NPL National Physical Laboratory

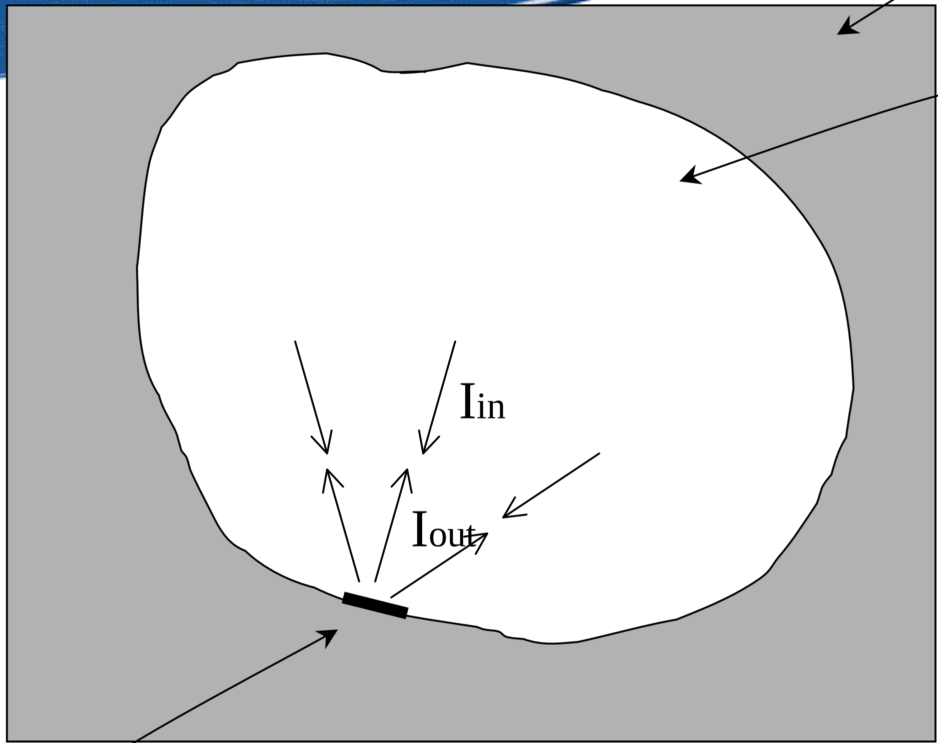
Reflecting cavity blackbodies for radiometry

Eric Usadi

National Physical Laboratory, UK

NEWRAD 2005, Davos

block @ temp T



closed cavity within block

characteristic unit surface element $\boldsymbol{S}$

emissivity ε

I_{in} = irradiance into $\boldsymbol{S}$

I_{out} = irradiance out of $\boldsymbol{S}$

I_{bb} = irradiance emitted by perfect blackbody

$\boldsymbol{\varepsilon}$ = emissivity of $\boldsymbol{S}$

$\boldsymbol{R}$ = reflectivity of $\boldsymbol{S}$

$= 1 - \boldsymbol{\varepsilon}$

Note that

(i) $I_{out} = \boldsymbol{\varepsilon} I_{bb} + \boldsymbol{R}\, I_{in}$

and that at equilibrium

(ii) $I_{in} = I_{out}$

(i) & (ii) => $\boxed{I_{in} = I_{out} = I_{bb}}$

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Why ?

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Why ?

reflector emits less than **absorber**

$\Rightarrow$ contributes less to cavity emission

$\Rightarrow$ thermal uniformity requirements relaxed

Why ?

Blackbodies

- easier to achieve ultrahigh T uniformity over plate only
- thermally freely floating reflector possible
- mobile / in-flight operation
- solid state thermal control

Radiometers

- need to measure radiation absorption by plate only

Quinn & Martin 1986

Metrologia 23, 111 – 114 (1986/87)

metrologia

A Black-Body Cavity for Total Radiation Thermometry

T. J. Quinn[1] and J. E. Martin[2]

[1] Bureau International des Poids et Mesures, F-92312 Sèvres Cedex, France
[2] National Physical Laboratory, Teddington, UK, TW11 0LW

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In recent radiometric measurements of thermodynamic temperature T and the difference $T - T_{68}$ at a series of temperatures in the range $-40\,°C$ to $+100\,°C$, the present authors [1, 2] used a black-body radiator whose whole internal surface was coated with a black paint (3M-C401, Nextel). To extend those measurements above 100 °C, while maintaining an accuracy of about ± 3 mK, one of the most serious problems will be the determination of the effective temperature of the radiator. It is evident that a practical black-body cavity whose emissivity for 273 K radiation departs from unity by only a few parts in 10^5 while having an aperture whose diameter is of the order of 1 cm, must be large. In our case the cavity was some 60 cm in length and had a maximum diameter of 12 cm. It was difficult, even at 100 °C, to maintain a uniformity of temperature sufficient to determine an effective temperature of the radiator to within about 1 mK. To do so at temperatures up to 420 °C appears at present to pose formidable – although perhaps not insuperable – problems. Much of the difficulty in establishing the effective temperature arises from the fact that the measured radiation originates from elements over the whole of the internal surface and not just from those elements viewed directly. It is, therefore, necessary to measure the temperature distribution over the whole internal surface of the black body. By using a black paint whose emittance is high it is of course the case that most of the measured radiation is emitted by those elements of surface viewed directly and is therefore characteristic of the temperature of these surfaces. Nevertheless we found that, if an accuracy of 1 mK is sought in assigning an effective temperature to the radiator, the temperature of those elements of the surface not viewed directly must not differ in temperature from those that are by more than about 40 mK. Failure to maintain such temperature conditions would result in it being necessary to apply complex and usually uncertain corrections.

In an attempt to overcome these problems, the black body shown in outline in Fig. 1 has been designed. In this black body less than one fifth of the internal surface area is black; the rest is highly polished gold whose emittance for 273 K radiation is only about 0.008 [3, 4]. The principle of using a

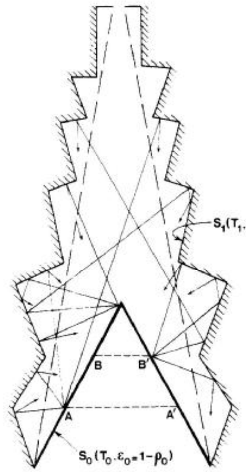
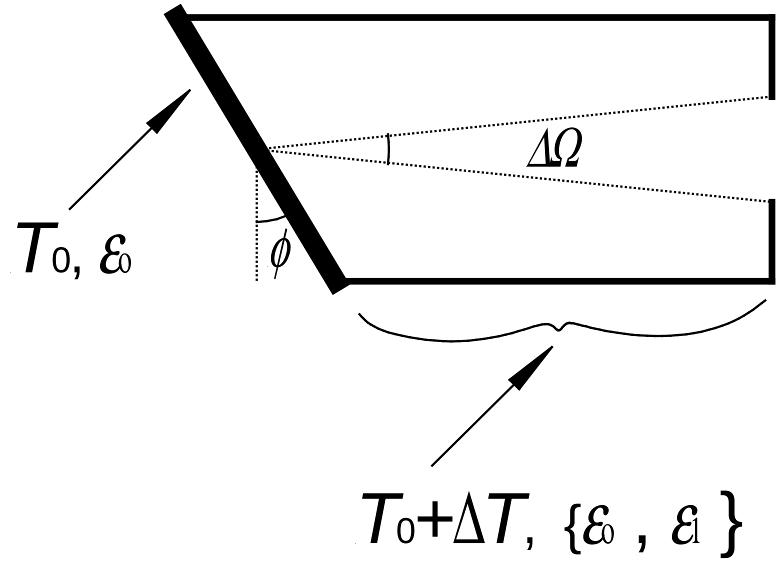


Fig. 1. Schematic of a black body in which the conical diffusely-reflecting surface S_0 has a high emittance and is at a uniform temperature T_0, and the rest of the surface is a specular reflector having a very low emittance and at a uniform temperature T_1. The dashed lines indicate the marginal rays of the measured beam of radiation leaving the black body through the aperture at the top. Not shown are those rays leaving the black body through the aperture after one or more reflections at S_1



