Python Project

PROJECT SUBMISSION INSTRUCTIONS:

1) Copy-paste : “HeatTransferProject” into the subject of your email: (don’t include double quotation marks)

2) Attach Python code as **.txt**

    Name your file as **yourfirstname_yourlastname.txt**

3) Attach your project report as pdf. Follow the same naming convention as above for your pdf file as well

If you try to send a .py file, outlook will reject the email because .py files are a security risk.

4) Hit ‘Send Email’ button. Email should be received by **Dec 6, 2022, 3 PM**.

STATEMENT

Problem: In process plants, hot fluids are often transported in pipes. The temperatures of these fluids can be high, and a person accidentally touching the surfaces of these pipes can get severe burn injuries. In addition to these safety risks, the pipe will be exposed to ambient conditions, and will be subject to extreme weather temperatures in summer and winter, which can cause the fluid to lose heat to varying degrees in the summer versus the winter. As such, not only is heat loss an economic loss, but it can cause fluctuations in the process, which can generate unfavorable consequences downstream.

Remedy: To overcome the above problem, pipes are insulated to reduce heat loss, and to bring the surface temperature down so that it is safe to touch. The insulation is further covered by what is called a 'jacket'. This jacket can be made of different materials including, metals (such as aluminum), fiberglass cloth, fabric etc. The jacket materials have different emissivities, and this factor alone can play an important effect on the final surface temperature of the jacketed pipe. Even when the jacketed material is selected, the emissivity can be changed by simply applying paint (for example white paint versus black paint, and matte finish versus satin finish).

Goal of this project: The goal of this project is to understand the effect that 'emissivity' of jacket has on the final surface temperature of insulated and jacket pipe, and the heat loss, when considering flow of hot fluid in a pipe.

Assumptions:

1) The temperature of the fluid in the pipe is also the temperature of the pipe surface (in other words, we assume that the thermal resistance of the pipe material is low and there is no temperature drop across the pipe metal wall).
2) Steady state
3) The 'jacket' does not introduce any thermal resistance of conduction due to jacket material.
4) The 'jacket' is thin and does not increase thickness of insulation.

Parameters:

Based on Reference (see Appendix-1)

- *Pipe outer diameter = d_1 = 20 inches (see Fig 1 in Appendix-1)*
- *Temperatures of fluid to consider = 800 F, 900 F, 1000 F, and 1100 F*
- *Emissivity of jacket = 0.09 (for shiny metal such as aluminum)*
  0.9 (for canvas/cloth with matte-black color)
- *Pipe length = 1 ft*
- *Temperature of surrounding = 70 F*
- *Thermal conductivity of insulation = 0.05 BTU/(h ft F)*
- *Stefan-Boltzmann constant = 0.171×10^{-8} BTU/(h ft^2 R^4)*
- *Insulation thickness cases to consider = 2, 3, 4, 5, 6, 7, 8 inches.*
- *Safe temperatures to touch:*
  - *140 F for shiny or matte-black metal jacket*
  - *113 F for canvas*

<u>Action items for students:</u>

Write a ‘PYTHON’ code to:

a. Compute surface temperature of the jacket and verify the following statement from the reference Appendix paper:

> oil-bound paint. For example, this difference in surface emissivity alone can reduce the jacket surface-temperature from 286°F to 192°F for a pipe temperature of 1,100°F on a 20-in.-dia. header having 2-in.-thick insulation.

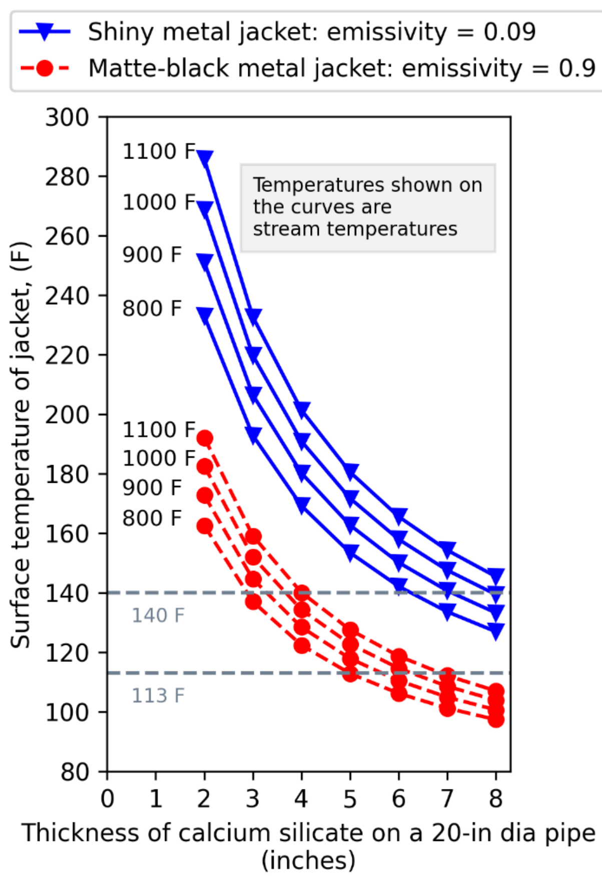
To do so, have your code print the following to the computer screen:

```
Fluid temp = 1100 F, Pipe OD = 20 inches, Insulation thickness = 2 inches, Jacket emissivity = 0.09, Outer temperature = 286 F
Fluid temp = 1100 F, Pipe OD = 20 inches, Insulation thickness = 2 inches, Jacket emissivity = 0.90, Outer temperature = 192 F
```

