

A FUNDAMENTAL APPROACH TO FIREBOX HEAT EXCHANGE

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BACKGROUND

This work forms part of an ongoing project to develop a design tool to predict steady state boiler performance from the boiler geometry and operating parameters.

The aim is to work from well established modern principles avoiding empirical correlations of historical test results.

PART 1

**WHY DO WE NEED ANOTHER
WAY?**

WHY DEVELOP ANOTHER WAY?

Existing correlations :-

Nicholson

Rowland, Fry, Hudson & Orrok, Klie, Giesl
to pick just a few from APT's book.

**All rely on correlations of test data derived
from burning lump coal.**

WHY DEVELOP ANOTHER WAY?

To improve our understanding of what goes on.

Existing correlations cannot deal with:

- Superheaters in the radiant space.
- Firing with fuels such as gas or oil – especially blue flame burners.
- Miniature or model locomotive boilers

WHY DEVELOP ANOTHER WAY?

- Existing correlations have a hidden assumption about how the radiant heat is transferred.
- Early correlations tend to assume the firebed radiates as a black body. (A good approximation)
- Later correlations assume gas radiates very like a black body. (It ain't necessarily so)

WHY DEVELOP ANOTHER WAY?

If we are going to avoid those assumptions we need to be more precise about :-

- Where combustion takes place in the box.
- The radiative properties of combustion gas.
- How heat radiates from the fuel to the water or steam.

PART 2

COMBUSTION

COMBUSTION

Where does heat release take place?

- With a lump coal fire, mostly in the bed. Only a small fraction combusts in the firebox volume.
- With gas, oil or pulverised fuel, nearly all combustion is in the firebox volume.

For gas or oil firing, Ortiz proposes a heat release of the form :- $Y = 1 - \exp(-4.6 x/L)$

COMBUSTION

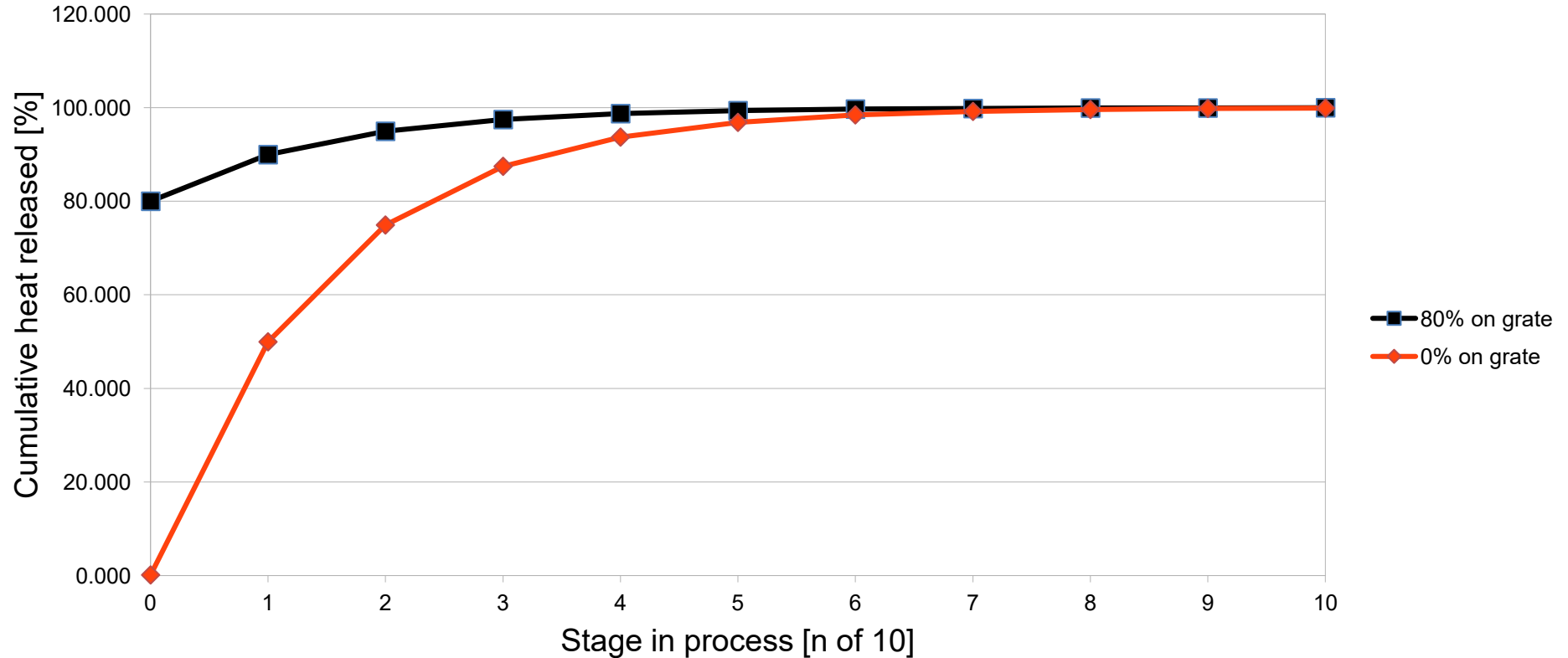
I have extended that to a 2 part model :-

Let A = proportion that burns **ON** the grate.
(Approximately the fixed carbon content in a coal.)

Then the fuel combusts in the firebox volume according to:-

COMBUSTION

The effect of where fuel is burned.

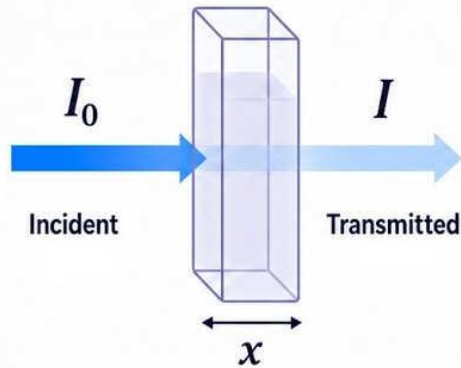


PART 3

COMBUSTION GAS RADIATION

COMBUSTION GAS RADIATION

Grey gases – Definition



$$I = I_0 e^{-\alpha x}$$

α = Absorption Coefficient

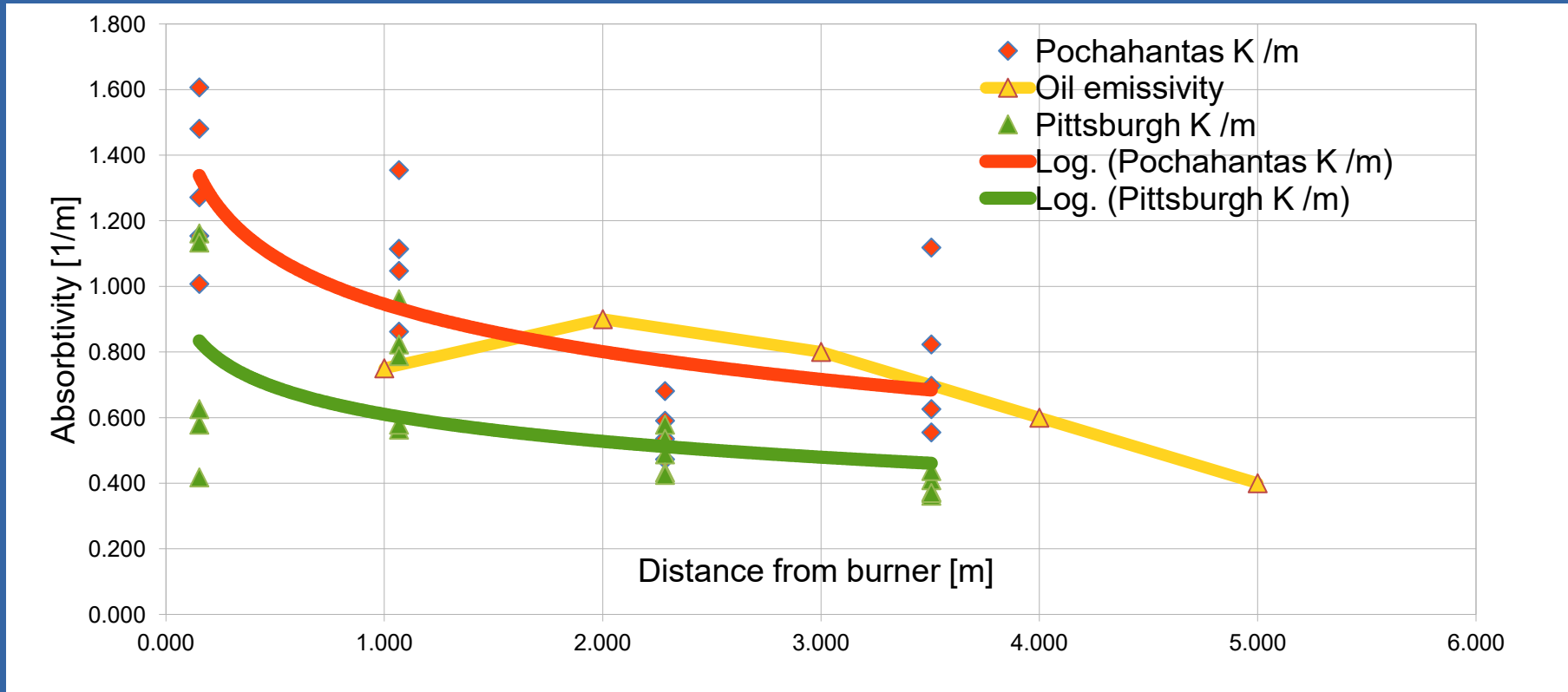
- If the medium is non-reflecting, $\tau_\lambda + \alpha_\lambda = 1$
- And the spectral absorptivity α_λ over the path L is $\alpha_\lambda = 1 - e^{-\kappa_\lambda L}$
- When Kirchhoff's law is applicable, the spectral absorptivity α_λ is equal to spectral emissivity ε_λ

