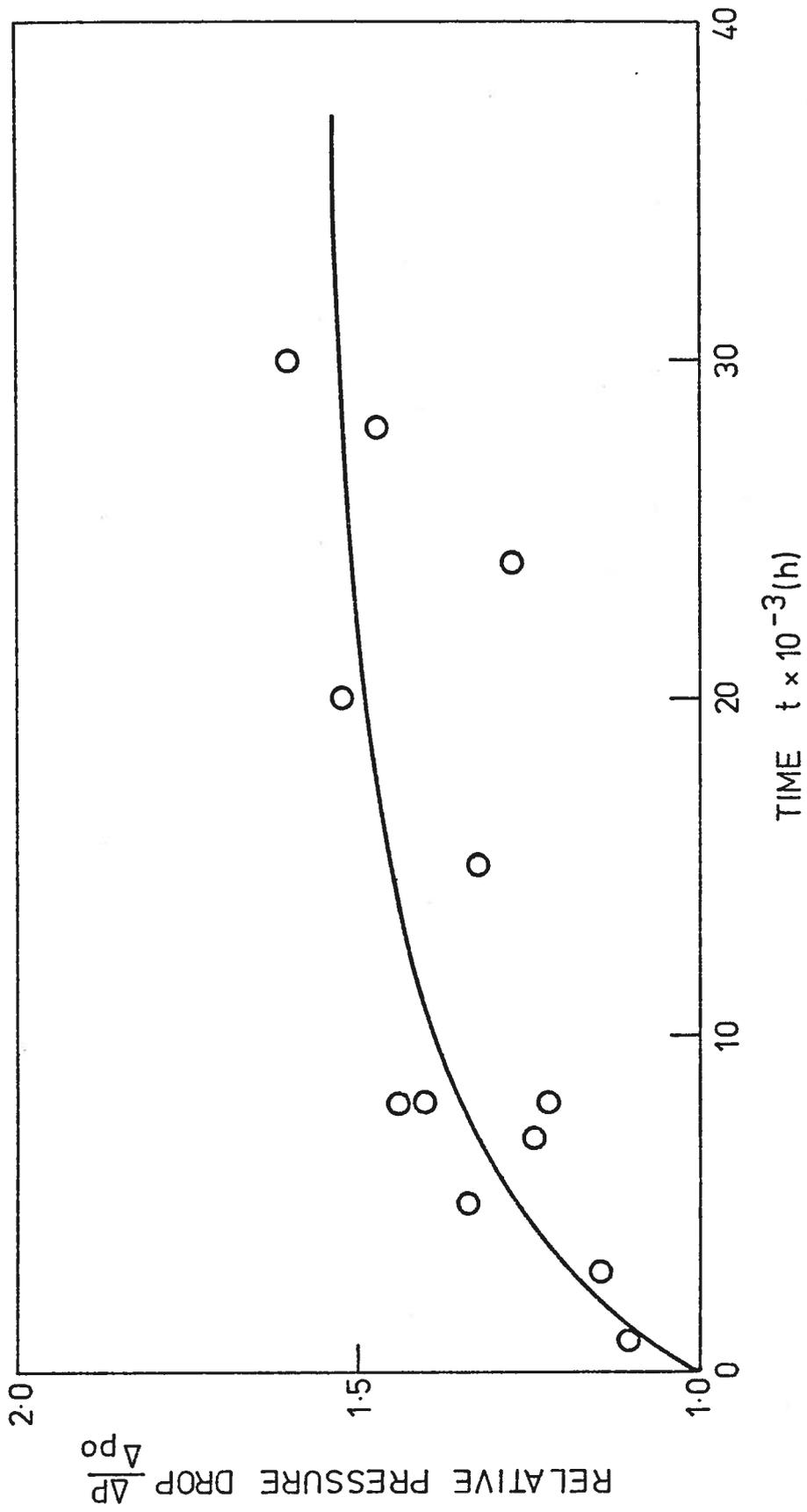
AERE R8738 FIG.1. RELATIVE PRESSURE DROP IN THE ECONOMISER-EVAPORATOR
SECTIONS OF SEVEN SUBCRITICAL BOILERS (REF 11)

