

LAGGING FIRES : THE PRESENT POSITION

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In this contribution I have attempted to review the published technical literature on lagging fires. In addition I have presented analytical and computer methods as well as experimental and practical experience. A short discussion on the practicabilities of eliminating this hazard is included.

Lagging fires have been the source of at least nuisance and occasionally disaster in practically every industrial field involving high-temperature processes. Most industrial plants, to achieve their maximum commercial returns, require to conserve heat. This goal is relatively cheaply, expeditiously and efficiently attained by the use of a handful of proprietary insulating materials, most of which have the principal characteristic of an open pore structure in which air is trapped in such a manner as to eliminate convection as a heat transfer mode.

By restricting attention in this paper to 'high-temperatures' in excess of 100°C, the need to consider the behaviour of intrinsically combustible laggings is avoided. Such laggings are typically the foamed plastics which are more appropriate to, for example, hot water central heating or refrigeration duties. Here attention will be devoted to laggings which are inherently non-combustible by any definition and also those in which the geometrical form is fixed by small quantities of resins. The latter may indeed still be non-combustible as defined by their performance in, for example, the British Standard fire tests for non-combustibility BS 476 : part 4 : 1970.

I hope to review comprehensively the published literature which might be of assistance to plant designers and managers in helping them to appraise potential or actual hazards, and offer remedies. Summarising the physical situation with

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which this paper is concerned : the particular hazard considered is the escape of involatile combustible liquids, on to porous and inert or incombustible lagging materials manifesting a temperature gradient, and their subsequent self-heating to ignition.

Literature Review

Although the mechanisms involved in the occurrence of lagging fires are now well understood, for a variety of reasons a coherent, reliable and systematic approach to the problem has not yet emerged. Two of these reasons, of paramount importance, are the present lack of a theoretical treatment of sufficient accuracy or simplicity, and difficulties in the reliable experimentation which is necessary to establish data for the theoretical treatment and for testing the performance thus predicted of actual lagging situations. Consequently attention in the published scientific literature has become polarised towards either theoretical or practical evaluations with little endeavour applied to developing a comprehensive appraisal. Also, whereas there has been much study of lagging fire criteria, relatively little has been said about how the risks may be minimised, how a lagging fire should be dealt with, and what - if any - are the long term prospects of their successful elimination.

The work of Bowes and Thomas both separately and in concert (1-7) has created an edifice of theory appropriate to this problem based firmly on the established and classical work of Frank-Kamenetskii (8,9). A convenient and comprehensive review, in the English language, of this theory, as well as basic and parallel considerations, appears in Oxidation and Combustion Reviews, Volume 2 (10). So far as this contribution is concerned the most relevant theoretical references are 3, 6 and 7 although consultation of the earlier references is probably essential for an understanding of the arguments and nomenclature.

Bowes' name again is prominent, both alone and in association with co-workers, in experimental work in this connection (11-13). Other experimenters were Miedeck (14), Lindner and Seibring (15), Ettlign & Adams (16), Morgan (17), Petkus (18,19) Craven and Greig (20) and Langford (21).

Bowes, in association with Langford (12), has endeavoured to achieve a correlation between theory and experiment in the lagging situation. The same is true in what is occasionally an allied problem in lagging, namely self-heating in two-component systems (5, 13) (although not studied in lagging geometrics or with imposed temperature gradients), where a lagging material may be bound by resin during manufacture to maintain its shape and become contaminated in service.

Theoretical : The Analytical Method

As already stated the principal architects of the published theoretical treatment of this problem are Bowes and Thomas. Their contribution to this field has already been

comprehensively reviewed (10) and will not be presented here in detail. Their basic starting point was the fundamental heat transfer equation :

$$c\rho \frac{\partial T}{\partial t} = \text{div}[k.\text{grad}T] \quad (1)$$

where c is the specific heat
 ρ is the density
 T is the temperature
 t is time
 and k is the thermal conductivity.

This equation transforms, on the assumption of constant thermal conductivity, to :

$$c\rho \frac{\partial T}{\partial t} = k.\nabla^2 T \quad (2)$$

where ∇^2 is the laplacian operator.