$$\varepsilon_\lambda = 1 - e^{-\kappa_\lambda L}$$

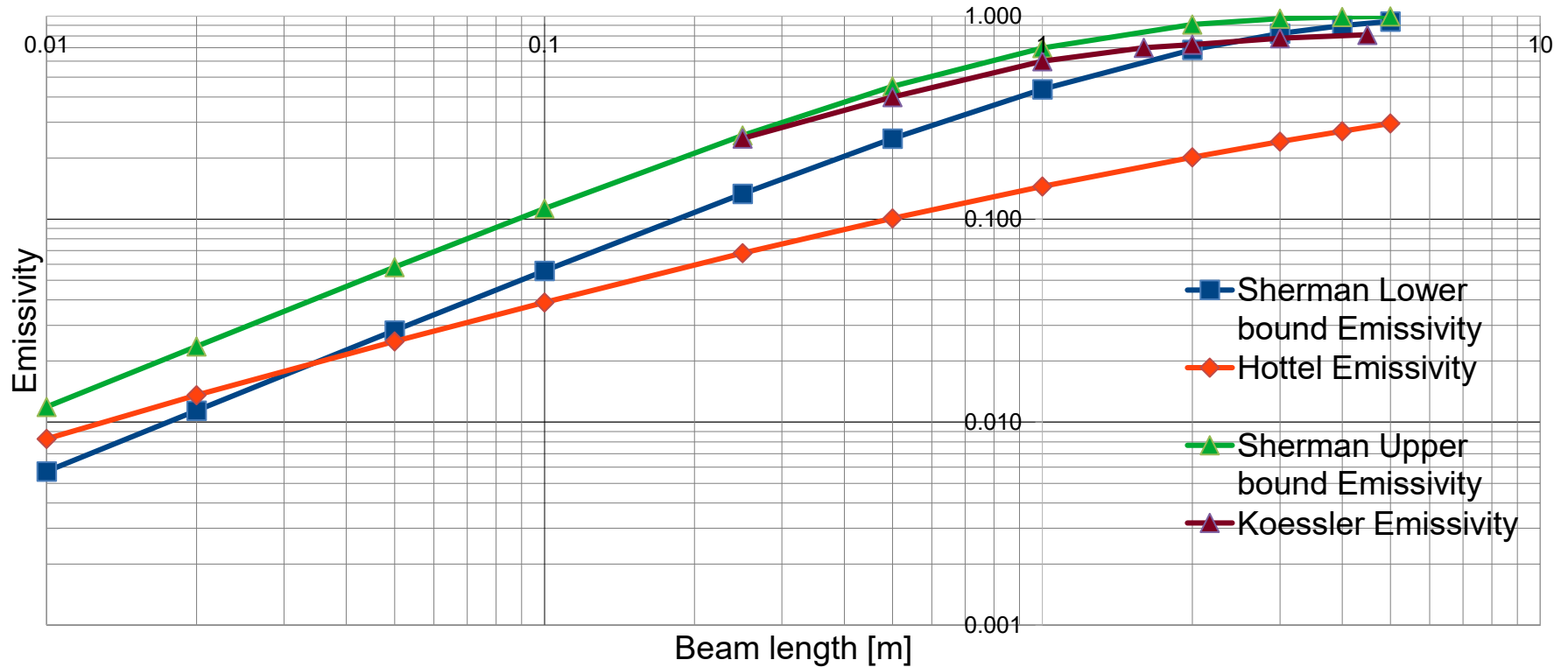
Absorption coeff. does not vary with wavelength

COMBUSTION GAS RADIATION

Pulverised fuel research by Sherman, Trans. ASME. May 1934,
56(5): 401-409



GAS RADIATION – SIZE MATTERS!



PART 4

RADIATION NETWORKS

RADIATION IN A FIREBOX

A firebox typically comprises 4 different surfaces :-

- Firebed, Gas, Brick Arch (or Radiant superheater), Wall.
- The relative importance of firebed and gas radiation varies with scale, fuel type & burner.
- The relative temperatures of the 4 surfaces can change with firing type (e.g. coal, gas or oil).

RADIATION RADIATES TO EVERYTHING ELSE

How to cope with such a
calculation?

Combinations of 4 bodies:

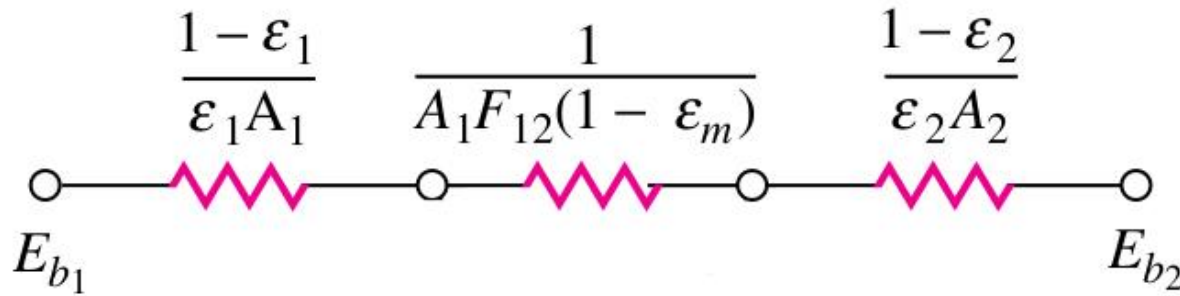
1 radiates to 2, 3, & 4

2 radiates to 3 & 4

3 radiates to 4

RADIATION RADIATES TO EVERYTHING ELSE

A 2 body model:



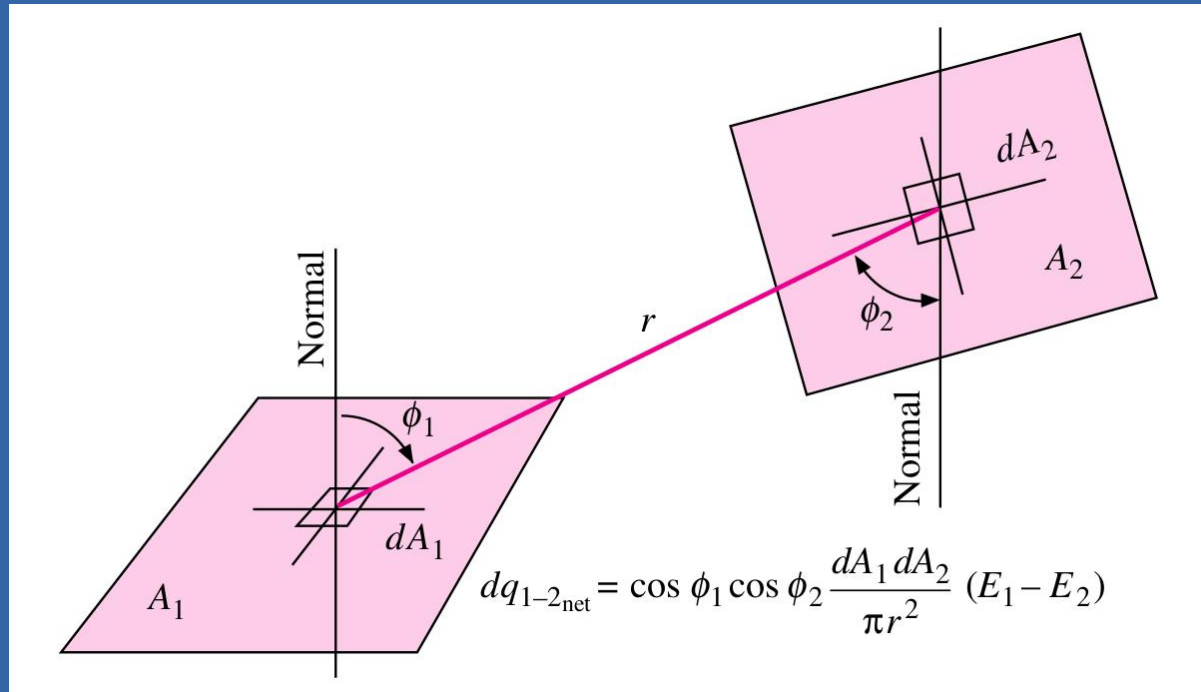
$$E_b = \sigma T^4$$

$E_b \equiv$ Volts
Heat flow $\equiv$ Amps

This can be reduced to a single equation

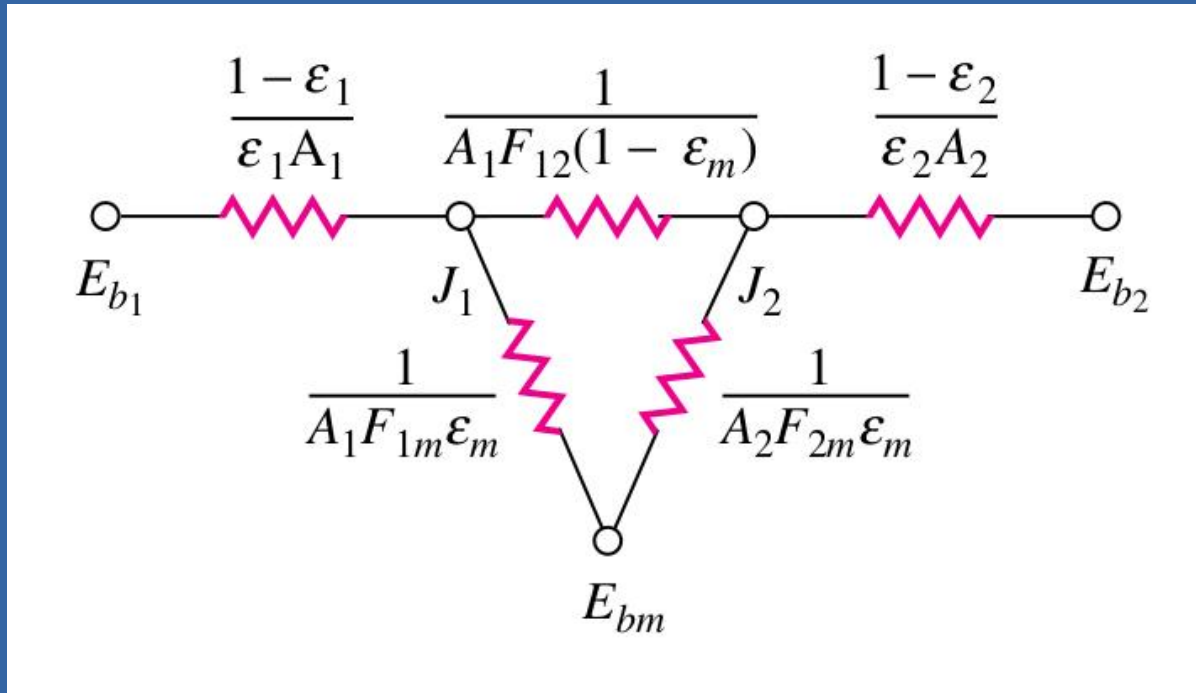
RADIATION NETWORKS

FORM FACTORS



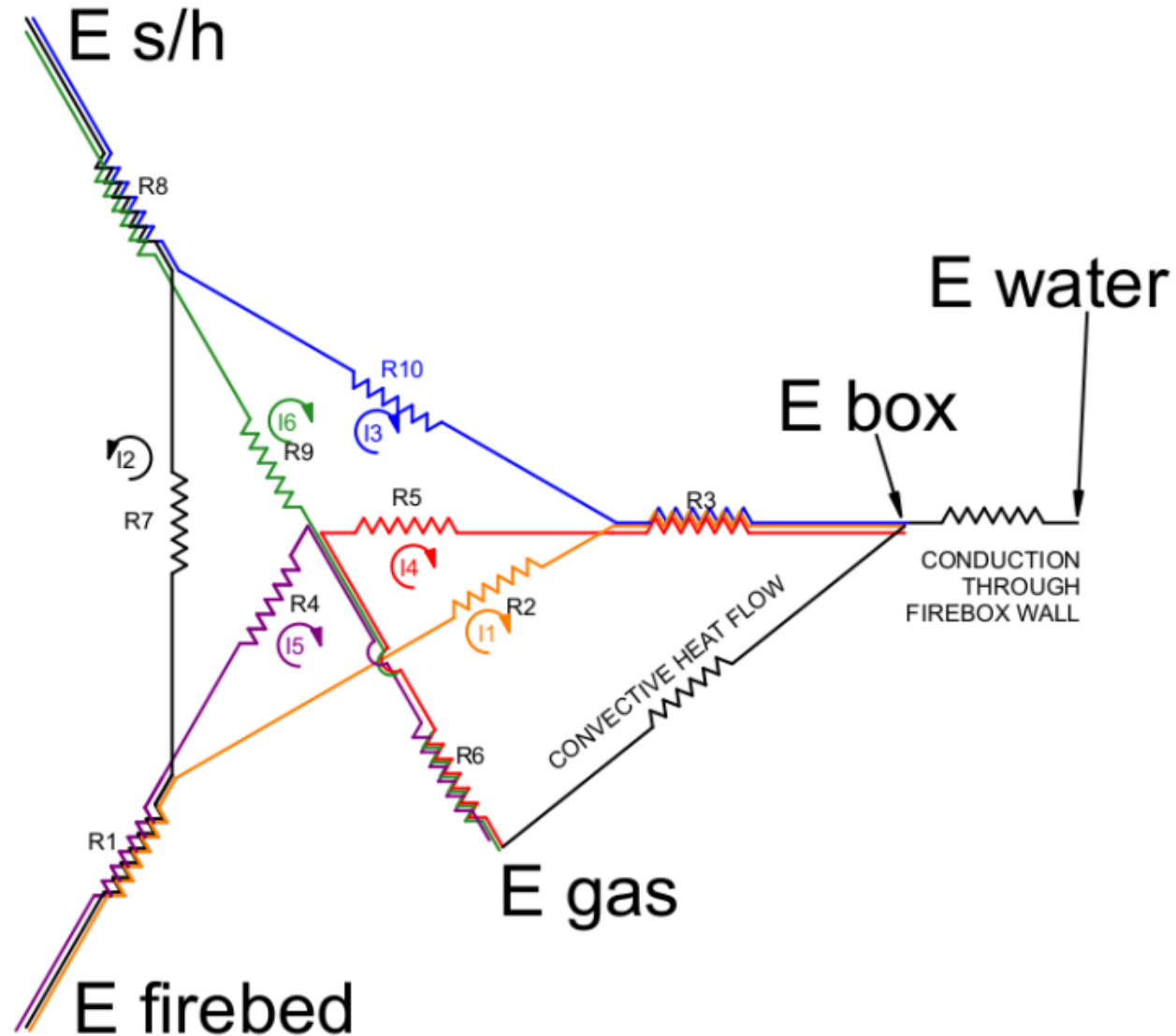
RADIATION NETWORKS

2 BODIES + GAS



This cannot be reduced to a single equation

RADIATION DIAGRAM 3 BODIES + GAS



RADIATION DIAGRAM

3 BODIES + GAS

$$E_{grate} - E_{box} = R_3(I_1 + I_4 + I_3) + R_2(I_1) + R_1(I_1 + I_5 + I_2)$$

$$E_{grate} - E_{sh} = R_8(I_2 + I_6 - I_3) + R_7(I_2) + R_1(I_2 + I_5 + I_1)$$

$$E_{sh} - E_{box} = R_3(I_1 + I_4 + I_3) + R_{10}(I_3) + R_8(I_3 - I_2 - I_6)$$

$$E_{gas} - E_{box} = R_3(I_1 + I_4 + I_3) + R_5(I_4) + R_6(I_4 + I_6 - I_5)$$

$$E_{gas} - E_{sh} = R_8(I_2 + I_6 - I_3) + R_9(I_6) + R_6(I_6 + I_4 - I_5)$$

$$E_{grate} - E_{gas} = R_6(I_5 - I_4 - I_6) + R_4(I_5) + R_1(I_1 + I_5 + I_2)$$

RADIATION DIAGRAM

3 BODIES + GAS

Re-arranging and grouping the I terms gives the following matrix:

	I_1	I_2	I_3	I_4	I_5	I_6
$E_{grate} - E_{box}$	$R_3 + R_2 + R_1$	R_1	R_3	R_3	R_1	0
$E_{grate} - E_{sh}$	R_1	$R_8 + R_7 + R_1$	$-R_8$	0	R_1	R_8
$E_{sh} - E_{box}$	R_3	$-R_8$	$R_3 + R_{10} + R_8$	R_3	0	$-R_8$
$E_{gas} - E_{box}$	R_3	0	R_3	$R_3 + R_5 + R_6$	$-R_6$	R_6
$E_{gas} - E_{sh}$	R_1	R_1	0	$-R_6$	$R_6 + R_4 + R_1$	$-R_6$
$E_{grate} - E_{gas}$	0	R_8	$-R_8$	R_6	$-R_6$	$R_8 + R_9 + R_6$

Use “Matrix Invert” and “Matrix Multiply” spreadsheet functions to solve I values
(You can’t do division with matrices)

SOLVING 3 BODIES + GAS

Summary :-

- 4 body radiation diagram gives 6 simultaneous equations (1 for each heat flow).
- Manipulate to give a 6x6 matrix in R and a 6 term vector in ΔE .
- Use “Matrix Invert” and “Matrix Multiply” spreadsheet functions we get the corresponding heat flows for the 6 possible circuits.

PART 5

TEMPERATURE – THE GREAT UNKNOWN

4 PROBLEMS

- Firebox wall temperature – known (approx.)
- Radiant superheater wall temperature – a function of heat flow, steam conditions & flow.
- (or Brick arch temperature – not known.)
- Gas temperature – not known & varies through firebox.
- Firebed temperature – not known.

FIREBED TEMPERATURE

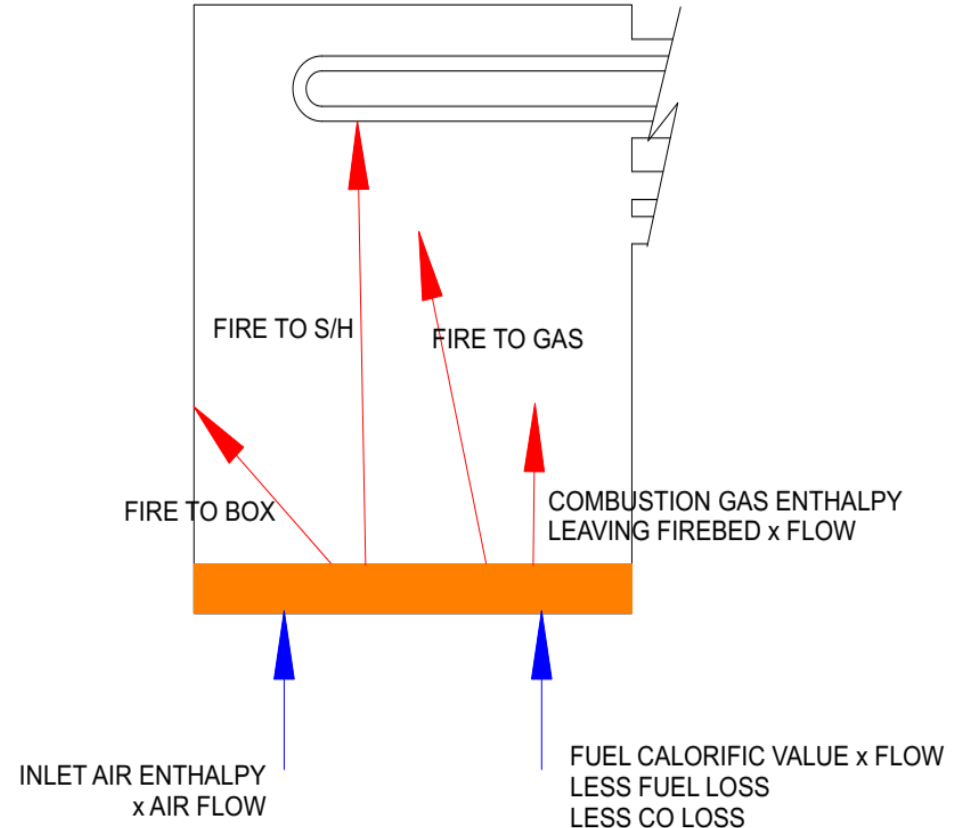
1st Guess: Take adiabatic combustion temp. =
Firebed temp. = Gas temp.