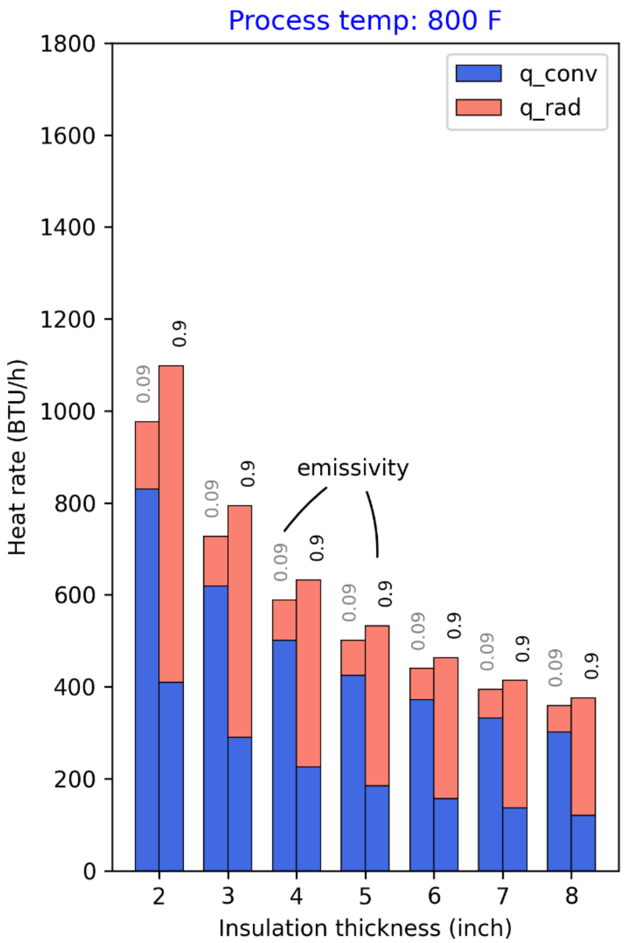
The surface temperatures (286 and 192 F) must be computed correctly by your code.

b) Plot Fig 3 of Appendix-1 (see below as an example)

Your figure does not have to look the same as below or in the reference appendix, but you must capture all the aspects in your own figure.



c) Compute the heat rate of convection and heat rate of radiation for each combination of fluid temperature, insulation thickness and emissivity. Plot the result in the following format.



ADD FOR 900 F

ADD FOR 900 F

ADD FOR 900 F

d) Using these different plots, you have made, answer the following:

Q1) As the thickness of insulation increases, what happens to the surface temperature?

Q2) As the jacket emissivity increases from 0.09 to 0.9, what is the effect on surface temperature and total rate of heat loss? How does this effect tie into selection of appropriate jacket types for safety and proper balance of economics of running a plant.

Q3) As the jacket emissivity increases from 0.09 to 0.9, what change does it produce on the relative contribution of heat loss by radiation and convection towards the total heat loss? Make an argument to explain this observation.

Learning resources and tips

Insulations and jackets

https://www.globalspec.com/learnmore/manufacturing_process_equipment/stock_fabricated_materials_components/insulation_jacketing

https://www.foamglas.com/en/advice-center/general-advice/emittance-and-jacket-temperature

Plots

Use can use matplotlib library to plot graphs in python (another one is plotly, and perhaps there are others). The two types of graphs you will need are line plots and bar plots (in particular stacked bar plots).To make plot in item (c) you can use the 'subplot' feature in matplotlib. The 'annotation' and 'text' feature of matplotlib can be used to write and draw arrows/lines in the plots.

Solving equations

To solve equations you can use different libraries, example "scipy", and in particular fsolve function of scipy.

REPORT (email as pdf)

Page 1: Title page: Clearly identify your name and R#

Subsequent pages should contain the "Action items for students" (see above)

Page 2: Copy paste your output from screen for item (a)

Page 2: Underneath this printed result paste your plot for (b)

Page 3: Paste your plot for (c)

Page 4: Write your responses for Q1, Q2, Q3 in item (d)

Your python code must be emailed as a separate file as a .txt file

Preventing burns from insulated pipes

Personnel safety depends not only on pipe insulation thickness, but on the insulation jacket. The difference between a shiny and a dull jacket-surface can mean the difference between a serious burn and mild discomfort.

M. McChesney and P. McChesney, Fuel Save Associates

☐ Recently the writers were asked to advise on the insulation of steam headers—the main steam line into which boilers are connected—to ensure that the insulation was not only economic but also safe. Because of the very high steam-temperatures involved, together with the new tough laws on health and safety at work, it was imperative that there should be no risk of skin burns to those who came into contact with the insulated headers.

Steam headers are usually large-diameter pipes (up to 30-in. dia.) and in this particular case we were asked to consider both 10- and 20-in. pipes. Their insulation is essential not only to conserve heat but also to avoid high boiler base-loads, which increase the fuel bill out of all proportion to their size.