In the case where there is superimposed a distributed source of heat per unit volume, q , equation (2) becomes :

$$c\rho \frac{\partial T}{\partial t} = k.\nabla^2 T + q \quad (3)$$

If the assumption is that this source of heat arises from a zero-order thermally rate-determined chemical reaction, then q has the familiar Arrhenius form, i.e.

$$c\rho \frac{\partial T}{\partial t} = k.\nabla^2 T + \Delta H.\rho.A.e^{-\frac{E}{RT}} \quad (4)$$

where ΔH is the heat of reaction per unit mass
 A is the pre-exponential or frequency factor for the reaction
 e is the base of naperian logarithms
 E is the reaction activation energy
 and R is the gas constant.

Re-arrangement of equation (4), formulating the approximation

$$\exp\left[-\frac{E}{RT}\right] = \exp\left[-\frac{E}{RT_0}\right].\exp\left[\frac{E}{RT_0^2}(T-T_0)\right]$$

defining dimensionless terms :

$$\theta = \frac{E}{RT_0^2}(T-T_0)$$

$$\delta = \frac{\Delta H.\rho.A}{k} \cdot r^2 \cdot \frac{E}{RT_0^2} \cdot e^{-\frac{E}{RT_0}}$$

$$z = \frac{x}{r}$$

$$\tau = \frac{kt}{c\rho r^2}$$

where r is the semi-thickness or radius (appropriate to the symmetry)
 and substituting :

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial z^2} + \frac{\delta}{z} \cdot \frac{\partial \theta}{\partial z} + \delta.e^\theta \quad (5)$$

where m has the value 0, 1 or 2 according to planar, cylindrical or spherical symmetry respectively.

For the stationary state where thermal equilibrium is attained $\frac{\partial \theta}{\partial z} = 0$ equation (5) gives for planar symmetry :

$$\frac{\partial^2 \theta}{\partial z^2} = -\delta e^\theta \quad (6)$$

for which the general solution is :

$$\theta = \ln B - 2 \ln \left[\cosh \left(z \sqrt{\frac{\delta B}{2}} + C \right) \right] \quad (7)$$

where B and C are constants

B is a function of the centre temperature

$$B = e^{\theta_m}$$

Conventional analytical methods enable the maximum possible values of δ and θ_m to be determined for the case where $\theta_c = 0$ and for symmetrical heating (in which case $C = 0$). These are the 'critical' values which define the boundary between safe and hazardous self-heating :

$$\left. \begin{aligned} \delta_c &= 0.88 \\ \theta_c &= 1.19 - 2 \ln [\cosh(1.2z)] \\ \theta_{mc} &= 1.19 \end{aligned} \right\} \underline{\underline{\text{Slab}}}$$

A slab of insulation may be considered to behave as the planar model above, but of half thickness, if certain boundary conditions are applicable. These are that the hot face is in contact with a perfect insulator, and the cold face is in contact with a perfect conductor. For a given ambient temperature δ_c determines the thickness of insulation τ , and θ_{mc} proscribes the hot face temperature beyond which super-critical self-heating and ignition is likely.

The more usual situation is that both hot and cold faces are in contact with perfect conductors. Concomitantly the boundary conditions are altered : in particular C in equation (7) is non-zero. In this case no explicit expressions for δ and θ for the critical state exist but the numerical solution has been performed (6) and tabulated values are presented.

Equation (5) for cylindrical symmetry becomes :

$$\frac{\partial^2 \theta}{\partial z^2} + \frac{1}{z} \cdot \frac{\partial \theta}{\partial z} = -\delta e^\theta \quad (8)$$

for which the general solution is :

$$\theta = \ln \left[\frac{8G}{\delta(Gz^2 + 1)^2} \right] \quad (9)$$

for a solid cylinder where δ is a constant of integration. Again applying conventional analytical methods critical conditions are defined by :

$$\delta_c = 2.00 \quad ; \quad \theta_c = \ln \left[\frac{4}{(z^2 + 1)^2} \right] \quad ; \quad \theta_{mc} = 1.39$$