The adiabatic temperature is based on combustion within the firebed only (i.e. excluding combustion within the box volume).

The fire will be cooler than adiabatic temperature as it radiates energy to the firebox.

FIREBED TEMPERATURE

- Fire bed approximate heat balance
- Gas temperature is not known.



GAS TEMPERATURE LEAVING FIRE BED

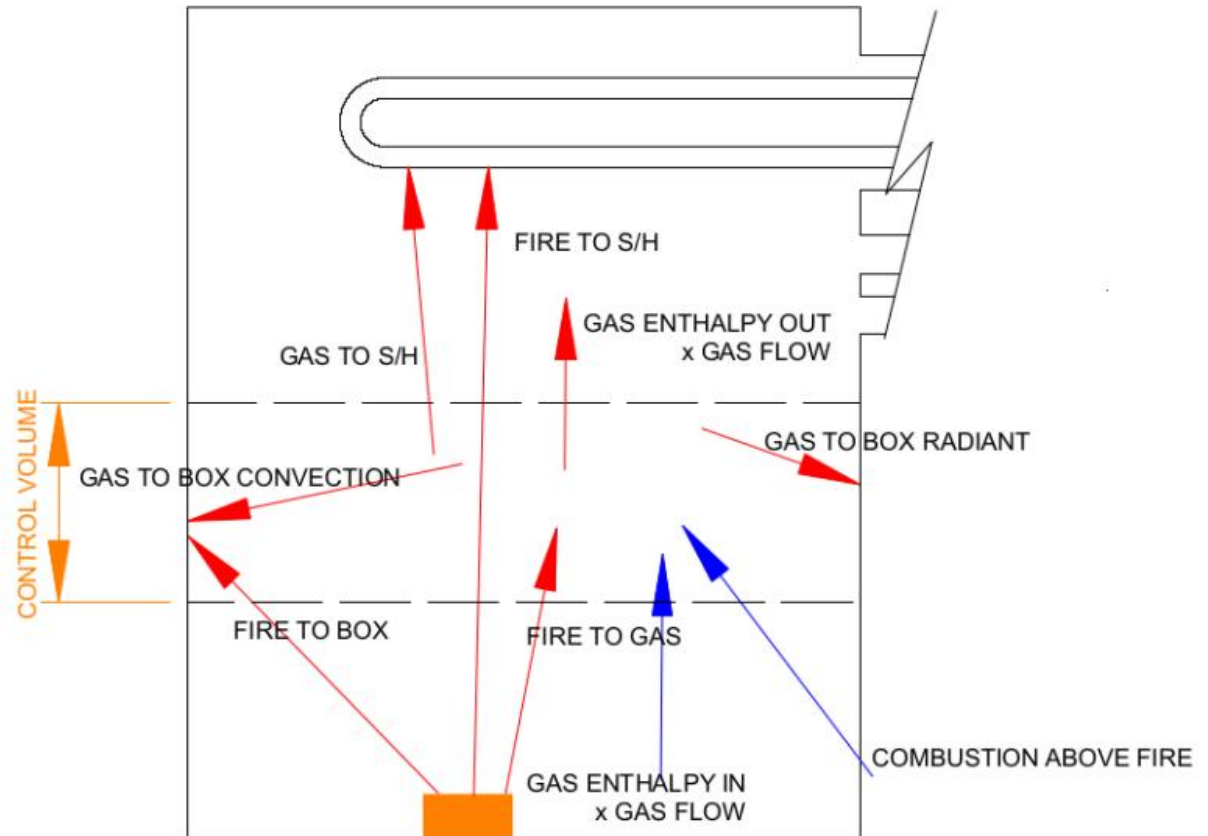
- 2 Cases to consider :-
 - Oil or Gas Burners – No heat generated IN firebed, so gas temperature = air temperature.
 - Lump Coal Burners – Heat is generated within firebed but relative gas and solid temperatures not known. **Assume** gas = solid temperature within bed.

GAS TEMPERATURE

- Assuming we know gas temperature leaving firebed.
- We now split the firebox into 10 imaginary sections.
- Each of $1/10$ the area and $1/10$ the volume.
(More on that later)
- For each section, the heat balance and gas temperature drop is calculated.

DETAILED ENERGY BALANCE

Heat balance for
each
1/10 element
leads to a gas
temperature
profile.



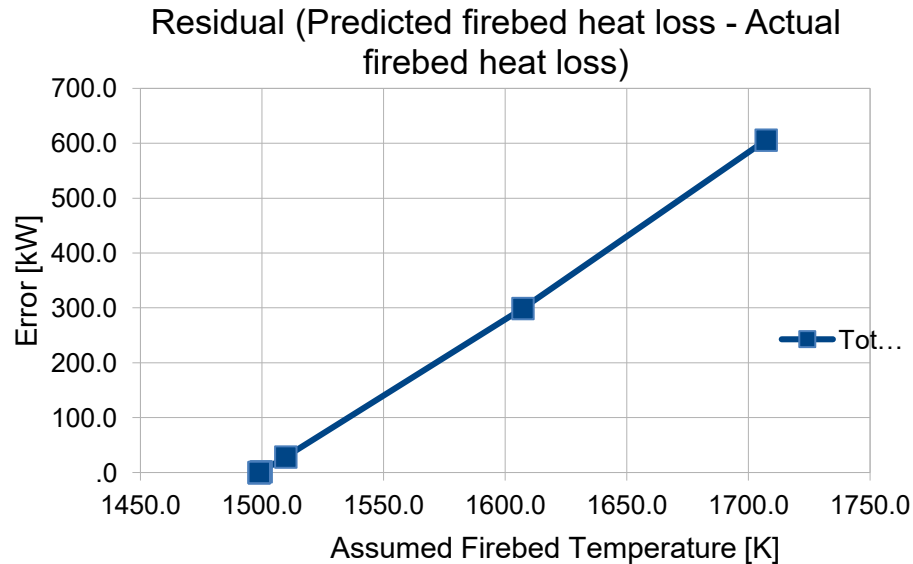
DERIVING A TEMPERATURE PROFILE

- Since each 1/10 section in the firebox is gaining or losing heat, the gas temperature changes from the firebed temperature.
- The temperature change across the 10 sections are numerically integrated to derive a temperature profile. Use Runge Kutta 4th order method.

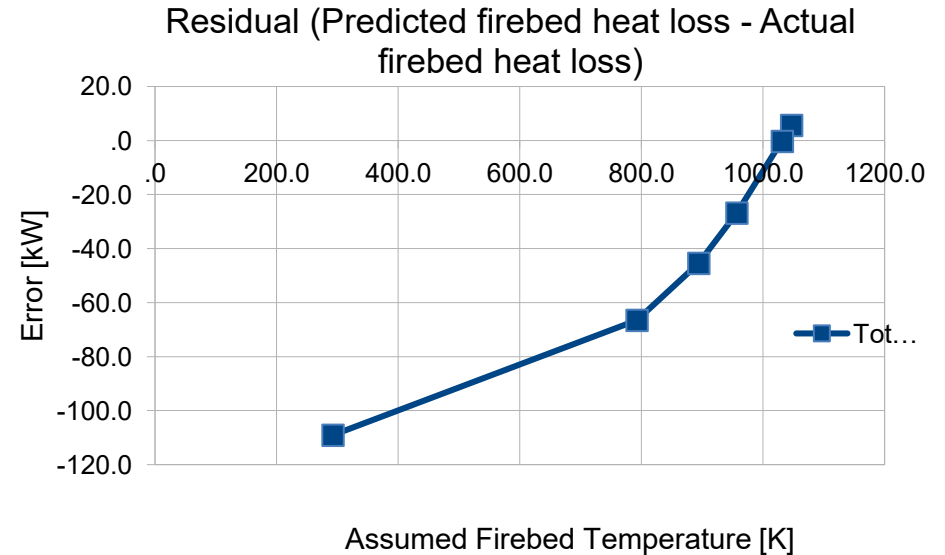
DERIVING A TEMPERATURE PROFILE

- To derive correct firebed temperature, we have to satisfy the energy balance :- Energy into the firebed = Energy out of the firebed.
- Use a Newton Raphson iteration to find the firebed temperature that satisfies energy balance.
- During this stage we can also assess firebox wall temperature drop.

FINDING FIREBED TEMPERATURE



Coal Fire



Oil / Gas Fire

DERIVING RADIANT SUPERHEATER TEMPERATURE

- Unknowns at this stage :-
- Steam flow, steam temperature, steam properties for convection heat flow calculation.
- Those variables cannot be known until firebox calculation is complete and tube bank performance calculated.