Insulation guidelines

There are general guidelines for header insulation laid down by various organizations. In the U.S., those given by NIMA (National Insulation Manufacturers Assn.) are typical [*1*]. Specifically, large-diameter hot pipes should be insulated with curved preformed sections, which should have an outer covering to ensure, among other reasons, that the insulation is neither damaged nor crushed and that it is fully protected from the weather.

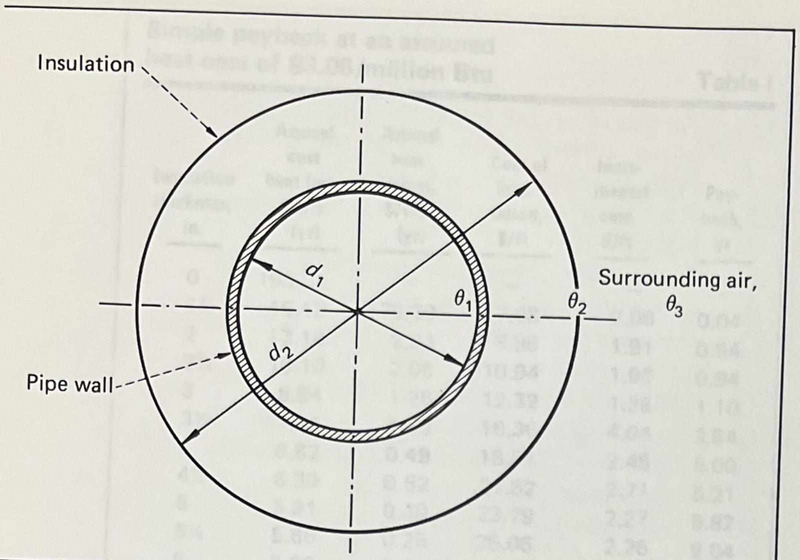
This outer finish depends upon where the pipes are. For example, if they are indoors, the finish can be lightweight canvas; but if outdoors, the finish must be completely waterproof. This is obvious, and yet what is not often realized is that once wet, insulation may never become dry. Even a steam header at 1,000°F may have wet insulation because some of the insulation will be below 212°F; the heat transfer through the insulation will only completely dry it as far as the 212° isotherm, leaving the outermost insulation still damp. Insulation containing water is only about a tenth as effective as the same insulation when completely dry.

Although both weather-barrier mastic and aluminum (or perhaps even stainless steel) jacketing are used for outdoor weather protection, the metal jacketing is to be preferred since there is a chance it will allow water vapor to escape outwards.

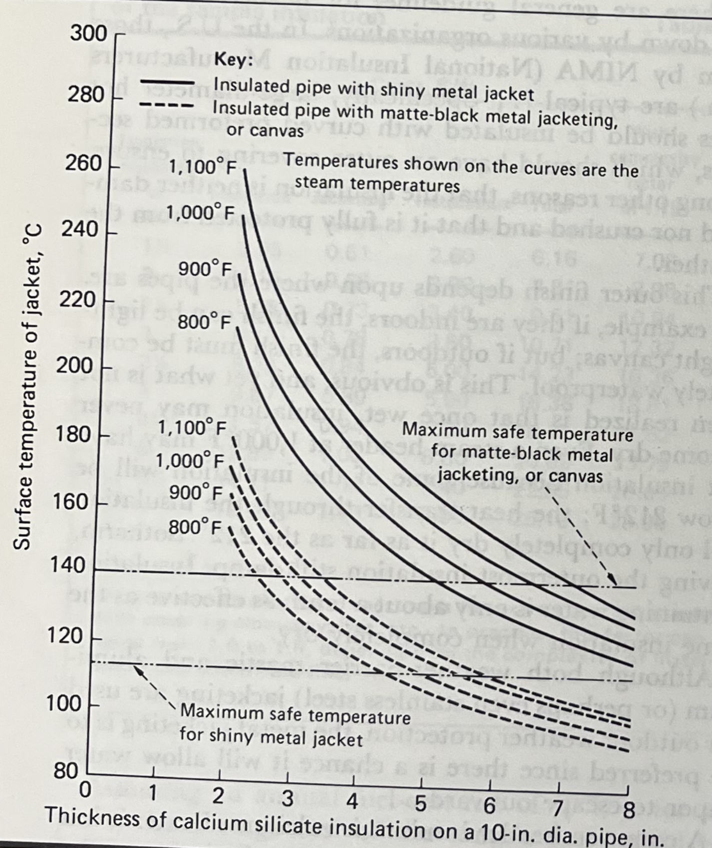
A common header insulant is calcium silicate: it has high compressive and flexural strength, it meets the specifications for prevention of stress-corrosion cracking of austenitic stainless steels and, being a mixture of lime and silica reinforced with fibers, it can readily be moulded into preformed sections. Weather protection of calcium silicate is essential since not only can it hold about 70% of its own weight of water without losing rigidity, but it has the astonishing capability of being able to hold about 350% of its own weight of water without actually dripping (showing that it is wet)!

