105. Tagung der DGaO 2004

Thermal Management of Large Scale Optical Systems

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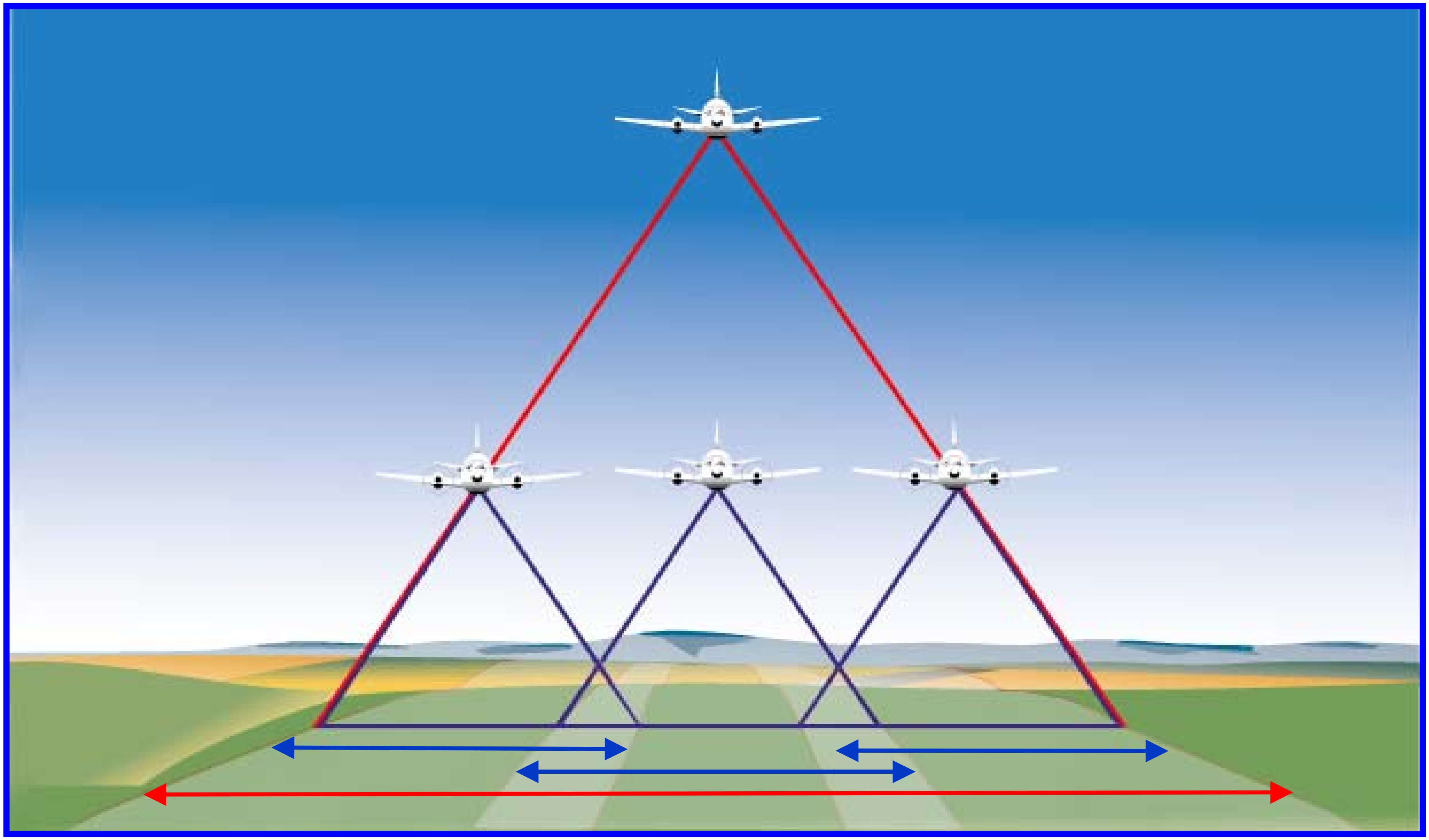
Airborne Sensing and Mapping