Reflective: $\varepsilon \cong 1-(1-\varepsilon_0)\frac{\Delta\Omega}{\pi}Cos(\phi)-4n\varepsilon_1(1-\varepsilon_0)\frac{\Delta T}{T_0}$

Absorbing: $\varepsilon \cong 1-(1-\varepsilon_0)\frac{\Delta\Omega}{\pi}Cos(\phi)-4(1-\varepsilon_0)\frac{\Delta T}{T_0}$

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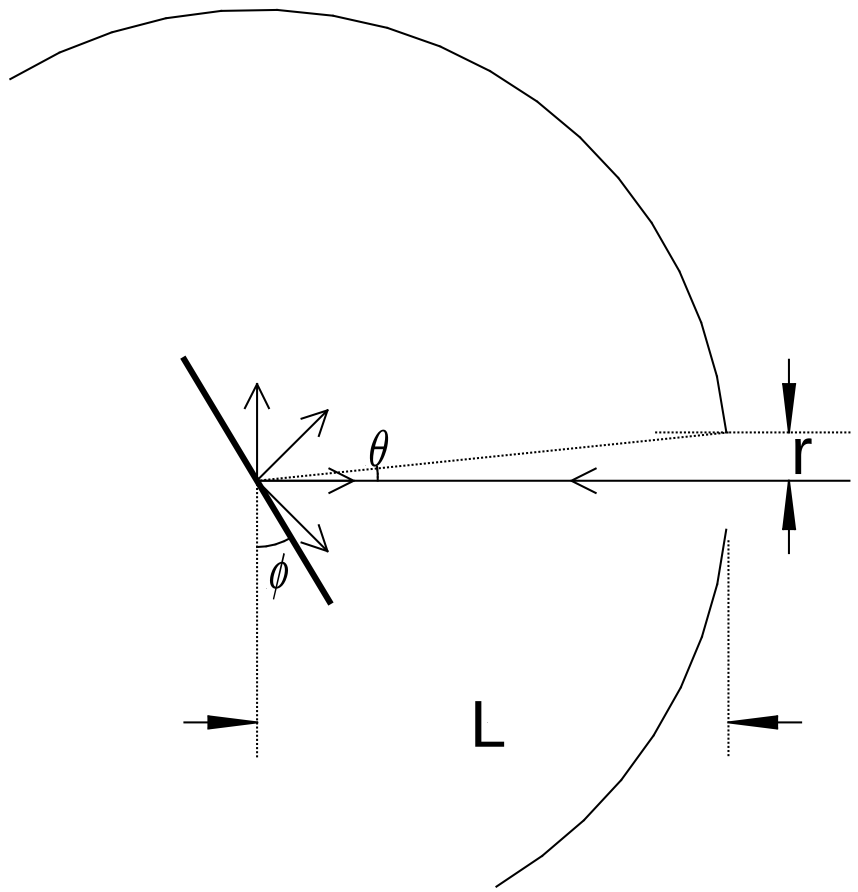

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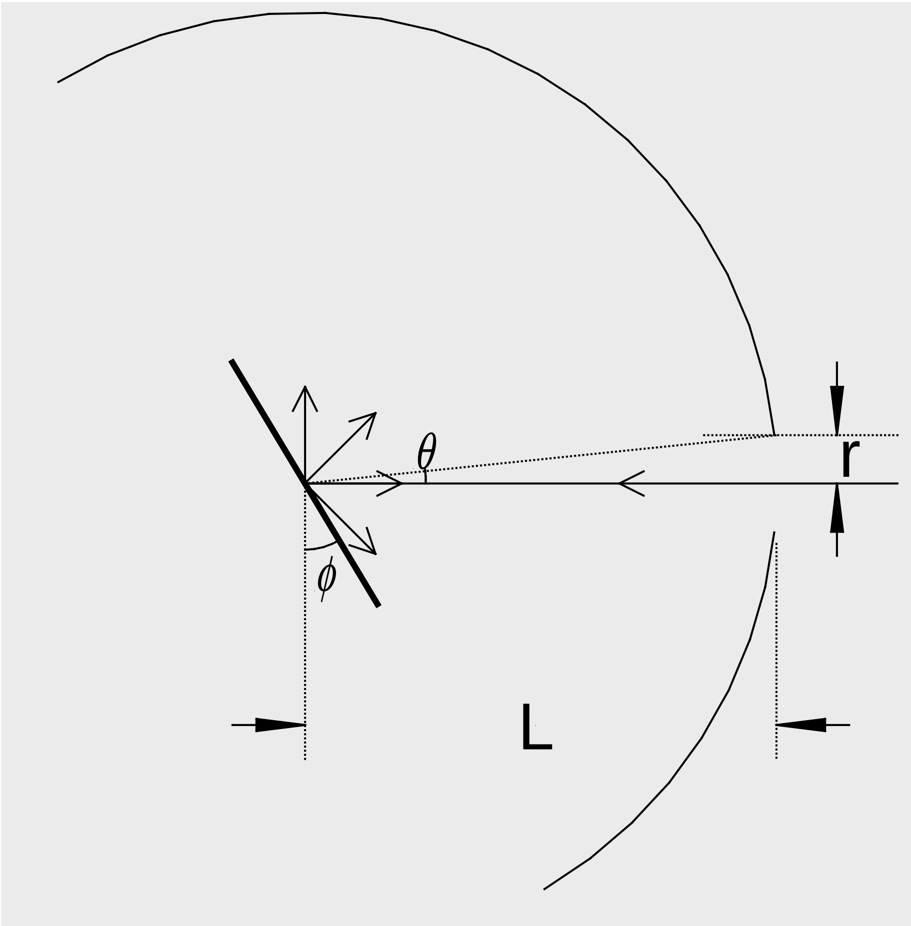
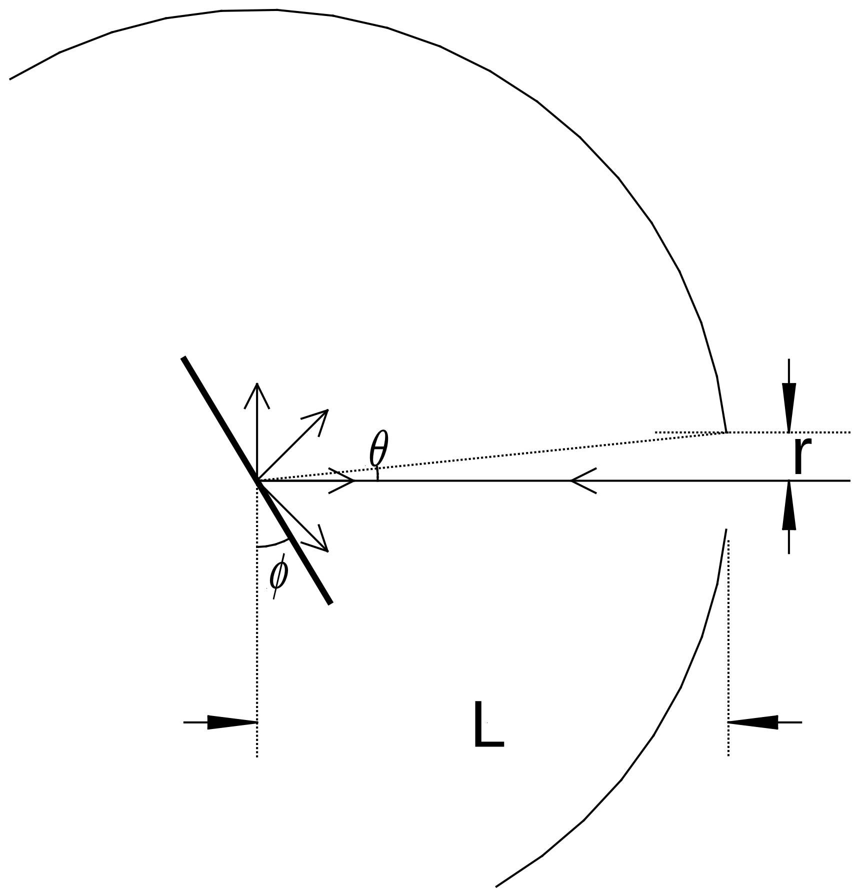
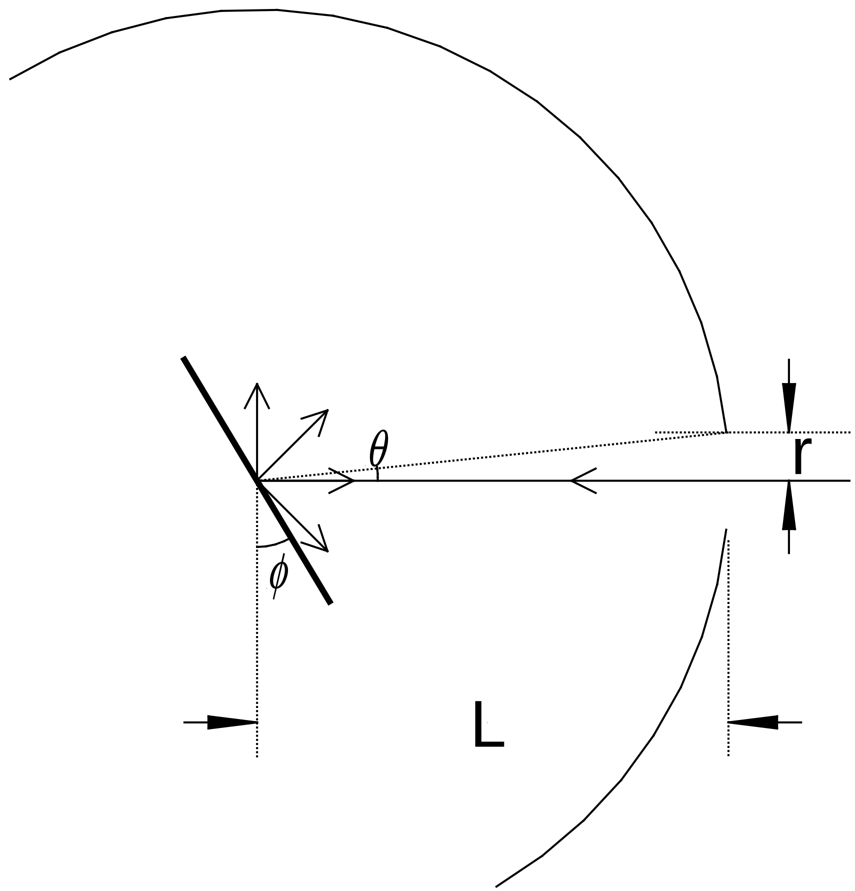
Analysis via Kirchoff law