Solid cylinder

More pertinent to this paper is the hollow cylinder. The form of the integration of equation (8) - which is the appropriate differential equation, is changed by the boundary conditions. Thus

$$\theta = \ln \left[\frac{2F^2 G z^{F-2}}{\delta(Gz^F + 1)^2} \right] \quad (10)$$

where F and G are constants of integration (δ is defined by r_i , the inner radius of the cylindrical annulus). The boundary conditions here lead to a critical value expressed implicitly, of :

$$F = \frac{2(1+G)}{1-G} \quad ; \quad \delta_c = \frac{8G}{(1-G)^2} \quad ; \quad \theta_s = \ln \left[\frac{2F^2 G z_s^{F-2}}{\delta_c(Gz_s^F + 1)^2} \right]$$

Hollow Cylinder

where θ is defined in this case as $E/R_T^2(T-T_r)$ and is negative. Accordingly $\theta = 0$ at the inner face of the insulation. This treatment implies heat transfer rates at the inner surface, substantially less, and at the outer surface substantially greater than those within the thickness of the insulation, i.e. a perfect insulator and a perfect conductor in contact with the respective faces. The suffix S refers to the outer radius (surface) condition. Appendix I presents calculations of safe insulation thicknesses based on physical and chemical data established in a real system.

These treatments though approximate would appear to have promise in the prediction of critical conditions. Unfortunately, despite painstaking work, the correlations (6,5) have not been as good as those found in the classical cube studies on homogeneous materials. The reason would appear to lie in the very great difficulty in achieving homogeneity in contaminant distribution which is a prerequisite for satisfactory prediction. The kinetic and thermo-chemical constants are of course another difficulty but one which in principle is susceptible to effective remedy. A simple series of cube experiments such as is outlined in references 13 and 17 or the technique presented in reference 22 will enable the kinetic constants to be derived. Alternative techniques, thermo-gravimetric and differential thermal analysis (T.G.A. and D.T.A.), are available. Specimens used

in the latter are small and the degree of homogeneity and reproducibility obtainable is good whereas cube tests display gradations in concentration of, for example, oil due to drainage and/or capillary action.

This feature of behaviour renders quantification of the hazard imprecise, in particular it makes identification of the worst condition difficult. This unfortunate aspect of contaminant behaviour is exacerbated in, for example, pipe lagging which not only tends to be more irreproducible but is sufficiently different in symmetry from the cube to be difficult to relate on any basis.

Despite these difficulties Bowes and Langford (12) have produced a correlation with cube experiments which, whilst not wholly satisfactory, suggests that the prognostic theory could well be a sound tool. Given the kinetics and thermochemistry (or having determined them by test) and having ascertained experimentally the density of contaminant loading producing the most severe exotherm, then the variables pipe diameter, pipe temperature, ambient temperature, and insulation type and thickness may be evaluated such that critical conditions are never achieved in practice.

The Computer Method

Unpublished work, using a computer, has demonstrated that theory and experiment can agree closely if sufficient care is taken. The computer handled a programme which was based upon the precise theory and not the Frank-Kamenetskii approximation, moreover it accounted for temperature-dependent thermal conductivity. This was necessary, because with large temperature gradients conductivity is found to be cubically related to temperature in porous materials. The basic equation used was :

$$c.p. \frac{\partial T}{\partial t} = \text{div} [k. \text{grad } T] + \Delta H.p.A.e^{-\frac{E}{RT}} \quad (11)$$

Equation (11) may be rewritten for slab and pipe insulation as :

$$c.p. \frac{\partial T}{\partial t} = k. \left(\frac{\partial^2 T}{\partial x^2} \right) + \frac{\partial k}{\partial x} \cdot \frac{\partial T}{\partial x} + \Delta H.p.A.e^{-\frac{E}{RT}} \quad (12)$$

and

$$c.p. \frac{\partial T}{\partial t} = k \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} \right] + \frac{\partial k}{\partial r} \cdot \frac{\partial T}{\partial r} + \Delta H.p.A.e^{-\frac{E}{RT}} \quad (13)$$

respectively. Finite difference methods of solution, such as that described by Crank and Nicolson(23), may be applied so that errors in computation become insignificantly small - although computer usage can become unduly prolonged. The use of this technique requires that k be established accurately as a function of temperature in addition to the other parameters already alluded to.