Operating Conditions of Airborne Cameras

- Flight height (0,…3,…,9) km,
  - equivalent to
  - Pressure (760,…526,... 231) Torr
- Temperature (-30 … +60) °C

- Narrow specifications of
  - Image registration : focal length, distortion
  - Image quality : resolution, MTF

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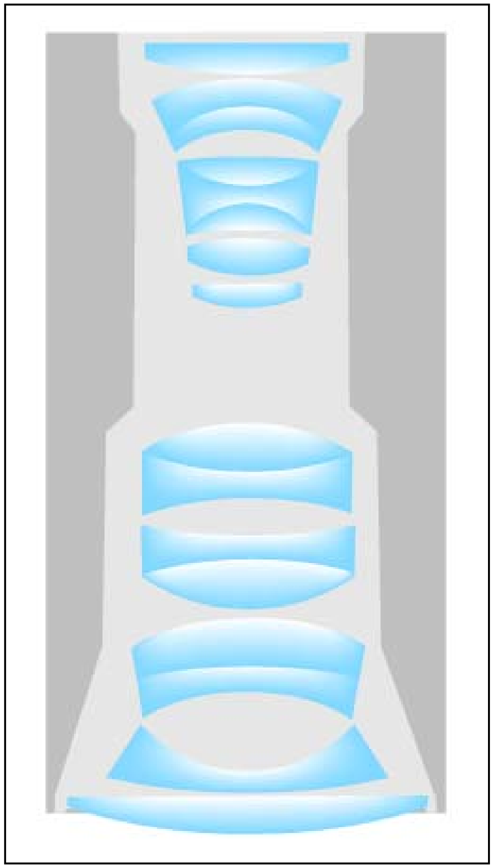
Airborne Lens



- 420-900 nm spectral range
- Resolution ~ 150 lp/mm
- Wide angle
- Large depth of focus
- Registration accuracy 1 µm
- *Thermal & pressure stabilization*

Technical Solutions

- **Control of performance degradations**
  - Pressure variations
    - ☞ *Mechanical sealing of the lens* ☑
  - Temperature variations
    - *Two step process*
      - ☞ Stationary : Optomechanical athermalization ☑
      - ☞ Non stationary : Thermal management ?

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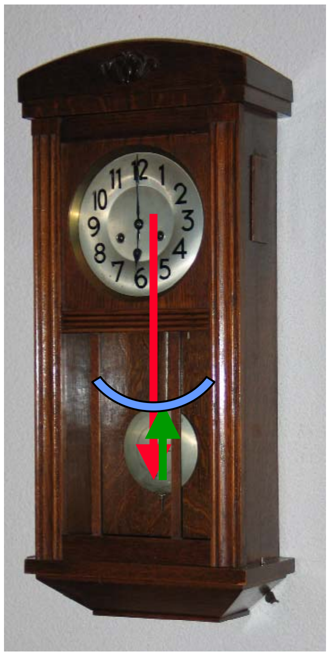
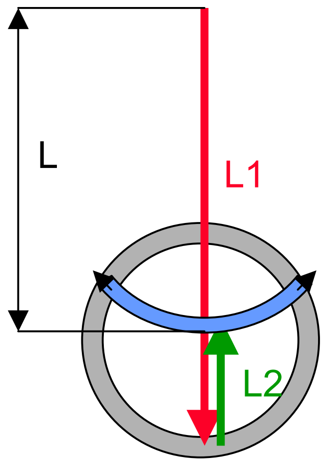
Athermalization