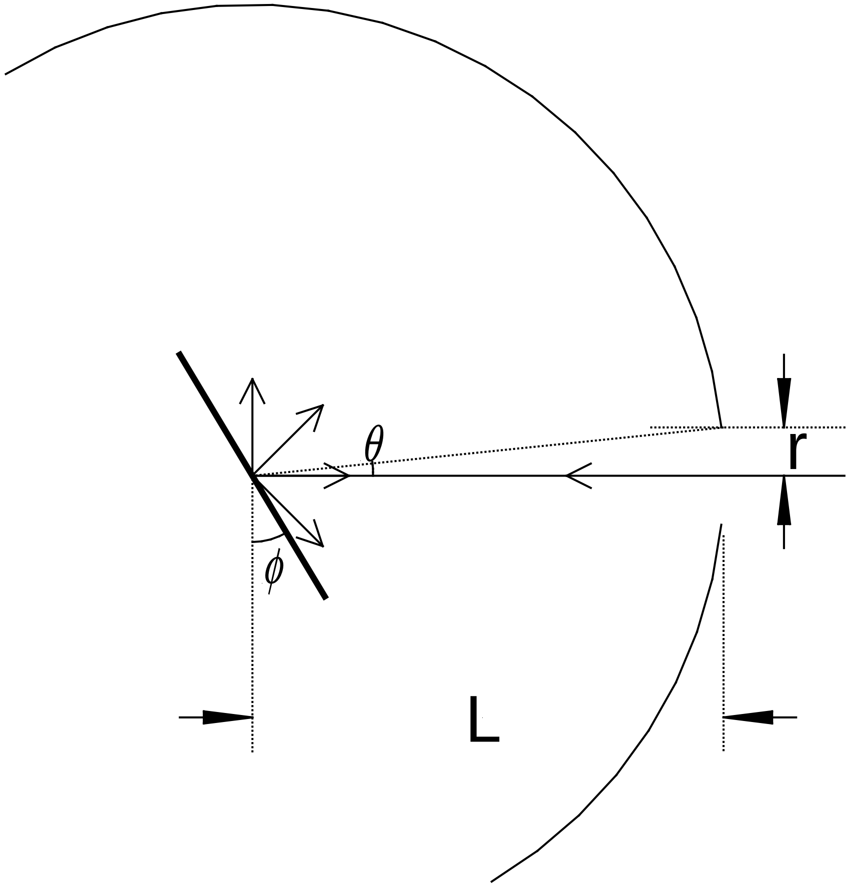
$$lossA_1 = (1-\varepsilon_0)\cdot \tfrac{1}{2}(1-Cos(2\theta))\cdot Cos(\phi)$$





$$lossA_1 = (1-\varepsilon_0)\cdot\tfrac{1}{2}(1-Cos(2\theta))\cdot Cos(\phi)$$

$$\varepsilon_{max} = 1 - lossA_1$$



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$$\varepsilon_{\max} = 1 - lossA_1$$

$$\varepsilon_{\max}\Big|_{\theta\to 0} \cong 1-(1-\varepsilon_0)\theta^2 Cos(\phi)$$

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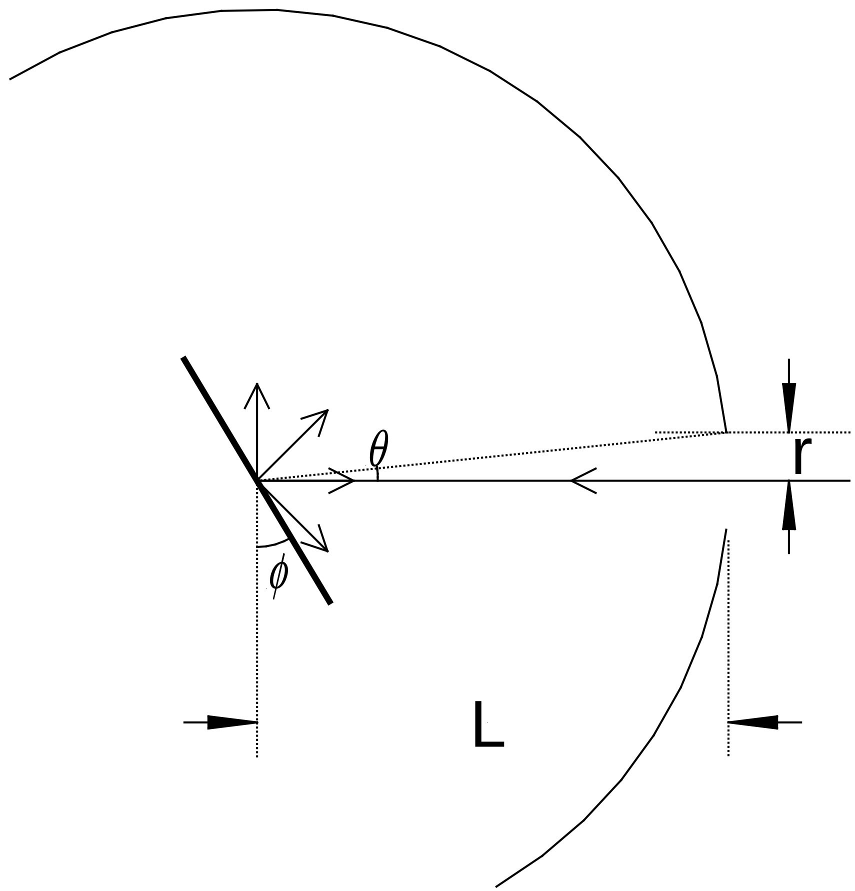