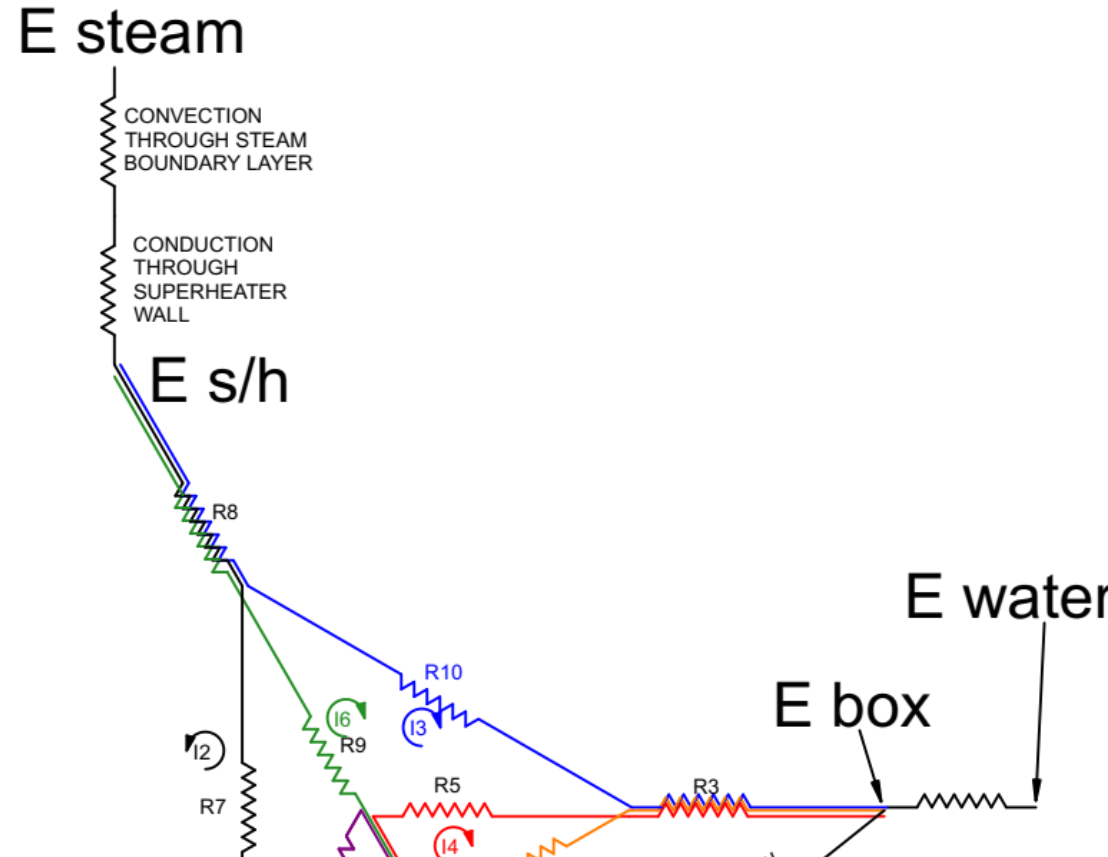
DERIVING RADIANT SUPERHEATER TEMPERATURE

Stage 1 :-

Assume a wall temperature for superheater elements.

So that :-

$E_{s/h} > E_{\text{saturated steam}}$



DERIVING RADIANT SUPERHEATER TEMPERATURE

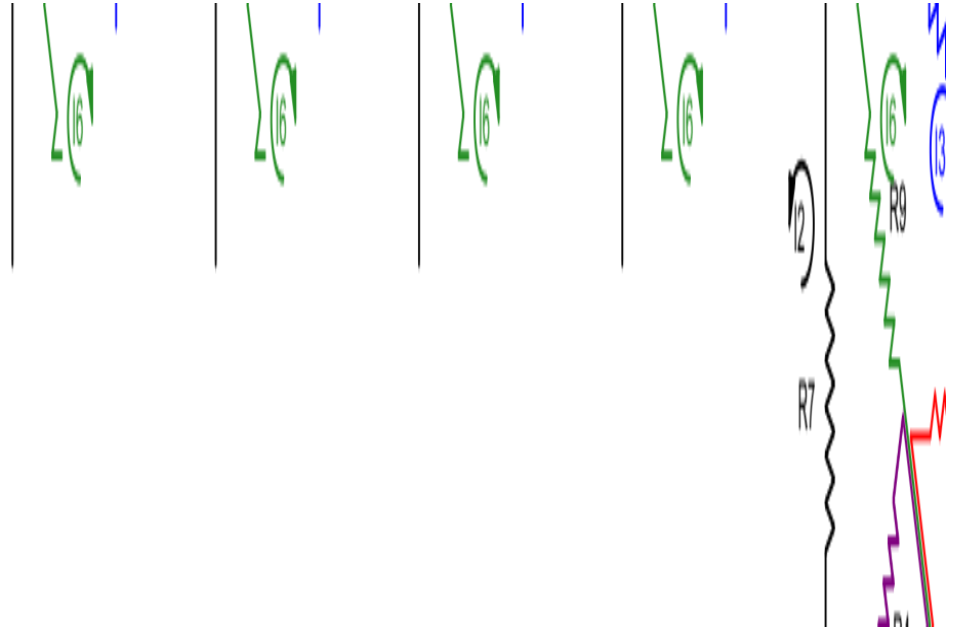
- Stage 1 approximate calculation allows the tube bank calculation to proceed and derive an evaporation rate and superheater element performance within the tube bank.
- With those variables Stage 2 can refine the solution.

DERIVING RADIANT SUPERHEATER TEMPERATURE

Stage 2 :-

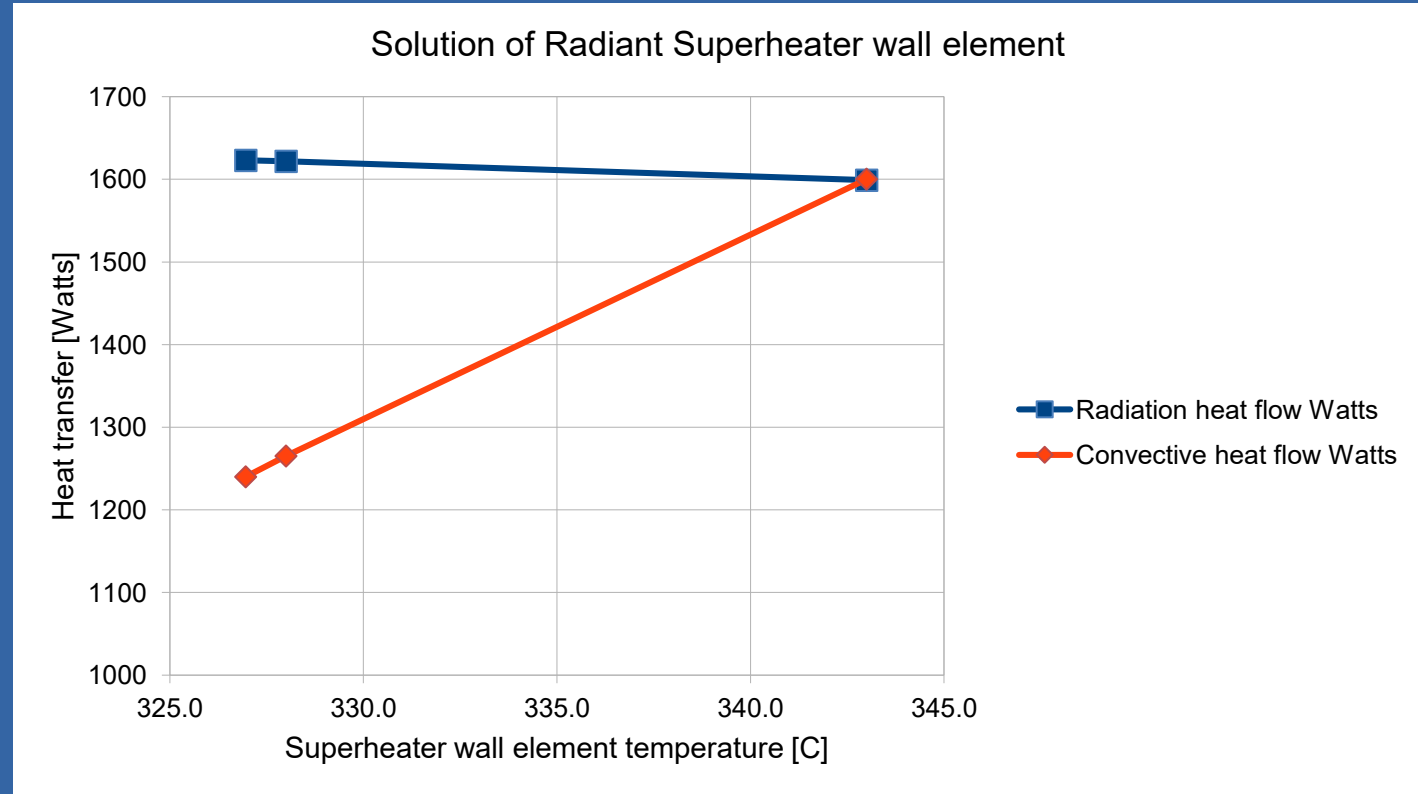
Split each radiant
leg into 5
sections.

By iteration find E
s/h value that
satisfies heat in =
heat out.



DERIVING RADIANT SUPERHEATER TEMPERATURE

Only one wall temperature achieves equal radiant and convective heat flow.



DERIVING RADIANT SUPERHEATER TEMPERATURE

- Steam starting temperature found from tube bank calculation.
- Each leg (4 for a Schmidt style) is treated as 5 separate zones.
- This gives a slightly different total heat flow to Stage 1 calculation.
- Adjust firebox gas exit temperature to satisfy conservation of energy.
- Fortunately, the adjustments are small.

PART 6

SUMMARY OF ASSUMPTIONS & LIMITATIONS

ASSUMPTIONS 1

- 4 Body model – but we have fire + 10 slices of gas + 20 superheater zones + firebox = 32 body model!
- That would need 496 simultaneous equations and 496 double integrated form factors!
- Assumption is that each gas body or superheater element does not radiate to it's neighbours.
- Since ΔT between elements is small, ignore.

ASSUMPTIONS 2

- Firebed coal = firebed gas temperature.
- Exponential combustion of fuel within the firebox volume such that 99% fuel burns before entry to tube stack.
- Each of 10 equal gas volumes has equal surface area – Not so in a typical firebox shape.
- Firebox filled with “grey” gas of given absorptivity.