Before attempting to calculate the economic thickness of insulation—and this proved to be a vexing problem for reasons we shall give in a later article—the writers considered the following problems: 1. What is the

Originally published July 27, 1981



Insulated steam header showing diameters and temperatures **Fig. 1**



How pipe jacketing influences surface temperature on a 10-in. header **Fig. 2**

maximum allowable "safe" temperature that the insulation surface can have such that if it is touched, either accidentally or on purpose, there is no possibility of skin burns occurring? 2. How does this surface temperature depend upon which type of insulation outer cover is used?

Effect of insulation outer-cover

It comes as a surprise to some people that the temperature of the insulation surface depends not only upon the pipe temperature and the thickness and thermal properties of the insulant, but also upon its surface condition—specifically its surface emissivity. A roughened matte surface will have a higher emissivity than a shiny metallic surface, meaning that the matte surface will have a *higher* radiation heat loss but a *lower* surface temperature than the metallic surface. There is therefore a conflict here because if we cover the insulation with canvas then we obtain a "low" surface temperature (good for personnel protection) but a "high" heat loss (bad for fuel conservation), whereas metal-jacketing the insulation will save fuel but perhaps cause skin burns to anyone unfortunate enough to touch the jacketing.

The effect of different surface emissivities is not small—we shall show that the insulation surface temperature can differ by almost 100°F, depending solely on the surface finish. Not only is this difference in temperature important from the insulation economics viewpoint, but it is crucial from the safety point of view since the rate at which skin tissue is damaged by heat depends exponentially on the temperature to which the skin is raised when in contact with a hot surface.

The heat-balance equation

Fig. 1 shows an insulated header carrying steam at a constant temperature. Even with insulation present the pipe will lose heat and, in the steady state (when the surface temperature of the insulation does not change), the heat-balance equation per foot length of pipe can be written:

Heat transfer from hot pipe through insulation by radial conduction = Heat loss from insulation surface by convection to the surrounding air + Heat loss from insulation surface by radiation to the surrounding air

Expressed mathematically:

$$\frac{2\pi k(\theta_1-\theta_2)}{\ln(d_2/d_1)} = \pi d_2 h_c(\theta_2-\theta_3) + \pi d_2 \epsilon\sigma[(\theta_2+460)^4-(\theta_3+460)^4] \quad (1)$$

Steady-state heat-balance equations often appear in technical articles. In most cases it is all too common to see the radiation-loss term on the right-hand side either ignored altogether or else incorporated into the convection heat-loss to give a surface coefficient that is sometimes treated as a constant and sometimes (in the hope of increasing accuracy) taken as a variable. While this is a perfectly satisfactory procedure in many industrial situations, it can (as in the present case) lead to errors in the overall heat-loss calculation (which is likely not too important). However, it can also lead to errors in safety considerations, which are of paramount importance.

Numerical studies of laminar natural convection based upon the nondimensional heat-transfer equation

$$\begin{pmatrix}\text{Nusselt}\\\text{number}\end{pmatrix} = \text{Constant}\cdot\begin{pmatrix}\text{Grashof}\\\text{number}\end{pmatrix}\times\begin{pmatrix}\text{Prandtl}\\\text{number}\end{pmatrix}^n$$

show that an excellent, convenient and accurate approximation for the convective heat-transfer coefficient for a horizontal hot circular pipe is

$$h_c = 0.270(\theta_2-\theta_3)^{0.25}d_2^{-0.25}$$

In these equations the values of k and σ are taken as constants, while the values of d_1, d_2, θ_1, θ_3, ε are to be specified. This leaves the equation to be solved for θ_2, which is the all-important insulation surface-temperature.

The heat-balance equation cannot be solved algebraically since it is a quartic whose lower-order terms have non-integral powers, but it can be solved on a computer using the Newton-Raphson iterative technique. The results are shown in Fig. 2 and 3.

The substantial difference between the jacket surface-temperatures for the two chosen values of surface emissivity is very striking indeed. The value $\varepsilon = 0.09$ is a representative figure for shiny aluminum jacketing, while the value $\varepsilon = 0.9$ is typical of canvas either covered with thick dust or, better, painted with a matte oil-bound paint. For example, this difference in surface emissivity alone can reduce the jacket surface-temperature from 286°F to 192°F for a pipe temperature of 1,100°F on a 20-in.-dia. header having 2-in.-thick insulation.

This drop in surface temperature due to differences in surface emissivity decreases as the insulation thickness increases or the pipe temperature decreases, but it is still greater than 30°F even for a pipe temperature as "low" as 800°F with an insulation thickness as great as 6 in. Although a 30°F temperature difference is unimportant in terms of the economics of insulation, it is very important indeed from the safety viewpoint since it can make all the difference between the possibility of skin burn and no injury at all.