R48693
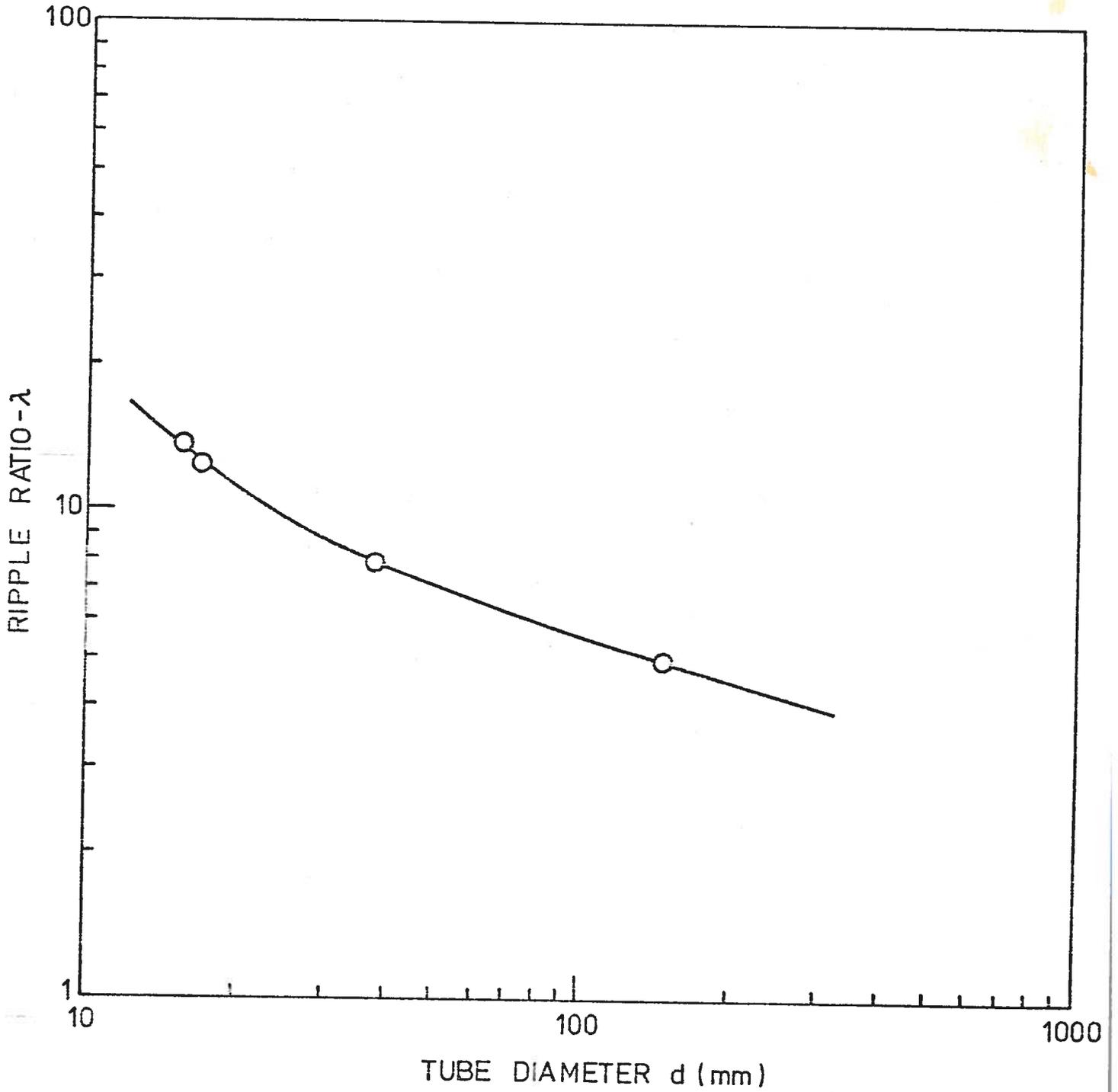
AERE R8738 FIG. 2 . RIPPLE RATIO AT DIFFERENT TUBE DIAMETERS

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