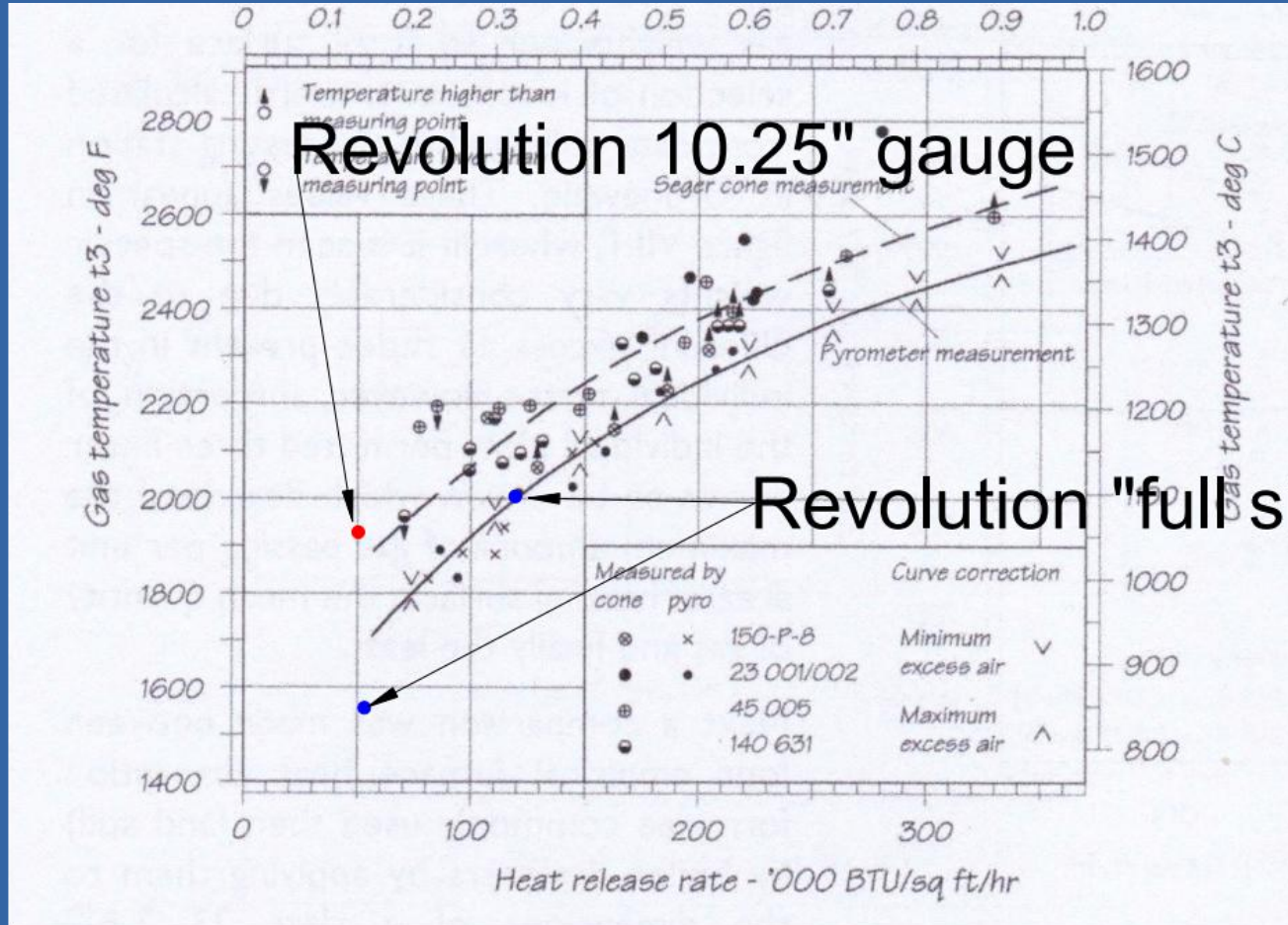
LIMITATIONS

- The model is limited to locomotive boilers with typical parallelopiped fireboxes.
- The model is limited to steady state conditions.

PART 7

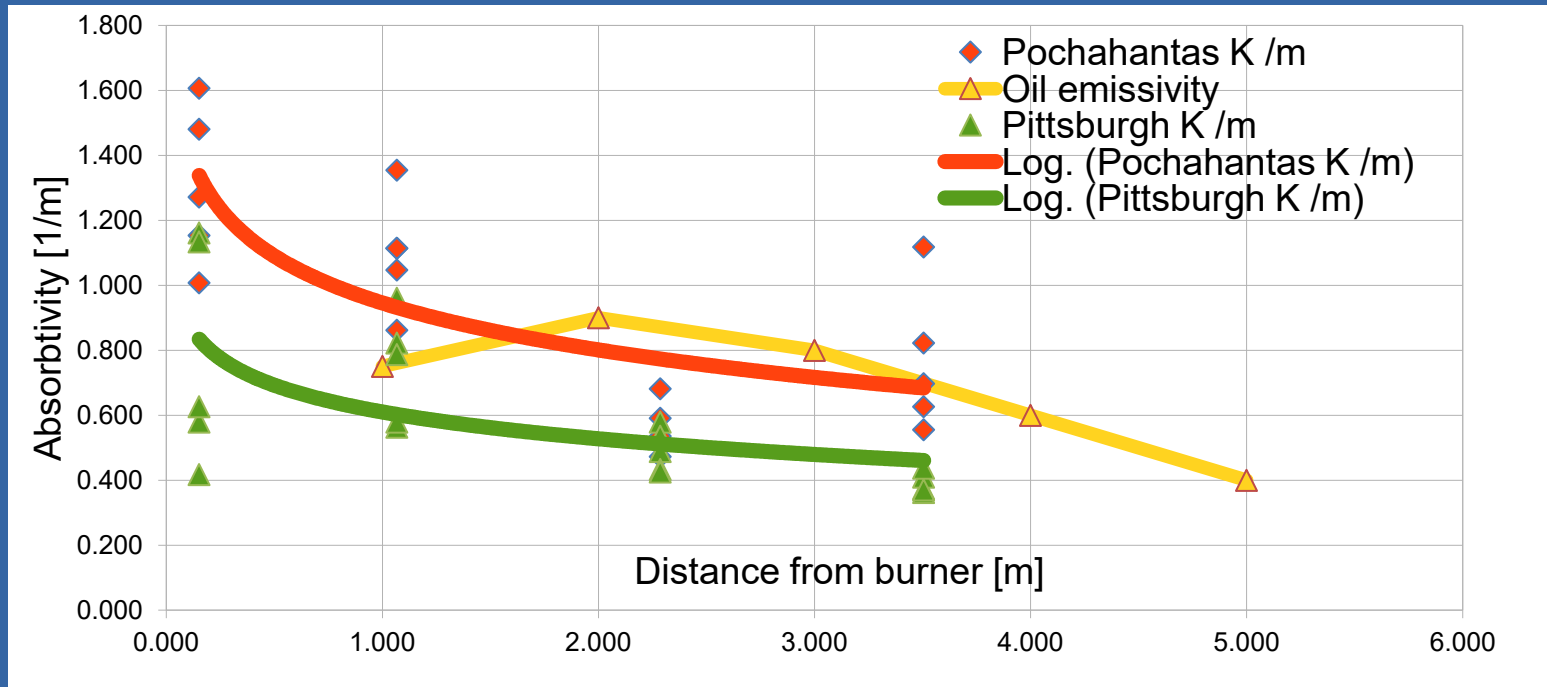
SOME EXAMPLE RESULTS

COMPARISON WITH TESTS



COMPARISON WITH TESTS

Agreement with Klie's graph requires gas absorbtivity of around 0.4

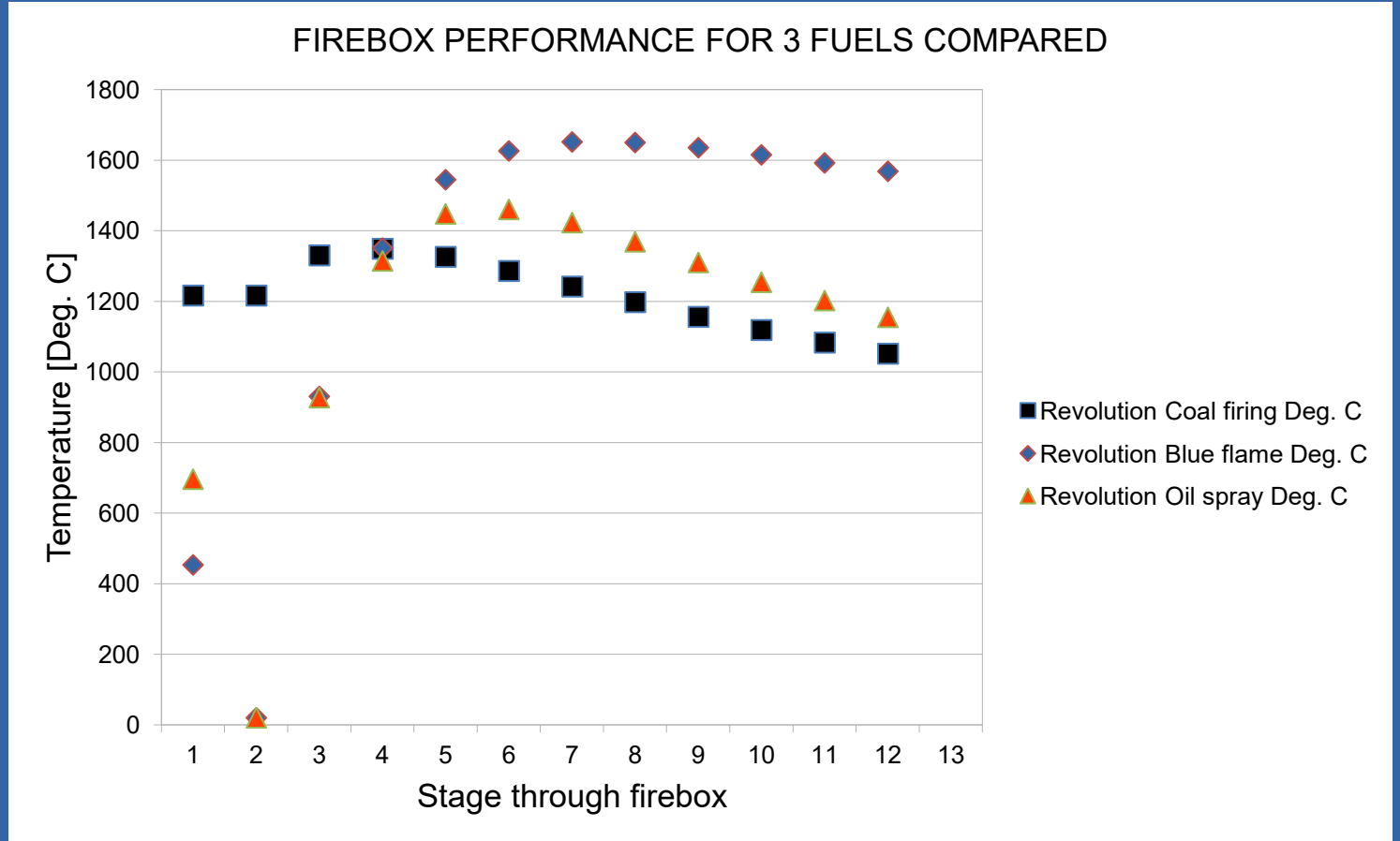


COMPARISON WITH TESTS

- Possible reasons :-
- Lump coal combustion is less radiant than pulverised coal? Particle size effect?
- Absence of brick arch in model?
- Is assumption about firebed and gas temperature valid?
- Is use of “grey” gas model valid?