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$$\theta^2 \cong \frac{r^2}{L^2} \cong \frac{\Delta\Omega}{\pi}$$

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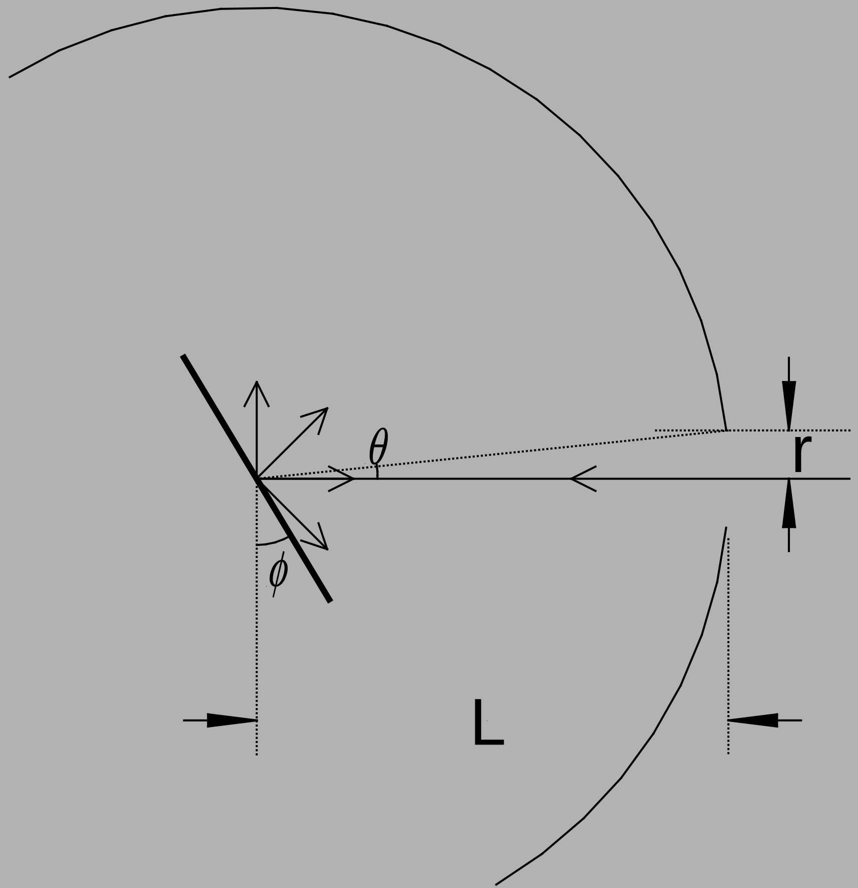

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Quinn & Martin

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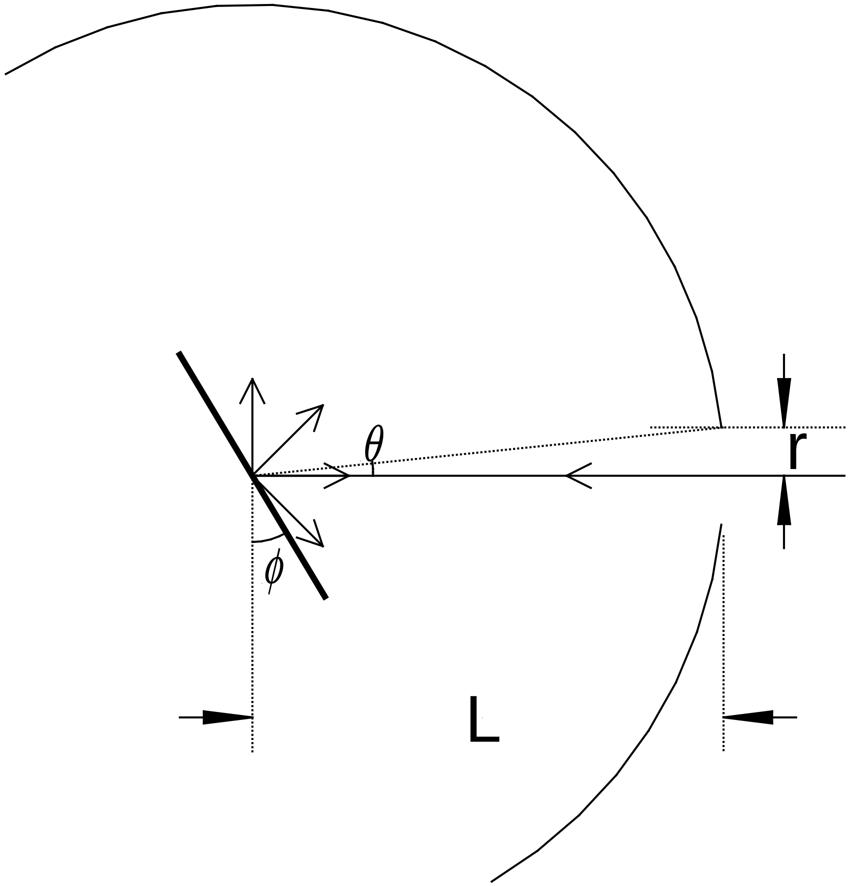

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$$\theta^2 \cong \frac{r^2}{L^2} \cong \frac{\Delta\Omega}{\pi}$$