The "safe" temperature

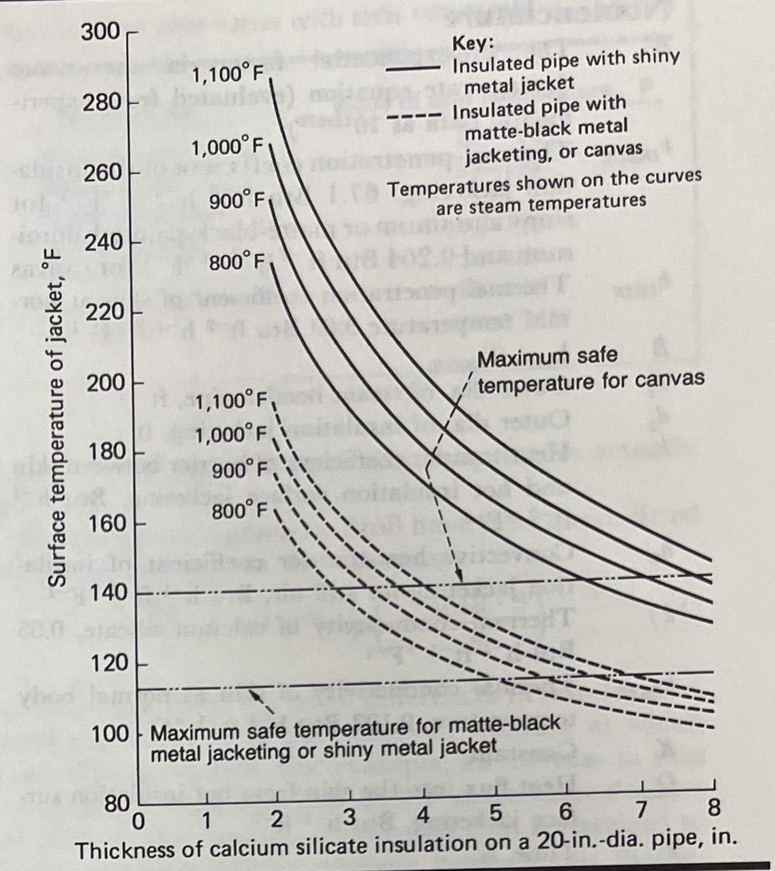
What is the value of an acceptable surface temperature to ensure that no skin burn will occur if that surface is touched? On reading through the literature, one finds that there is no single answer to the question. Malloy [2] remarks that "metallic surfaces at temperatures in excess of 145°F can cause skin burns but a specific figure is not available as this would depend upon the person concerned, the roughness of the metallic surface and the thermal properties of the insulation material." The British Standard, BS 4086 [3], states that for hot *domestic* (not industrial) equipment, the following are the maximum surface temperatures if skin burn is to be avoided:

- Metallic surface that will be gripped, 130°F.
- Metallic surfaces that will be deliberately touched but not gripped, 140°F.
- Metallic surfaces that may be accidentally touched but not gripped, 220°F.
- For vitreous or plastic materials the permitted maximum temperatures are higher.

The British Standard Code of Practice, CP 3005 [4], recommends that in industrial situations, the maximum "safe" temperatures are:

- Metallic surfaces that can be reached from the floor, 135°F
- Non-metallic surfaces that can be reached from the floor, 150°F

This range of "safe" temperatures is not helpful to the plant engineer concerned with insulation economics and safety because it is too large. If he accepts the higher temperatures, he may practice good economics but cause skin burn to personnel.



Influence of jacket type on surface temperature for a 20-in. header **Fig. 3**

Physiological studies of skin burn

Physiologists have studied pain and injury due to hot and cold surfaces for many years and have explained some—but by no means all—of the very complicated processes that occur within injured skin tissue. They make an important and clear distinction between pain and injury. In the context of skin burn, it is believed that the 21 just noticeable differences in pain intensity are in fact independent of the time taken for the skin to respond to a heat stimulus. However, the essential ingredient for injury, as opposed to pain, after exposure to heat (not necessarily actual physical contact with a hot surface) is a raising of the skin temperature to a threshold level of 113°F.

This temperature level, and of course higher temperatures, must be sustained for "a sufficient time"—not only the actual contact time with the hot insulation surface but also the remainder of the time that the skin remains above 113°F after physical contact has been broken.

The fact that the skin can continue to be damaged while cooling down is a very important consideration. In everyday life when we either blow upon a burn or hold it under a cold-water tap, we are instinctively trying to accelerate the cooling process.

Physiologists have found that equal heat loads (Btu/ft^2) do not produce the same skin damage. Damage depends upon the *rate* at which the heat is transferred to the skin—the higher this rate, the greater the injury.