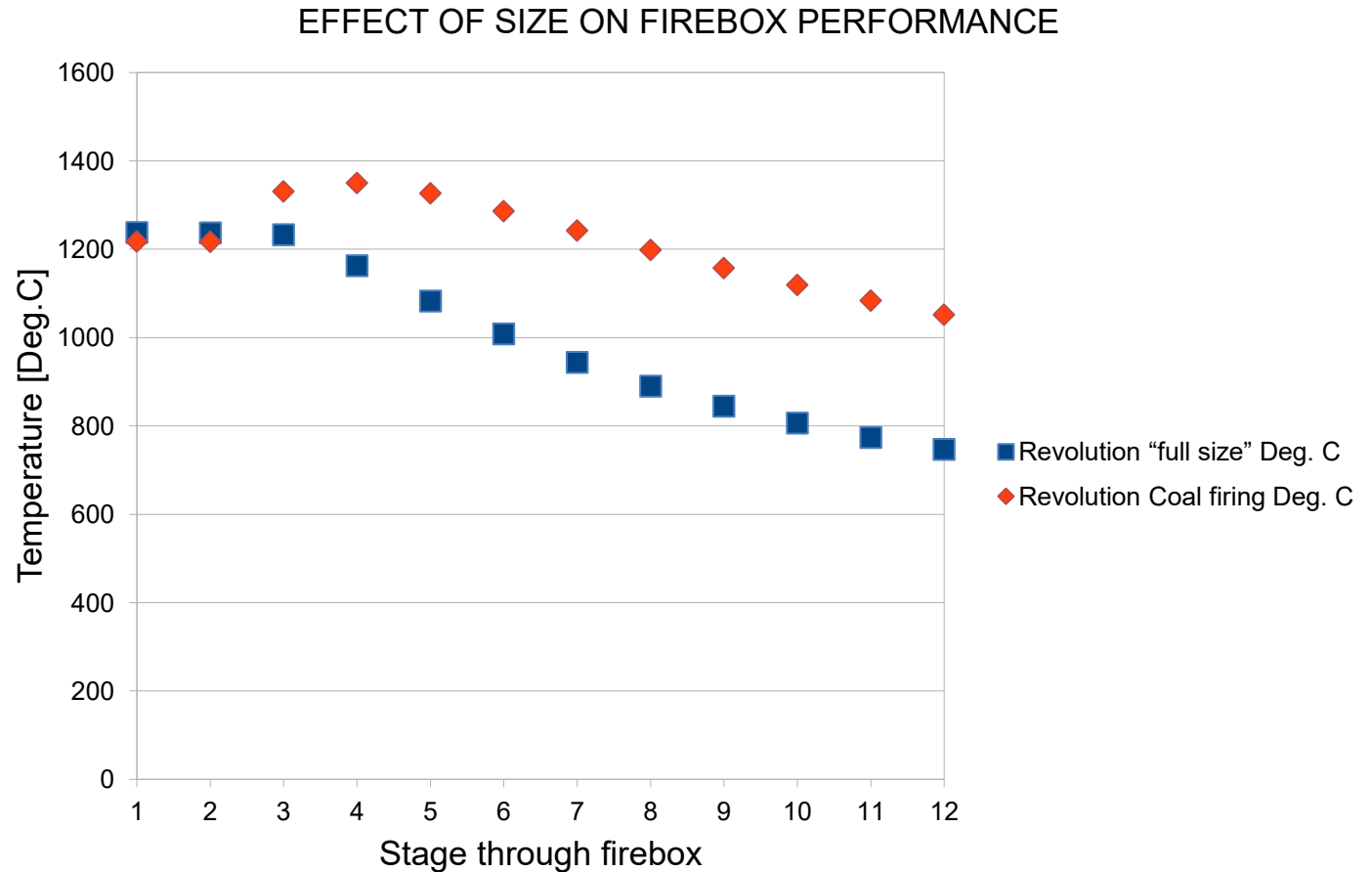
THE EFFECT OF FUEL & BURNER TYPE

Revolution
in 10 ¼"
gauge.



THE EFFECT OF SIZE

Revolution
4' 8½"
compared
to 10 ¼"
gauge.
Same fire
conditions.

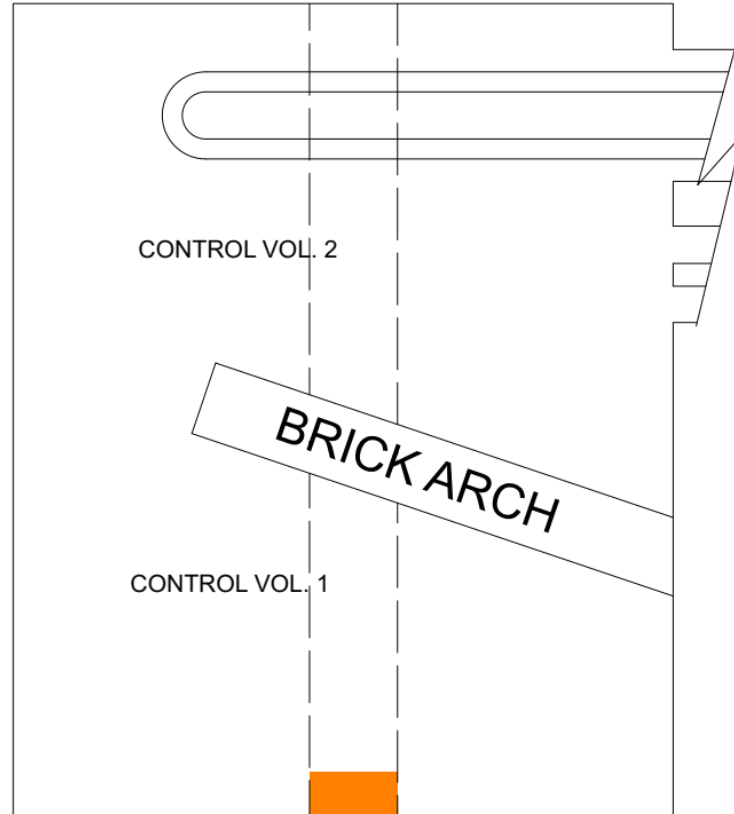


PART 8

WHERE TO NEXT?