Using this approach with very low levels of insulation contamination, where uniformity of distribution is not a

problem, and employing techniques such as T.G.A. and D.T.A. has demonstrated that it will accurately predict not only critical conditions but also non-steady state behaviour. It has also demonstrated that neither oxygen diffusion nor contaminant diffusion (albeit for very low contaminant loadings) are important criteria in the theoretical prediction of critical states. And, whereas zero-order chemical reaction enabled the best fit to be obtained between the computed results and experimental behaviour, it was found necessary to allow for reactant (contaminant) consumption. No correction for air convection within the lagging was required.

Unfortunately the practical difficulties already mentioned with regard to high contaminant loadings have prevented a full experimental survey of the hazard - including, of course, the establishment of the maximum hazard condition in a lagging situation. The theoretical treatment, discounting diffusion of air, predicts a continuously increasing hazard to the point where every pore of the entire lagging is filled with contaminant. This is, of course, fallacious since not only will air diffusion become important well before that point but the two additional factors - both leading to enhanced heat transfer (and thus reducing the self-heating risk) - a) vapourization and diffusion and b) thermal conductivity of the contaminant will assume predominance. Work with cubes of contaminated inert lagging media has revealed that the maximum ignition sensitivity probably arises in the range 6% to 12% by volume contamination.

Commentary

Clearly in the industrial context contamination, if it occurs, will not be uniform : it may result from a single incident or from a continuous leak. In either case, although both are different, a spectrum of concentrations will exist probably embracing the most susceptible values. Although this is, in principle, a problem which could be solved by computer, additional variables have to be considered such as - effect of contamination on thermal conductivity, vapourization and vapour and air diffusion, and liquid convection (in the case of a leak). The major imponderables would appear not to be these however but what are the correct boundary conditions to apply.

Experiment has shown, provided enough contamination occurs, that the single incident gives rise to the greater hazard and that progressively higher continuous leakage rates reduce the hazard.

The susceptibility of a given insulation to ignition when contaminated clearly depends upon the nature of the contaminant. In this respect those with the greater volatility are less hazardous because they vaporise readily and diffuse from the regions of high temperature. All non-volatile liquid combustibles however present problems when absorbed into lagging. Those that are intrinsically reactive such as the unsaturated oils, for example olive and linseed oils, are more

prone to self-heat than saturated mineral oils.

A league table of self-ignition temperatures appears in reference 15 to which may be added olive oil which would probably have ignited in the apparatus Lindner and Seibring used at about 120°C, and polyethylene glycol at about 110°C. These workers also observed that the most volatile materials do not display any tendency to self-heat. Extrapolation of self-heating critical temperatures from values such as those in the above reference, which were determined in a cylinder of height one-third the 200 mm diameter, to pipe or plate insulation is not possible but they illustrate the very low values that are found.

Again insulation material in the form of a right-cylinder 100 mm diameter and soaked with three times its weight of glycol (20) has been found to ignite from 150°C. It is interesting to note that for the more porous insulating media 6% to 12% by volume (defining the most hazardous contaminant loading) corresponds approximately to 150% to 300% by weight of, for example, mineral oil.

Hitherto the discussion has been concerned with inert lagging materials. Those that are themselves readily combustible such as foamed plastic although not usually used where temperatures exceed 100°C may display an enhanced susceptibility since experimental work (13,14,16) has demonstrated a co-operative self-heating effect with the contaminant. 'Inert' contaminants such as fire resistant chlorinated lubricating or hydraulic oils have revealed a greater reluctance to ignite (10) but they are by no means free from the risk, although higher temperatures are necessary to initiate combustion.

The type of (inert) lagging material has only a second order effect on ignition propensities. Every commonly used insulant with an open pore structure presents a risk when contaminated and so far as it is possible to inter-relate the various studies - which is difficult because different experimental conditions have been adopted by each group of workers - ignition temperatures are very similar for the same contaminant on different substrates. The only feature which seems to have a marked influence is the pore size, or density, of insulant. But since low density is a necessary feature for the practical objective of heat conservation, low density materials are adopted where possible.