$$\varepsilon_{max} = 1 - \sum_{i=1} lossA_i$$

$$lossA_i \propto (1-\varepsilon_0)^i$$

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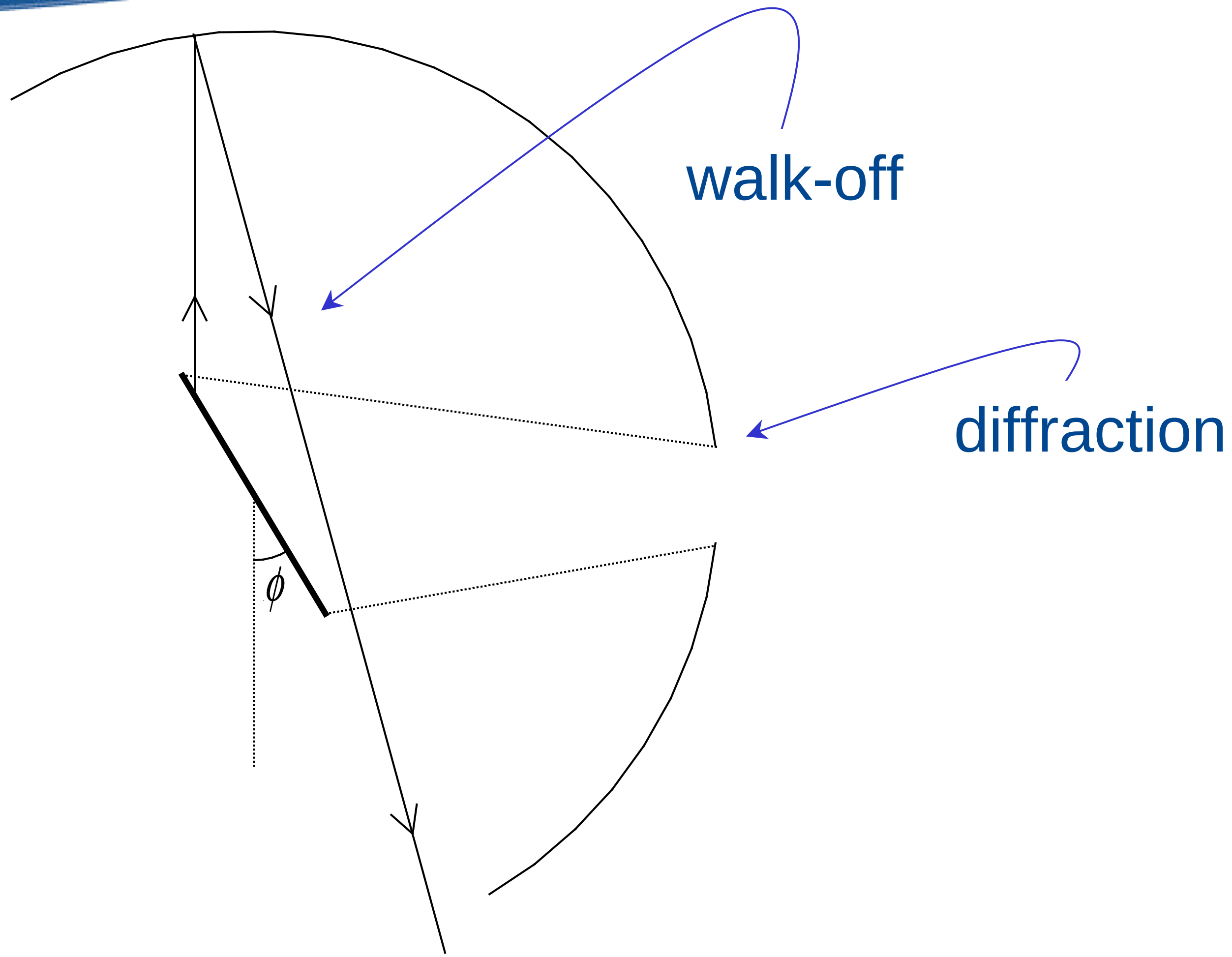
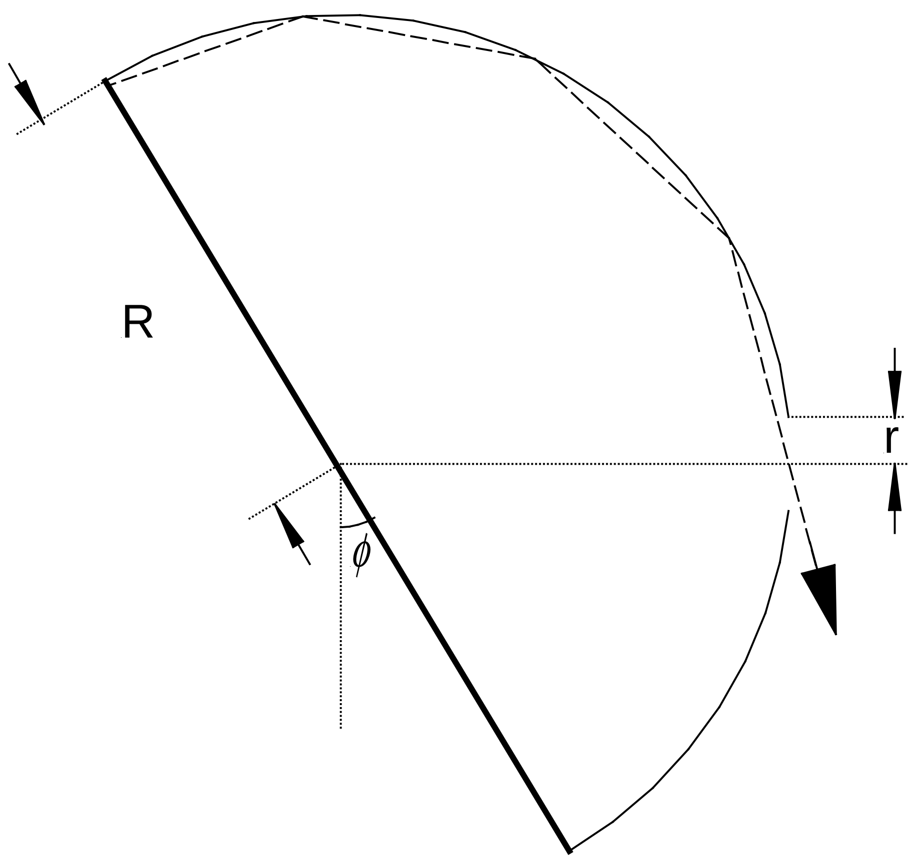

walk-off
diffraction
ϕ



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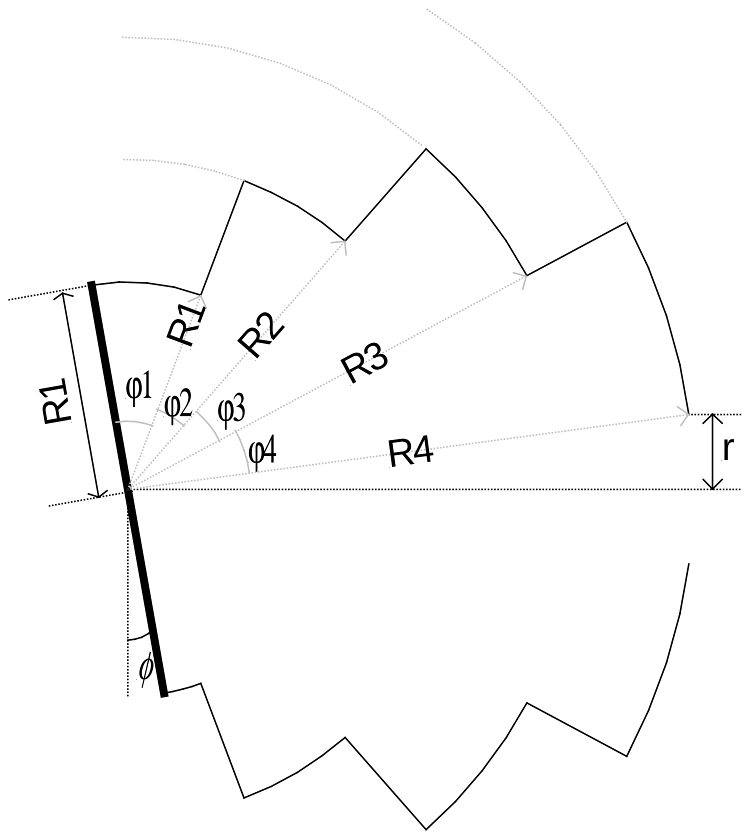

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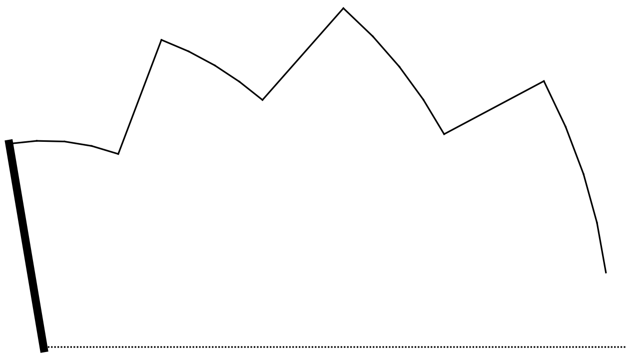