Nomenclature

- A — The pre-exponential factor in the tissue damage-rate equation (evaluated from experimental data as $10^{11.479}$)
- b_{INSUL} — Thermal-penetration coefficient of the insulation jacketing: 67.1 Btu ft^{-2} h$^{-1/2}$ °F^{-1} for shiny aluminum or matte-black-painted aluminum and 0.264 Btu ft^{-2} h$^{-1/2}$ °F^{-1} for canvas
- b_{SKIN} — Thermal-penetration coefficient of skin at normal temperature 3.69 Btu ft^{-2} h$^{-1/2}$ °F^{-1}
- B — b_{SKIN}/b_{INSUL}
- d_1 — Outer dia. of steam header pipe, ft
- d_2 — Outer dia. of insulation jacketing, ft
- h — Heat-transfer coefficient of barrier between skin and hot insulation surface jacketing, Btu h^{-1} ft^{-2} °F^{-1}
- h_C — Convective heat-transfer coefficient of insulation jacketing for still air, Btu h^{-1} ft^{-2} °F^{-1}
- k — Thermal conductivity of calcium silicate, 0.05 Btu h^{-1} ft^{-1} °F^{-1}
- k_{SKIN} — Thermal conductivity of skin at normal body temperature, 0.192 Btu h^{-1} ft^{-1} °F^{-1}
- K — Constant
- Q — Heat flux into the skin from hot insulation surface jacketing, Btu h^{-1} ft^{-2}
- t — Time, h
- x — Depth below skin surface, ft
- ε — Surface emissivity of the insulation jacketing
- θ_1 — Temperature of the steam in header, °F
- θ_2 — Temperature of the insulation jacketing, °F
- θ_3 — Temperature of still air (70°F)
- θ_4 — Instantaneous skin surface temperature, °F
- θ_5 — Normal surface temperature of the skin (95°F)
- $\theta(x,t)$ — Temperature of the skin as a function of depth x and time t
- σ — Stefan's radiation constant, 0.171×10^{-8} Btu h^{-1} ft^{-2} °R^{-4}
- ϕ — Nondimensional variable ($\exp \phi \simeq (1 + \phi)$)
- Ω — Degree of skin injury; $\Omega = 1$ is condition for complete trans-epidermal necrosis
- X — $b_{SKIN}x/2k_{SKIN}\sqrt{t}$
- erf — Error function
- exp — Exponential function

Mathematical modelling of skin heating

Let us try to model a situation where some exposed skin comes into contact with the hot surface of the pipe insulation—as idealized to the thermal contact between two semi-infinite bodies with a nonsteady conduction heat-transfer between them. This is a heat-transfer problem that has been solved by Hsu [5]; the result is:

$$\theta(x,t) = \theta_4[1 - \operatorname{erf}(X)] + \theta_5 \cdot \operatorname{erf}(X) \quad (2)$$

where

$$\theta_4 = \frac{\theta_2 + B\theta_5}{1 + B} \quad (3)$$

On elimination of θ_4, this gives:

$$\theta(x,t) = \frac{\theta_2 + B\theta_5}{1 + B} - \left(\frac{\theta_2 - \theta_5}{1 + B}\right)\operatorname{erf}(X) \quad (4)$$

The heat flux into the skin is:

$$Q = \frac{b_{SKIN}}{\sqrt{\pi t}} \cdot (\theta_4 - \theta_5) \quad (5)$$

$$= \frac{1}{\sqrt{\pi}\sqrt{t}} \cdot \left(\frac{1}{\frac{1}{b_{SKIN}} + \frac{1}{b_{INSUL}}}\right) \cdot (\theta_2 - \theta_5) \quad (6)$$

The meaning of Eq. (2) and (3) is that, at the moment of contact, the interface (i.e., the skin's surface) rises *instantaneously* to the temperature θ_4, and thereafter there is a heat flow from the hot insulation surface into the skin. This flow, according to Eq. (5) and (6), is instantaneously infinite but thereafter decreases to a finite value.

Let us use these equations to determine the value of the instantaneous skin temperature θ_4 for the two insulation surface coverings already discussed. For an aluminum jacket covering, B has a value of about 0.055, so that

$$(\theta_4)_{METAL} = \frac{\theta_2 + 5 \cdot 2}{1.055} \simeq \theta_2 \quad (7)$$

This shows that the instantaneous skin temperature is always close to the insulation surface temperature, which represents a considerable hazard indeed. However, for a canvas jacket, B has a value of about 14, so that

$$(\theta_4)_{CANVAS} = \frac{\theta_2 + 1330}{15} \simeq 89 + \frac{\theta_2}{15} \quad (8)$$

meaning that the instantaneous skin temperature is always slightly—but not significantly—greater than 95°F, provided that we are concerned with hot and not cold surfaces; this is excellent from the safety viewpoint.

In addition, Eq. (6) shows that

$$\frac{Q_{METAL}}{Q_{CANVAS}} = 14 \quad (9)$$

which means that the heat-transfer rate, for equal time intervals and equal values of $(\theta_2 - \theta_5)$, from the metal to the skin is 14 times that from the canvas to the skin.

These results, once again, confirm everyday experience, which tells us that it is safer to touch (or even grip) a hot canvas surface than an aluminum surface at the same temperature. Such confirmation gives us confidence in our mathematical model. Unfortunately, however, if we compare the actual numerical values predicted by the above equations with the values obtained in experiment by the physiologists, then there are considerable discrepancies.

In terms of body reaction, Table I shows what happens when the skin temperature is raised from a level where the normal sensation of warmth alters to a sensation of burning and pain, followed by a rising level of pain and increased injury, to severe and then intolerable pain, and finally numbness—with irreversible destruction of the skin tissue and loss of all sensation. Experiments reported by Stoll [6] consider the problem of a *variable*-thermal-property material (which is what skin is) being subjected to various heat fluxes so that its temperature rises slowly (measured in seconds) to a high value, but certainly not instantaneously as predicted by Eq. 2, 3 and 4. This slow rate of skin temperature rise observed in the real-life situation could be the result of one or more of a number of effects, such as a heat-flow contact resistance (a barrier to heat flow) arising because of the presence of sweat or dirt on either or both the skin and the insulation surface.