In no case has it been demonstrated that there is a specific chemical catalytic effect created by the inert material although this may have a role which is not distinguishable by the methods used to establish the kinetics. The slight differences which have been noted in ignition propensity of the same contaminant on different bases may be due to such an effect. It appears however to be no more than a second order effect if it exists.

The Future

The point has been made that all non-volatile combustible liquids whether fire-resistant or not may be subject to ignition in lagging. Those that are not intrinsically fire-resistant, that is not chlorinated hydrocarbons or phosphate esters, but which contain anti-oxidation additives are found to recover their ignition susceptibilities when they have been exposed in a self-heating situation for a moderate period. The longer delay between initial contamination and ignition arises through the sacrificial oxidation of the anti-oxidation component, which is progressively depleted until it no longer protects the bulk liquor from oxidation. Therefore it is likely that at best treating insulation with an anti-oxidation material will confer protection against the ignition of chance contamination for only a short period.

So far as the contaminant is concerned, it appears that no satisfactory method presently exists for eliminating the ignition hazard of intrinsically combustible liquids.

Another approach is to eliminate oxygen access to the insulation. This may be accomplished by adopting a closed-pore insulating medium such as, for example, foamed glass. Unfortunately this material is expensive and difficult to apply - open pore materials are not only much cheaper but they have advantages such as flexibility and resilience. Of course, access of oxygen can be limited, and this has been demonstrated to have a beneficial effect, by impervious shrouding. This can take the form of a bitumen coating on chicken wire mesh, on aluminium sheet. Again unfortunately the integrity of such sheathings may not be perfect and in fact rarely is at crucial points such as flanges. Moreover, unless maintenance workers take care when replacing sheathing its effectiveness can be negated.

The occurrence of a lagging fire is usually diagnosed by copious fuming. Rarely is it accompanied by external fire. However, with very severe contamination a fire may not be long in developing after the time of discovery. The real hazard of an internal fire is not so much in the spontaneous development of external flaming - the occurrence of which can be prevented by water application - but in the transformation to flaming which often accompanies removal of the affected 'smouldering' insulation. In flameproof areas this can be a problem and removal should be deferred until the entire suspect area of lagging has been thoroughly doused with water, observed for a considerable period and possibly monitored with thermocouples. There ought not to be any hazard associated with this action and process pipe-work can be maintained in service whilst this is done.

Examples of Lagging Fires

One which gave rise to an explosion and fire in a small chemical works was precipitated by a fire in the lagging of a process heating fluid cycle. The fluid concerned was a straight mineral oil of low volatility which had contaminated

a substantial run of pipework as a result of a defective pump gland. The first observation was of smoke arising from lagging remote from the fire; the second was that the heating fluid had exceeded the set temperature of 270°C by 50°C; and the third was that flames had enveloped the pump and a considerable length of adjacent piping.

Although the flames were quickly dealt with, temperatures in the fluid cycle continued to rise and a short while later a small explosion occurred in the covered oil header tank of the heating fluid system which was housed within a building. This was accompanied by the release from the header tank of copious oil fumes which some few seconds later ignited and exploded with violence, severely damaging the building.

The explanation appeared to be that oil beyond its spontaneous ignition temperature had been forced by expansion back up to the header tank where its vapour ignited in contact with air. The subsequent explosion may have been caused by an adventitious source of ignition, of which there were many, as the electrical equipment in use in that area was neither flame-proof nor non-sparking.

The situation was such as to lead to rapid disaster since the process heating oil cycle was a closed loop of low capacity.

The second example is of an incident which involved a heavy fuel oil. The plant concerned was a large spray drying installation directly heated from a combustion chamber. The plant was newly erected and the combustion chamber had been running only some 24 hours on manual control at very low fire. The fuel oil had a viscosity of 600 centistokes at 43°C (110°F) and was pumped by a constant speed constant displacement pump through heaters, thermostatically controlled at 110°C (230°F) to the burner. Oil in excess of the burner requirements was returned to the upstream side of the pump and recycled. The whole of the heater and flow and recirculation system was lagged.