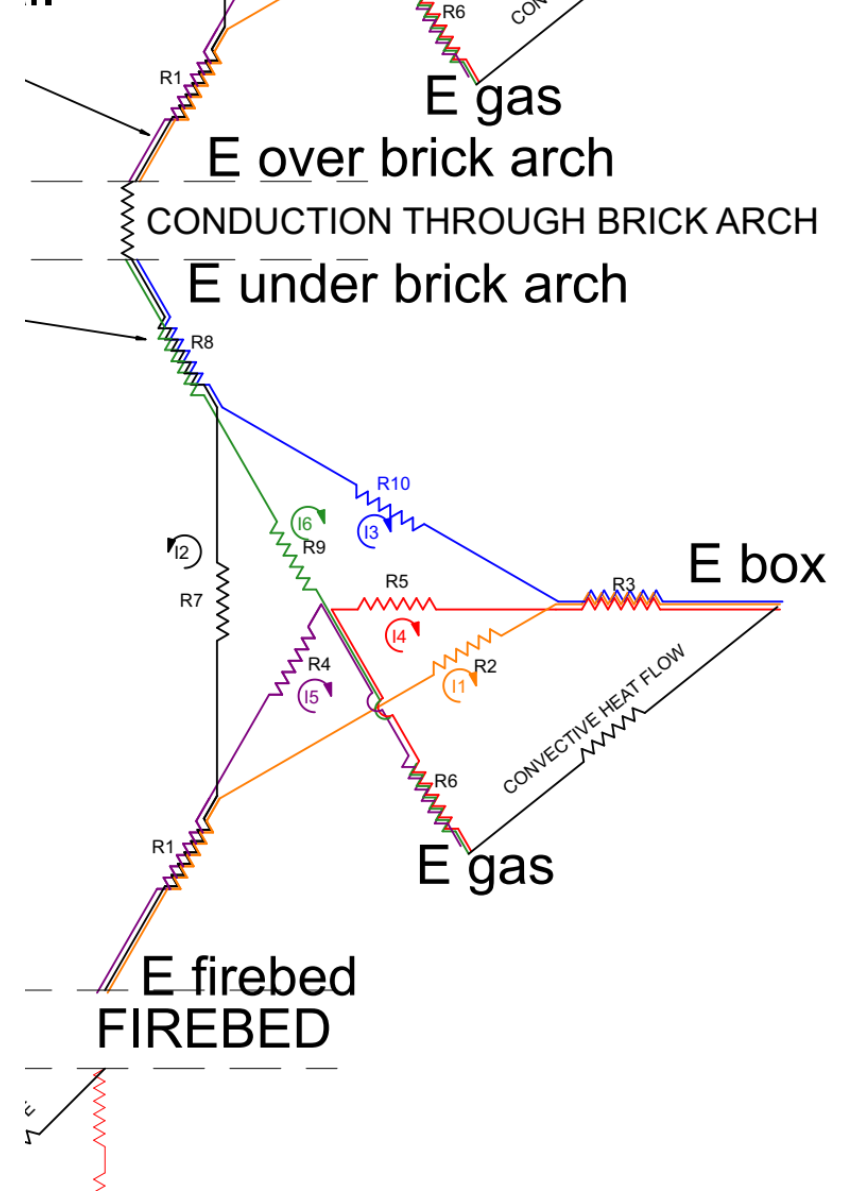
A BRICK ARCH MODEL

**Assumes heat
transfers
through the arch
only. (not along
the arch)**



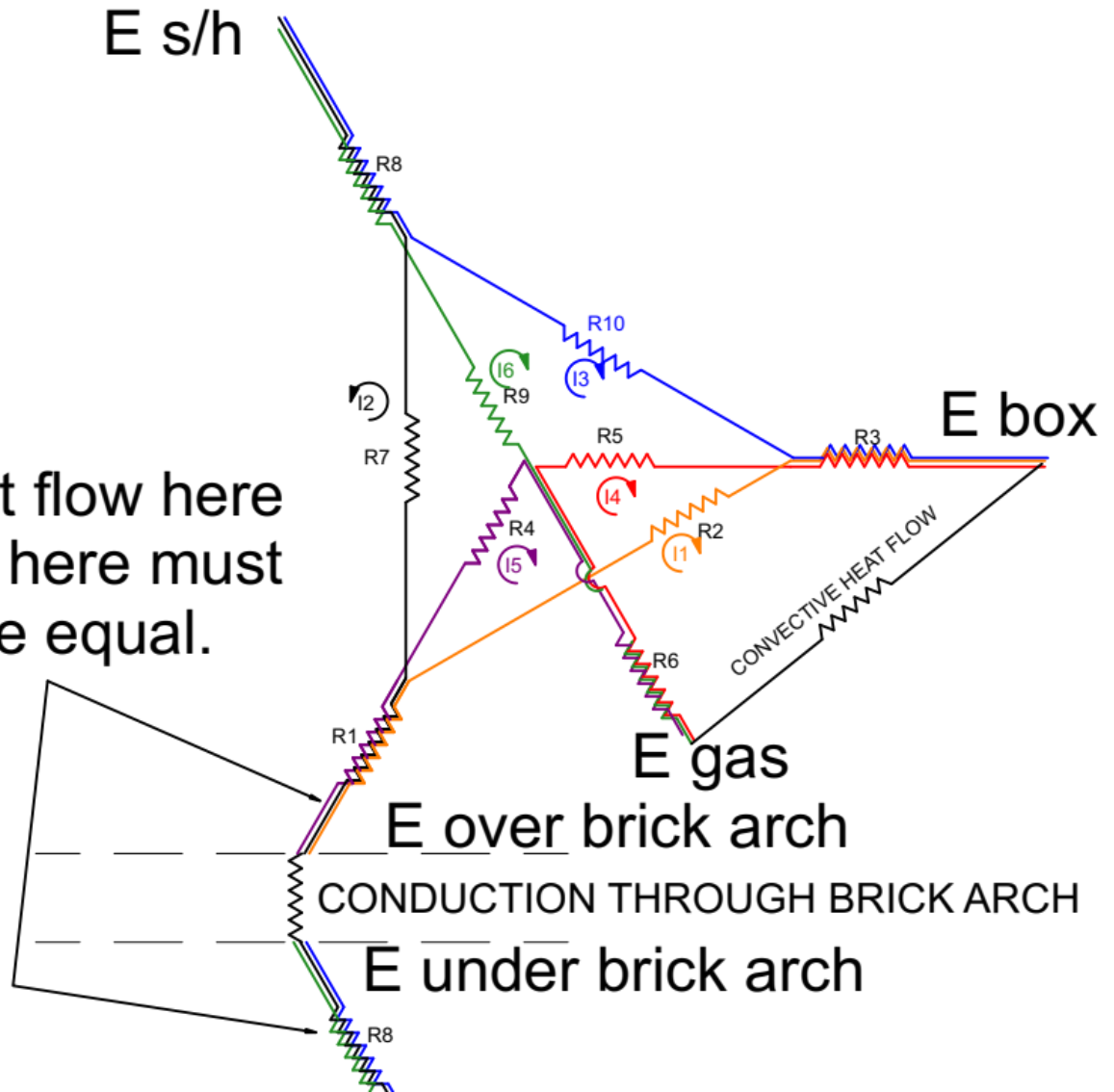
THE BRICK ARCH

Refine
assumption
of areas,
volumes &
form factors

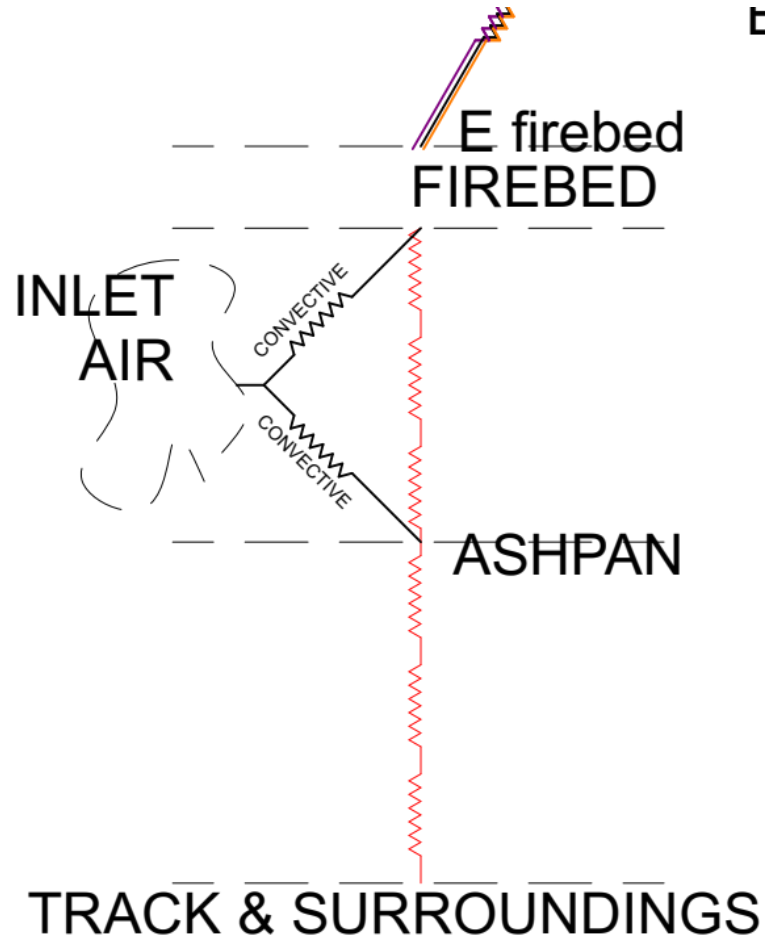


OVER THE BRICK ARCH

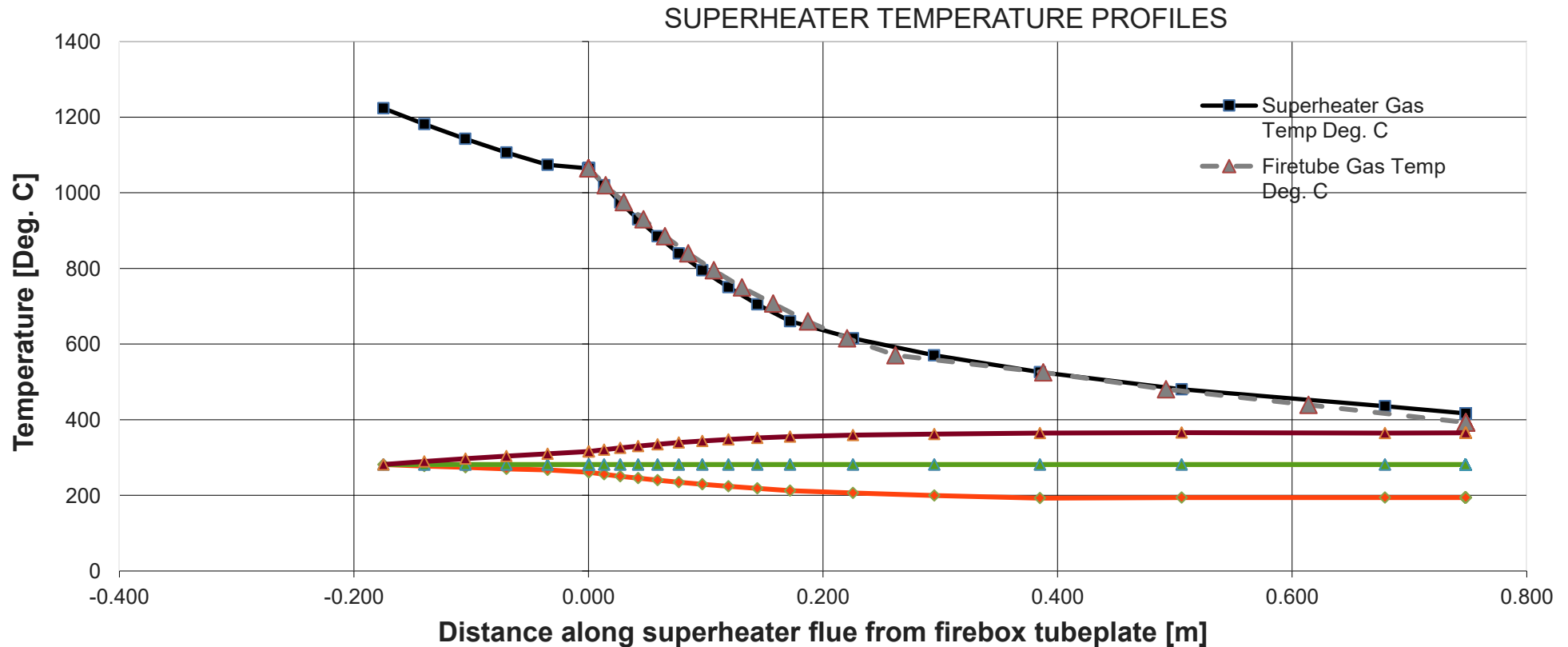
Heat flow here
and here must
be equal.



UNDER THE FIREBED



AND FINALLY - REVOLUTION



ACKNOWLEDGEMENTS

- Richard Coleby
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