Modelling a skin heat-flow barrier

A first attempt at a mathematical model is the thermal conduction interaction between two semi-infinite materials with a barrier of constant heat-transfer coefficient between them. Such a problem has been solved by Schneider [7], who gives the solution

$$\frac{\theta(x,t)-\theta_5}{\theta_4-\theta_5} = 1-\mathrm{erf}(X) - \left[\exp\left\{\frac{hx}{k_{SKIN}}+\frac{h^2t}{b_{SKIN}}\right\}\right]\cdot\left[1-\mathrm{erf}\left(X+\frac{h\sqrt{t}}{b_{SKIN}}\right)\right] \quad (10)$$

When there is no barrier present, $h \rightarrow \infty$ and Eq. (10) becomes identical to Eq. (2). If we concern ourselves with short times of exposure (measured in seconds rather than hours) and zero tissue depth, i.e. the surface of the skin, then using the mathematical approximations

$$\mathrm{erf}(X) \simeq X \quad \text{and} \quad \exp\phi \simeq 1+\phi$$

we obtain Eq. (10) in the form

$$\frac{\theta(0,t)-\theta_5}{\theta_4-\theta_5} = \frac{h\sqrt{t}}{b_{SKIN}} - \left(\frac{h\sqrt{t}}{b_{SKIN}}\right)^2 + \left(\frac{h\sqrt{t}}{b_{SKIN}}\right)^3 \quad (11)$$

For a thin film of moisture, taking values of h lying between 1 and 10 Btu ft^{-2}h^{-1}°F^{-1} and time intervals between 1 and 4 seconds, we find that the right-hand side of Eq. (11) has values lying between 4.5×10^{-3} and 9×10^{-2}, so that the skin temperature is close to its original value of 95°F. This means that the presence of even a thin barrier to heat flow can dramatically alter the value of the instantaneous skin temperature, reducing it from the high and dangerous values predicted, for example, by Eq. (7). It is arguable that considerations such as these, together with the fact that the value of b_{SKIN} is known to double at high skin temperatures due to vaso-dilation (increased blood flow producing increased thermal conductivity of the skin), cause the discrepancy between the predictions of Eq. 4 and 6 and the values actually observed, in the laboratory, by the physiologists.

The physiologists have empirically related skin-damage rate to the skin-temperature-versus-time behaviour in the form:

$$\text{Tissue damage rate} = \frac{d\Omega}{dt} = A\exp\left(-\frac{K}{\theta}\right) \quad (12)$$

where the total damage is

$$\Omega = \int_{HEATING}\frac{d\Omega}{dt}\cdot dt + \int_{COOLING}\frac{d\Omega}{dt}\cdot dt \quad (13)$$

such that $\Omega = 1$ is the condition for complete trans-epidermal necrosis. The integration limits in both cases are those appropriate to the threshold temperature for injury (113°F) and the peak skin temperature actually reached.

How level of pain varies with skin temperature — Table I

Sensation felt	Value of skin temperature, °F
No sensation	82–93
Warm to hot	93–113
Threshold of pain	113
Increasing pain	113–126
Severe pain	126–133
Intolerable pain	133–140
Numbness	Above 140

Numerical data given by Stoll have been curve-fitted by the writers to give the equation

$$\frac{d\Omega}{dt} = 10^{11.479}\exp\left(-\frac{3618\cdot 3}{\theta}\right) \quad (14)$$

which means that very small differences in skin temperature can make large differences in the rate at which tissue damage occurs. For example, an increase in skin temperature from 140°F to 145°F more than doubles the rate of skin damage. Clearly, all that is required to bridge the heat-transfer analysis given in our mathematical models to the physiological data is to evaluate Eq. (13) using Eq. (14) which relates the skin temperature to time, and then use $\Omega = 1$ as the skin-burn criterion. Unfortunately, it is this last step that, as yet, cannot be taken because there is no heat-transfer theory that reliably predicts how the skin temperature varies with time (as opposed to measuring it with live human beings in the medical laboratory and thereafter performing numerical integration, as has been done by the physiologists).

Proposals for "safe" temperatures

In spite of this failure to bring together heat-transfer theory and medical observation, we can draw upon some of the conclusions of the above analysis to frame tentative criteria for "safe" temperatures. Because of the uncertainty of the mathematical modelling, coupled with the most important consideration of ensuring safety to personnel, *these criteria must err very much on the side of caution* because of the extreme sensitivity of the damage rate to skin temperature. It was for just these reasons that the writers returned to the more exact heat-balance Eq. 1 for pipe heat-loss rather than that normally used in typical insulation-thickness studies.

Since Eq. (7) shows that the instantaneous skin temperature in the idealized heat-transfer analysis is always very close to the metal-jacketed-insulation surface temperature, and since the threshold of pain and injury is 113°F, we propose that for an aluminum jacket the surface temperature should never be higher than 113°F. However, in the case of the canvas jacketing, we recognize the lower instantaneous skin temperature and heat-transfer rate predicted by the idealized theory of Eq. (8) and (9) and therefore we can allow a higher insulation surface temperature.