The accident occurred early in the morning after the firing had been continuing unsupervised for some hours. There was a sudden eruption of flame through a hinged explosion panel close to the combustion chamber which enveloped a shift electrician as he was walking by.

Investigation revealed that the only explanation for the eruption of flame was gross overfuelling of the furnace and yet the manual valve controlling the burner was still at its original setting - indeed combustion was found to be continuing as peacefully after the event as it had been previously. Apparently in one aspect only was there a change, a considerable run of the lagging surrounding the oil flow and recirculation pipes was on fire.

The explanation appeared to be that the lagging had caught fire as the primary event: it was discovered that this lagging had been saturated with fuel oil shortly after installation due to pipe joints leaking when the first pressure

test was applied. Although the joints were tightened, the original contaminated lagging was replaced. Because of the almost closed loop operation the flow and return oil lines were raised to high temperature and ignited as a consequence. The lagging fire then raised the fuel oil temperature to greatly in excess of the thermostated value - with a concomitant reduction in viscosity. When this superheated oil reached the fixed aperture of the manual burner valve it flowed through rapidly, thus overfuelling the combustion chamber. In doing so it discharged the overheated oil from the pipe system and conditions were restored to normal when oil at normal temperature reached the valve once more. The rate of flow, whilst the overheated oil was entering the combustion chamber, was such that little temperature rise occurred in the fresh oil as a result of the lagging fire. Had the burner not been extinguished at that point a subsequent outburst of flame would probably have happened.

Summary

Whilst the present state of knowledge is that lagging fires are predictable and quantifiable occurrences, the demands of heat conservation tend towards an increased rather than a diminished hazard. For a given contaminant and given pipe and atmospheric temperatures the geometry of lagging is prescribed. Higher pipe temperatures exacerbate the ignition risk which can only be eliminated by reduced insulation thicknesses. This however is contrary to economy which demands a greater insulant thickness for higher service temperatures. Thus the choice must be the responsibility of the works management - there is no Right answer. The risks must be weighed against commercial considerations.

The correct weighting of risk is not easy : each situation must be considered on its own merits. It may be right to use foamed glass in group I areas and sheathed insulation in group II areas leaving to less hazardous areas the conventional materials. If the process is exothermic it might be economic to abandon lagging completely.

At present there is no prospect of totally eliminating the hazard of lagging fires either by physical or chemical means. The only procedure which can be advocated, unless intrinsic safety is adopted by pursuing the theoretical and experimental exercise outlined in this paper, is to exclude the ingress of air to the lagging.

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APPENDIX I : ILLUSTRATIVE EXAMPLE

This presents a calculation of maximum safe lagging thicknesses using the expressions for a hollow cylinder and measured physical and chemical data in a real contamination situation.

Two conditions are considered : one where process fluid at 200°C is conveyed in a pipe of 4 ins. O.D.; and the other where process fluid at 300°C is conveyed in a pipe of 4 ins. O.D. The maximum external surface temperature of the lagging must not exceed 40°C.

A comparison is made between the reduction in lagging thickness required for safe operation in the event of contamination with the increase in lagging thickness that would be desirable for similar heat conservation in the two cases.

Kinetic constants : $E = 6,000$ cal/mole
 $A = 0.04$ sec⁻¹

Thermal properties : $\Delta H = 2,000$ cal/g

Transport properties : $k = 10^{-4}$ cal/cm.sec°C

Density : $\rho = 0.03$ g/cm³

$$\delta_c = \frac{8G}{(1-G)^2} \quad (1) = \frac{\Delta H \cdot \rho \cdot A \cdot r_i^2 \cdot E}{k \cdot R T_p^2} \cdot e^{-E/RT_p} \quad (2)$$

$$\theta_s = \frac{E}{R T_p^2} (T_s - T_p) \quad (3) = \ln \left[\frac{2F^2 G \cdot Z_s^{F-1}}{\delta_c (G \cdot Z_s + 1)^2} \right] \quad (4)$$

$$F = \frac{2(1+G)}{(1-G)} \quad (5)$$

where r_i is the inner radius of the insulation (radius of the pipe) and Z_s is the ratio of the outer to the inner radii of the insulation.