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Artifice Images

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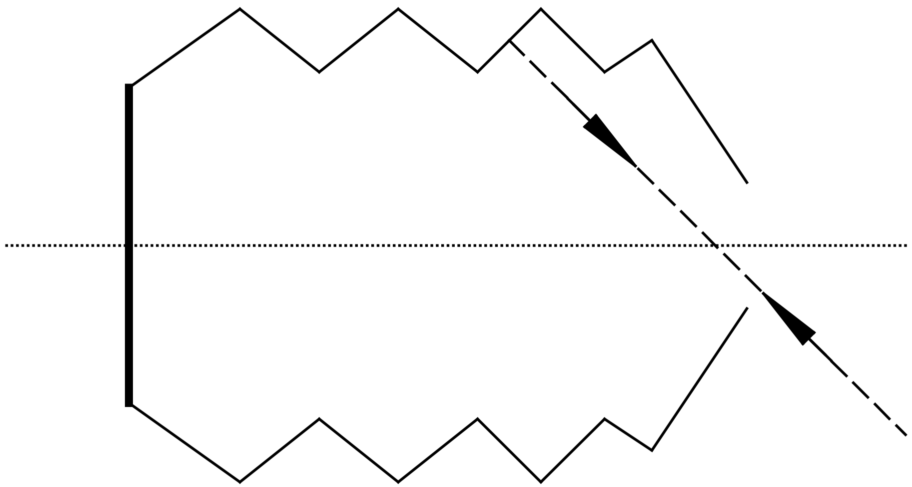
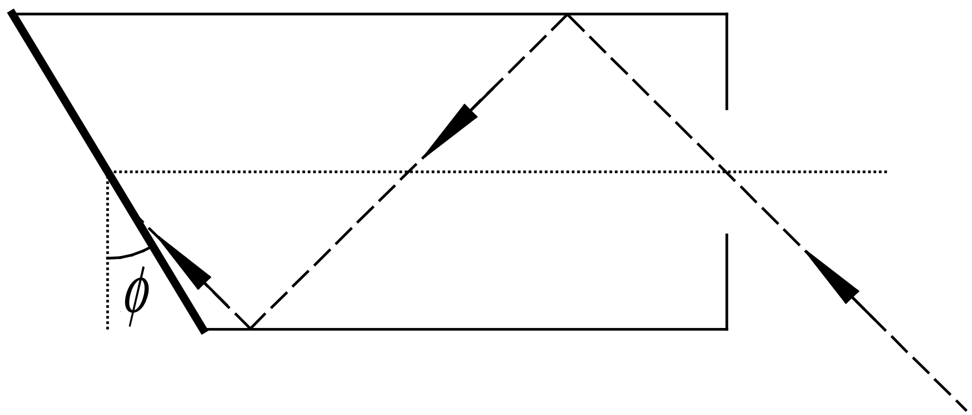
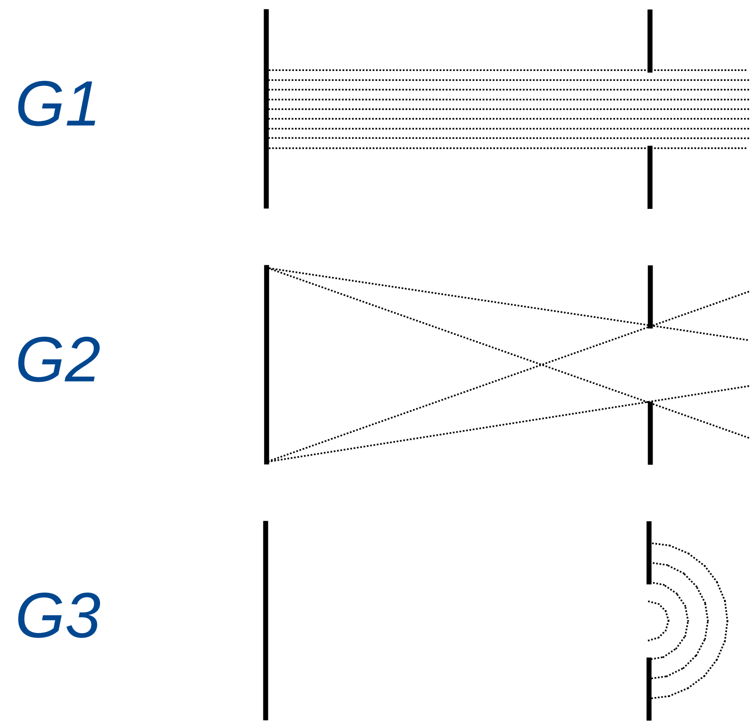
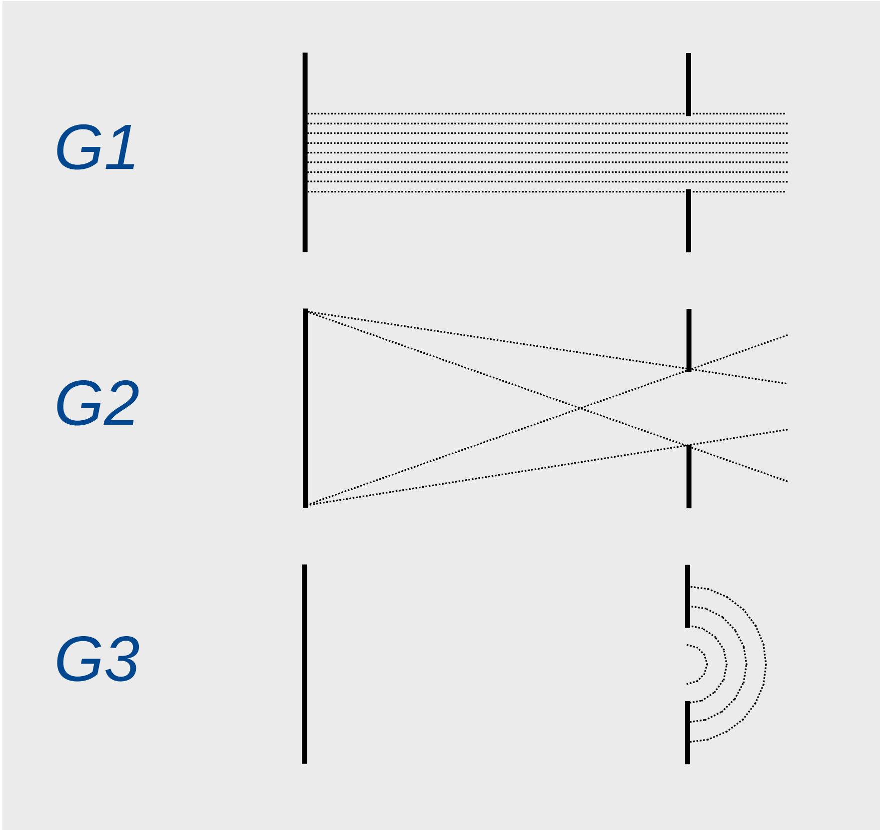


SOH diffraction loss:

Few hundred ppm


ϕ


G1
G2
G3



$L / r = 7.1$

$R_1 = 2.5 * r$

$R_2 = L$

Absorber:
95 % fully diffuse

Reflector
99% fully specular

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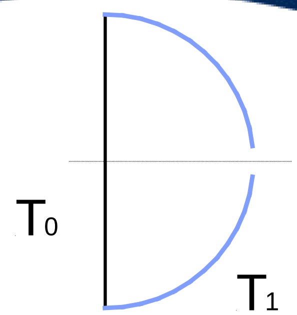
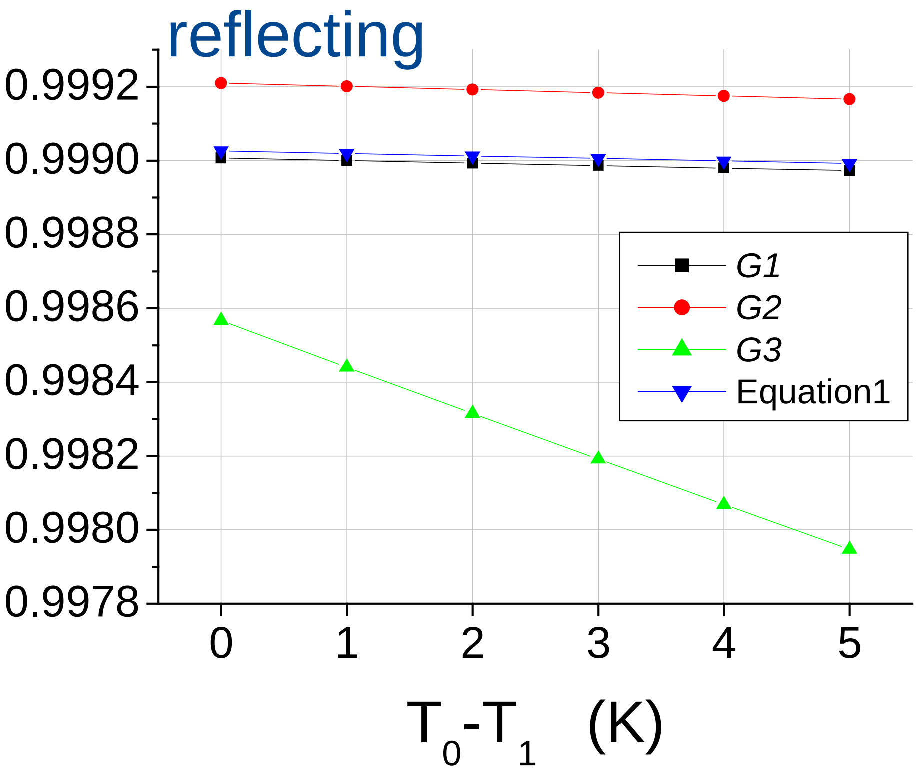
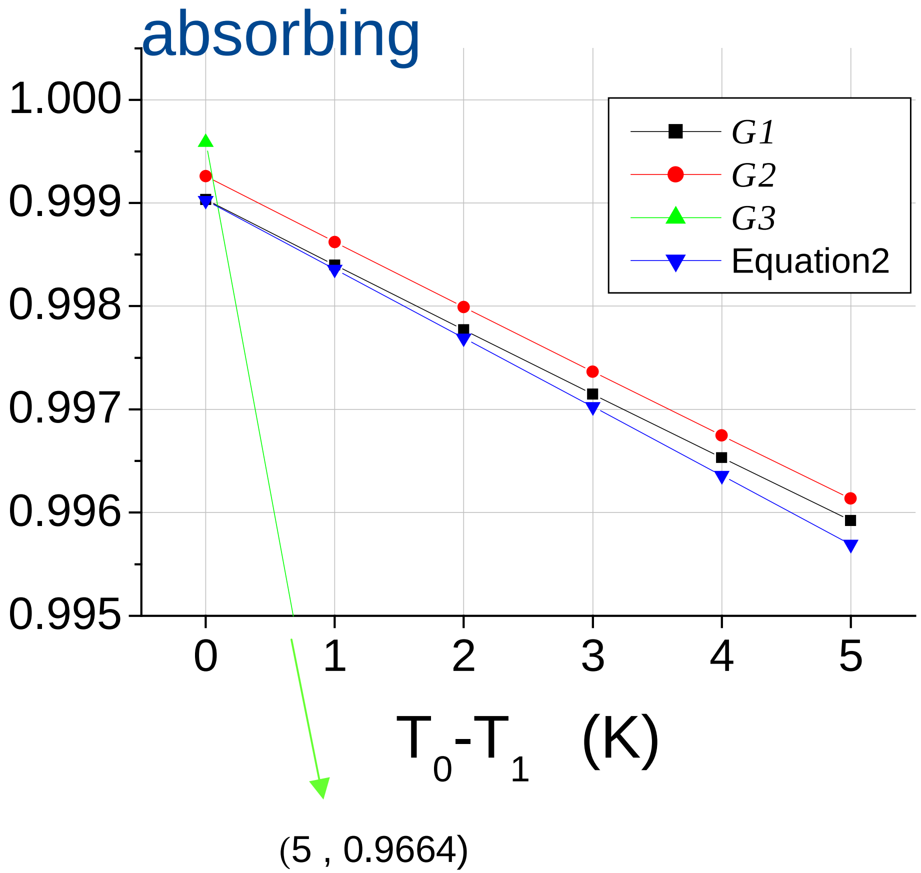


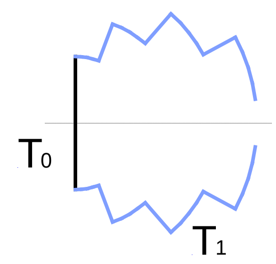
T0
T1



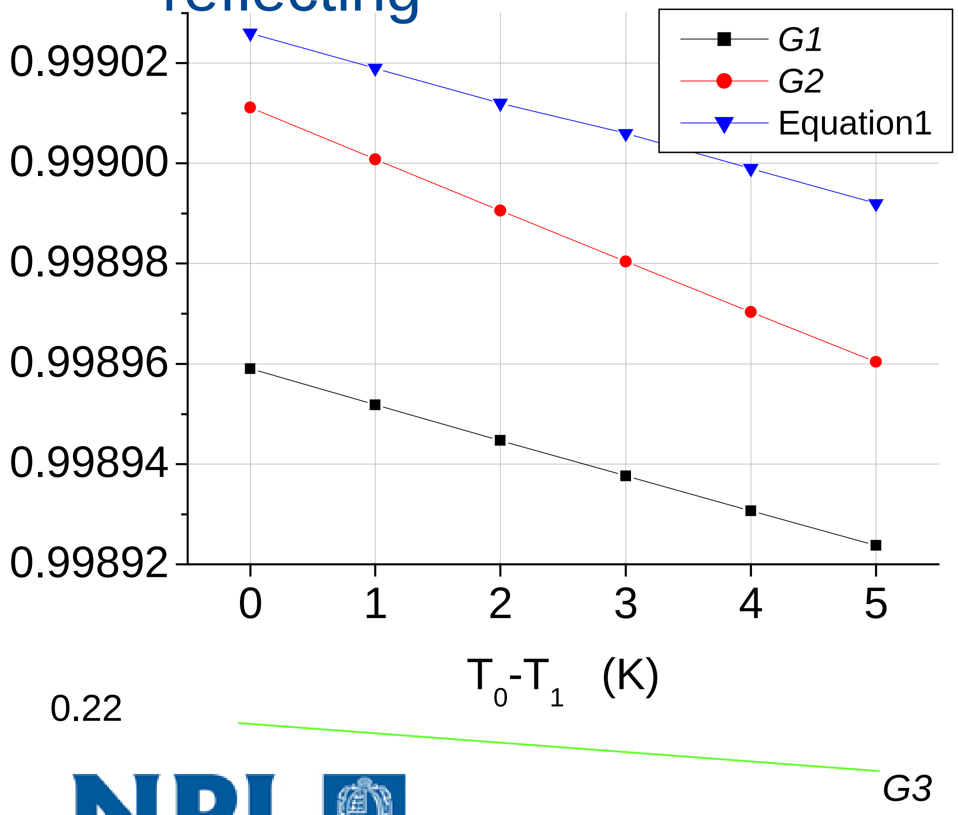
reflecting
0.9992
0.9990
0.9988
0.9986
0.9984
0.9982
0.9980
0.9978
0 1 2 3 4 5
T0-T1 (K)
G1
G2
G3
Equation1