Amount of calcium silicate insulation to ensure its surface temperature does not exceed 140° F — Table II

Steam temperature, °F	Minimum insulation thickness, in. 10-in. pipe	20-in. pipe
800	2½	3
900	3	3½
1,000	3½	4
1,100	3½	4

There is of course the possibility of an inherent danger in this slower heat-transfer rate because the skin temperature, although rising more slowly, can still rise to a value higher than initially appreciated and sensed, and skin damage will occur during the contact period combined with the noncontact period during which the skin is cooling down from its peak temperature back to 113°F. Since physiologists tell us that skin is destroyed "instantaneously" once its temperature reaches 162°F, we propose that the maximum temperature of the canvas jacket covering the insulation surface should be 140°F.

Effect of proposals on insulation thickness

One immediate and important consequence of these proposals comes from referring to Fig. 2 and 3. This is that even *6 in. of calcium silicate* over either the 10- or the 20-in. header is totally insufficient to reduce the temperature of the shiny aluminum jacket to the "safe" value we propose (113°F). It is also clear from the graphs that, depending on the value of the pipe temperature θ_1, it will be necessary to increase the thickness of the calcium silicate insulation up to what are likely to be unacceptable values (as much as 12 in.), or, more sensibly, to increase significantly the surface emissivity of the metal jacket.

There will inevitably be an increase in the surface emissivity of any initially shiny aluminum jacketing as it oxidizes by natural "weathering," but this is still not sufficient since the surface emissivity of heavily oxidized aluminum is only 0.31. It will therefore be necessary to paint the jacketing with a very thick layer of high-temperature-resistant matte ("flat") oil-bound paint to raise the surface emissivity to 0.9 or higher.

It might seem surprising that a thick coat of paint alone can cause such a great change in heat output and surface temperature. However, this is a well-known effect with central heating panels; tests have shown that painting these panels with ordinary oil-bound paints and enamels has little or no effect, irrespective of the color chosen, since all have high emissivities when dry. However, a coat of metallic paint on a central heating panel will reduce the overall heat output by up to 25% because of the reduction of 50% or more in the radiant heat output. In addition, these tests show that the heat output is substantially restored by two thick coats of clear varnish! Since central heating panels are really convectors rather than radiators and operate at temperatures far lower than the steam headers considered here, we have no difficulty in appreciating the great effect that the surface emissivity has on the surface temperature and heat output because of the Stefan-Boltzmann heat-loss equation, which contains the fourth power of the radiating-surface temperature.

Referring to Fig. 2 and 3 and the proposed criteria given for the "safe" temperature of aluminum jacketing with a thick matte finish (or, alternatively, a canvas jacket), we can draw up Table II which shows the minimum thicknesses of calcium silicate insulation that must be provided to ensure no hazard to personnel.

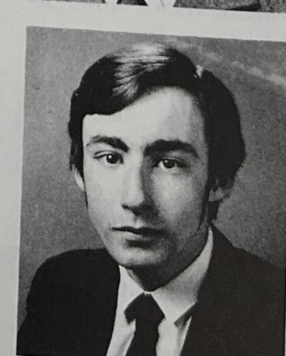
It must be remembered, of course, that this is only part of the story, because consideration must be given to reducing the heat loss from the steam headers to an acceptable value. The writers therefore turned their attention to calculating the economic thickness of insulation—subject to the proposed "safe" temperatures proposed here—using the ECON and ETI procedures, and after considerable computer analysis were obliged to abandon this orthodox methodology and adopt a totally different approach to sizing header insulation. The reasons for this form the contents of the article on p. 139.

References

1. Perry, R. H., and Chilton, C. H., "Chemical Engineers' Handbook," 5th ed., McGraw-Hill, New York, 1973.
2. Malloy, J. F., "Thermal Insulation," Van Nostrand-Reinhold, New York, 1969.
3. British Standards Institute, BS.4086: Recommendations for maximum surface temperature of heated domestic equipment, 1966.
4. British Standards Institute, Code of Practice 3005: Thermal insulation of pipework and equipment, 1969.
5. Hsu, S. T., "Engineering Heat Transfer," Van Nostrand, New York, 1963.
6. Stoll, A. M., "Advances in Heat Transfer," Vol. 4, "Heat Transfer in Biotechnology," Academic Press, 1967.
7. Schneider, P. J., "Conduction Heat Transfer," Addison-Wesley, Reading, Mass., 1974.

The authors

Malcolm McChesney is founder and Senior Associate of Fuel Save Associates, a group of energy consultants. He is also Senior Lecturer in Energy Studies and Thermodynamics in the Dept. of Mechanical Engineering, University of Liverpool, P.O. Box 147, Liverpool, L69 3BX, U.K. He has written over 20 research papers, three books, and articles for the Encyclopaedia Britannica and *Scientific American*.



Peter McChesney is a college student and Associate (computing) in Fuel Save Associates. He is the son of Malcolm McChesney. Since the age of 12 he has published articles on analog and digital circuitry, ranging from analog to digital converters through musical synthesizers to microprocessor-based hardware. He was a U.K. North-West prize winner in the 1979 Young Engineer for Britain Competition, for designing and constructing a multiplexed digital system for monitoring failure in a chain of steam traps.