From equation (2), with a pipe temperature of 200°C :

$$\delta_c = \frac{2000 \cdot 0.03 \cdot 0.04 \cdot (5.08)^2 \cdot 6000}{10^{-4} \cdot 1.987 (473)^2} \cdot e^{-\frac{6000}{1.987 \cdot 473}}$$

$$= \underline{\underline{14.1}}$$

from equation (1) : $14.1 = \frac{8G}{(1-G)^2}$

$$G^2 - 2.57G + 1 = 0$$

$$\therefore G = \underline{\underline{0.479}}$$

(selecting the value of G between 0 and 1)

and from equation (5) :
$$F = \frac{2(1 + 0.479)}{(1 - 0.479)}$$

$$\therefore F = \underline{\underline{5.68}}$$

Using equation (4) and assuming $z_s = 2$

$$\begin{aligned} \theta_s &= \ln \left[\frac{2 \cdot 5.68^2 \cdot 0.479 \cdot 2^{3.68}}{14.1 (0.479 \cdot 2^{5.68} + 1)^2} \right] \\ &= \underline{\underline{-3.15}} \end{aligned}$$

From which, using equation (3) :

$$T_s = 240^\circ\text{K} \approx \underline{\underline{-33^\circ\text{C}}}$$

re-calculate, assuming $z_s = 1.5$ then $\theta_s = -1.24$

$$\therefore T_s = 381^\circ\text{K} \approx \underline{\underline{108^\circ\text{C}}}$$

re-calculate, once more assuming $z_s = 1.75$ then $\theta_s = -2.21$

$$\therefore T_s = 309^\circ\text{K} \approx \underline{\underline{36^\circ\text{C}}}$$

This trial and error calculation reveals that the outer radius of the lagging should not exceed 8.6 cm; that is that the lagging thickness should not be greater than 3.5 cm.

This trial and error calculation may be repeated for a pipe temperature of 300°C . Assuming that the physical and chemical data used above remain constant at this higher temperature, then as previously :

$$\begin{aligned} \delta_c &= \frac{2000 \cdot 0.03 \cdot 0.04}{10^{-4}} \cdot (5.68)^2 \cdot \frac{6000}{1.987(573)^2} \cdot e^{-\frac{6000}{1.987 \cdot 573}} \\ &= \underline{\underline{29.3}} \end{aligned}$$

$$29.3 = \frac{8G}{(1-G)^2} \quad \therefore G = \underline{\underline{0.596}}$$

$$F = \frac{2(1 + 0.596)}{1 - 0.596}$$

$$= \underline{\underline{7.912}}$$

If in this case z_s is assumed to be 1.5 in the first instance, then :

$$\theta_s = \ln \left[\frac{2.7912^2 \cdot 0.596 \cdot 1.5^{5.912}}{29.3(0.596 \cdot 1.5^{7.912} + 1)^2} \right]$$

$$= \underline{\underline{-2.18}}$$

and

$$\therefore T_s = 336^\circ\text{K} \approx \underline{\underline{63^\circ\text{C}}}$$

Re-calculate, assuming $z_s = 1.65$ then $\theta_s = \underline{\underline{-3.06}}$

from which : $T_s = 240^\circ\text{K} \approx \underline{\underline{-33^\circ\text{C}}}$

Assuming that $z_s = 1.6$ then $\theta_s = \underline{\underline{-2.77}}$

from which : $T_s = 272^\circ\text{K} \approx \underline{\underline{-1^\circ\text{C}}}$

Assuming that $z_s = 1.55$ then $\theta_s = \underline{\underline{-2.48}}$

from which : $T_s = 304^\circ\text{K} \approx \underline{\underline{31^\circ\text{C}}}$

This result means that, at a pipe temperature of 300°C, the outer radius of the lagging should not exceed 7.8 cm. Accordingly the lagging thickness should not exceed 2.8 cm.

This example illustrates that, whilst the economics of heat conservation would demand a 30% increase in insulation cover to ensure that the rate of heat loss at the higher operating temperature is not increased, safety considerations require that a 20% reduction in insulation thickness should accompany this rise in service temperature to minimise the risk of fire should contamination occur.