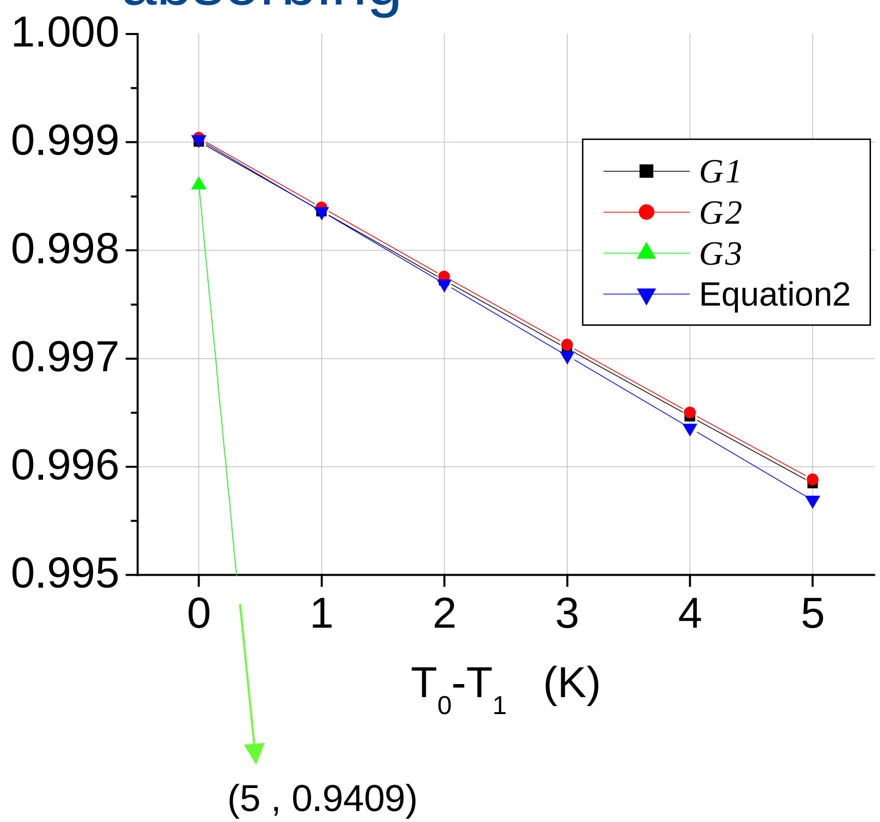
absorbing
1.000
0.999
0.998
0.997
0.996
0.995
0 1 2 3 4 5
T0-T1 (K)
G1
G2
G3
Equation2
(5 , 0.9664)

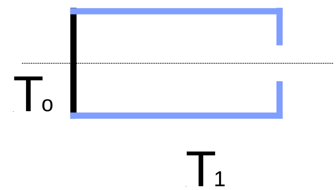


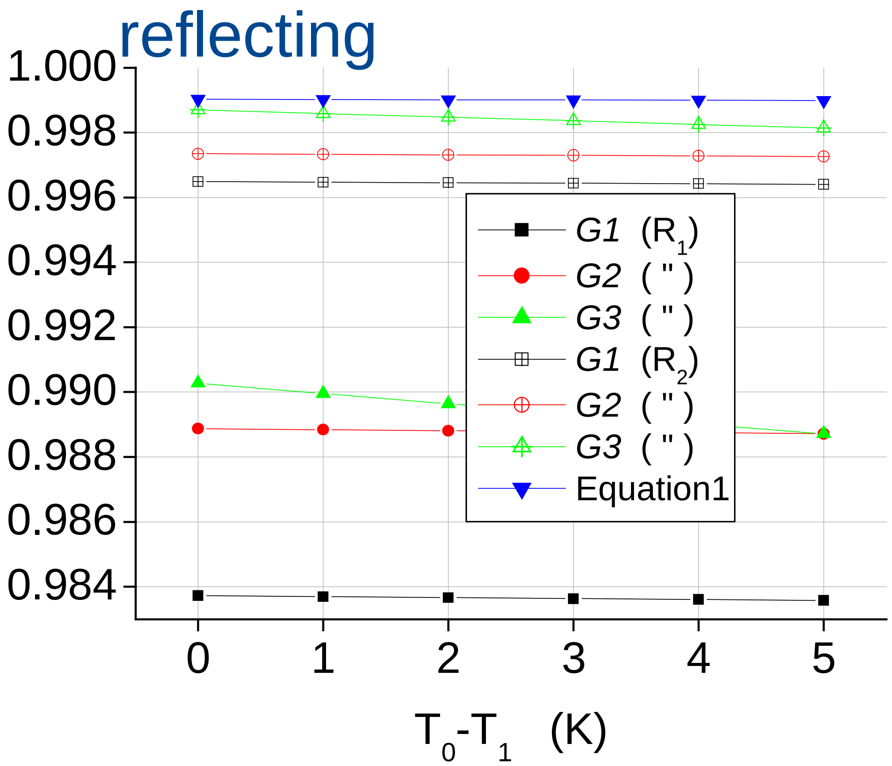
reflecting

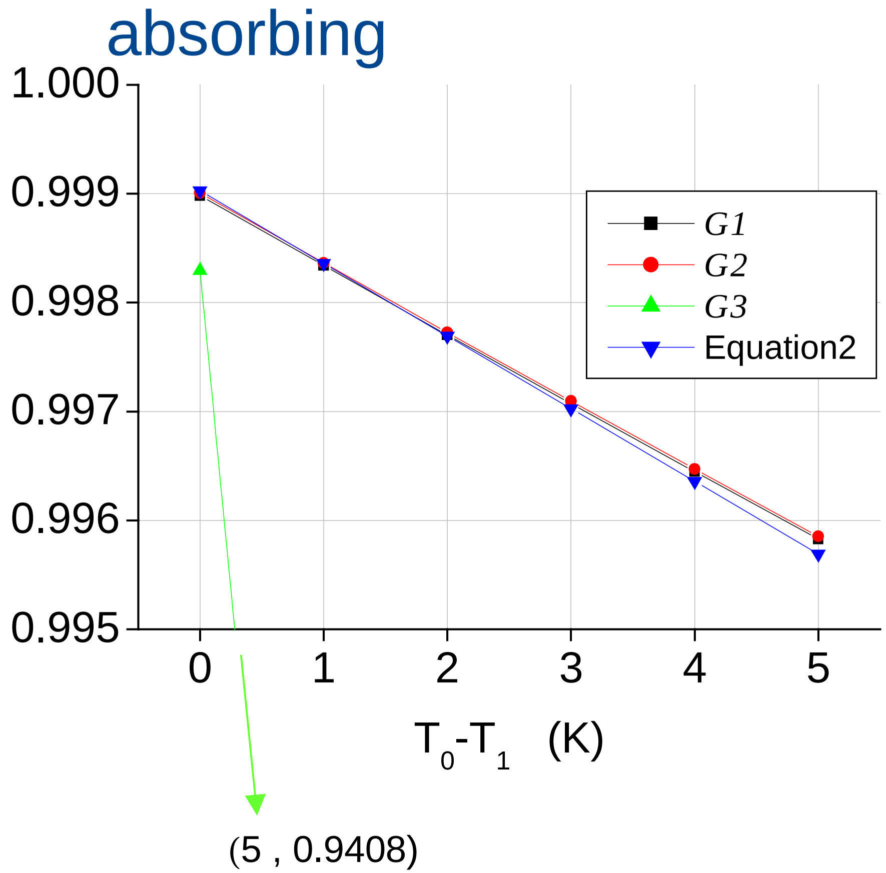


absorbing




T0
T1


reflecting
1.000
0.998
0.996
0.994
0.992
0.990
0.988
0.986
0.984
0
1
2
3
4
5
T0-T1 (K)
G1 (R1)
G2 (")
G3 (")
G1 (R2)
G2 (")
G3 (")
Equation1


absorbing
1.000
0.999
0.998
0.997
0.996
0.995
0
1
2
3
4
5
T0-T1 (K)
G1
G2
G3
Equation2
(5 , 0.9408)

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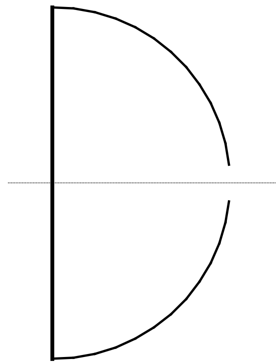
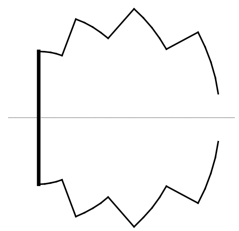


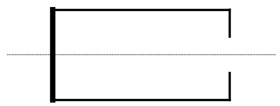
Hemispherical

- ultrahigh emissivity
- laboratory



SOH

- high emissivity
- lab, mobile or in-flight



Cylindrical

- medium emissivity
- lab, mobile or in-flight

Conclusions

- intuitive model of reflecting cavity blackbody concept developed
- validated by comparison with rigorous ray tracing calculations
- several cavity shapes analysed

Acknowledgements

UK Department of Trade and Industry

Many colleagues at NPL