Swiss watchmaker trick





$\Delta L / \Delta T = \alpha_1 L_1 - \alpha_2 L_2 = 0$

➔ $L_1 / L_2 = \alpha_2 / \alpha_1$

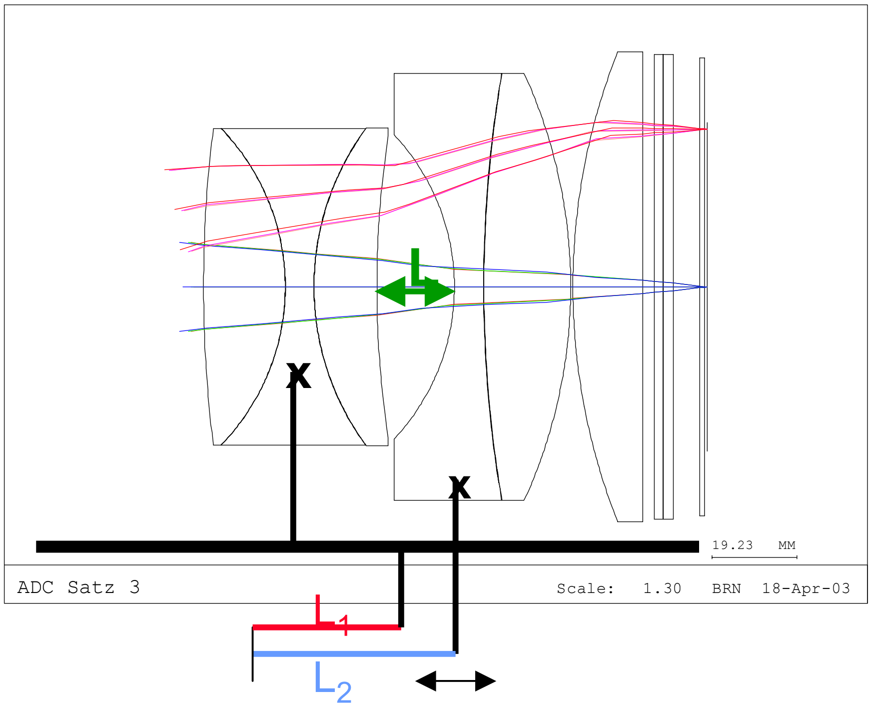
Zerodur glass ceramics

$\Delta V / \Delta T = \alpha_1 V_1 + \alpha_2 V_2 = 0$

- **α_1 [Crystalline] < 0**
- **α_2 [Amorphous] > 0**

➔ $V_1 / V_2 = - \alpha_2 / \alpha_1$ **> 0**

Optomechanical Athermalization



Lens group

$\Delta L / \Delta T = \alpha_1 L_1 - \alpha_2 L_2 = c \neq 0$

- α_1 [Aluminum]
- α_2 [Invar]

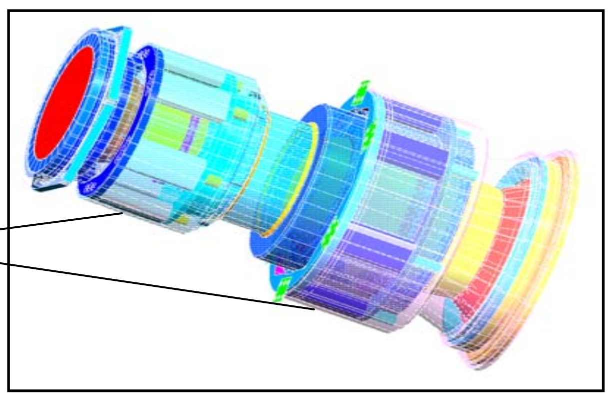
➔ $L_1 / L_2 = (c / L_2 + \alpha_2) / \alpha_1$

Optical system:

Several lens groups are mutually moved to fulfil

$\Delta F / \Delta T = 0$; Focal length

$\Delta s' / \Delta T = 0$; Best focus



Compensators

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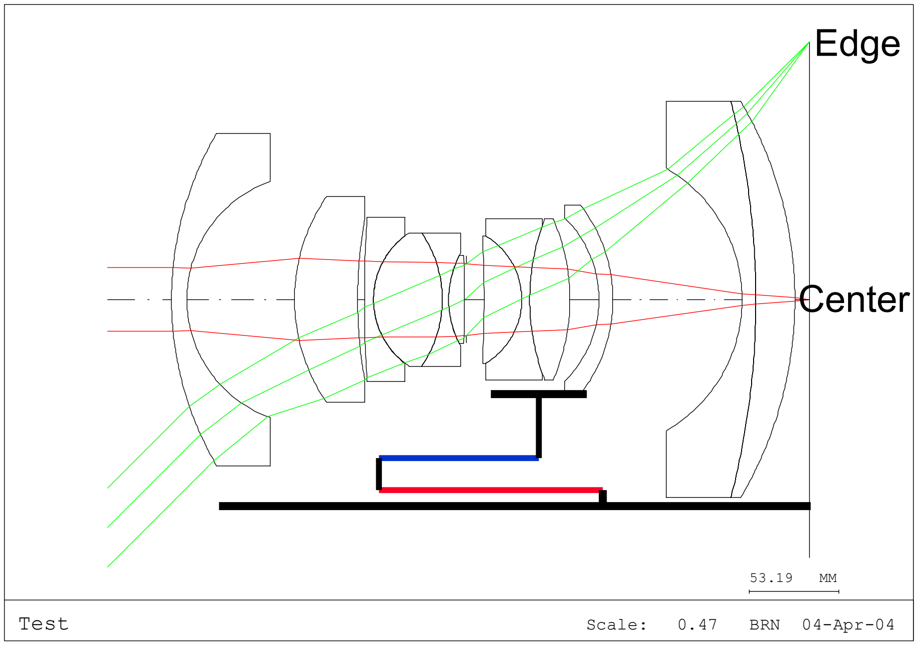
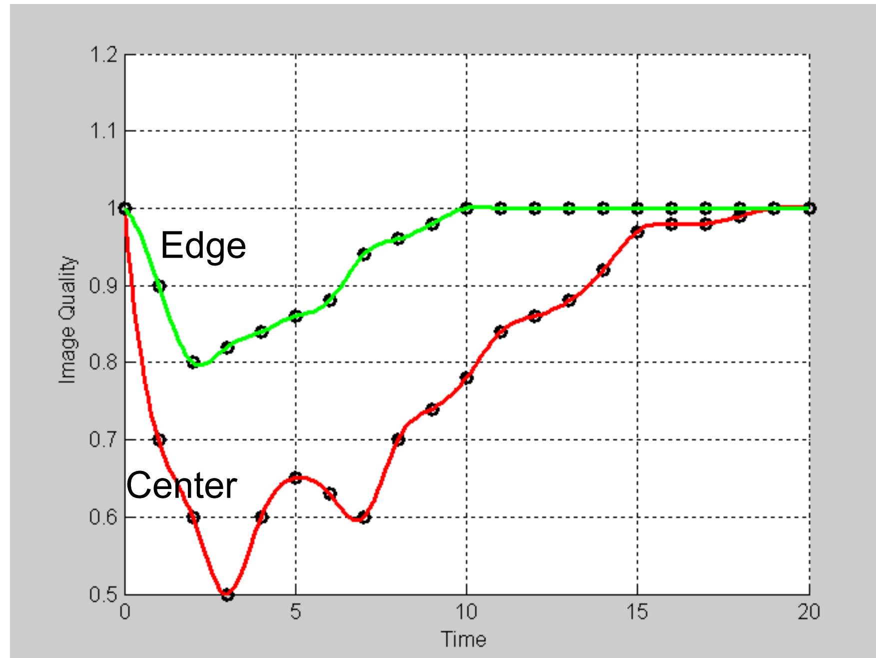
Image Quality for Different Image Zones





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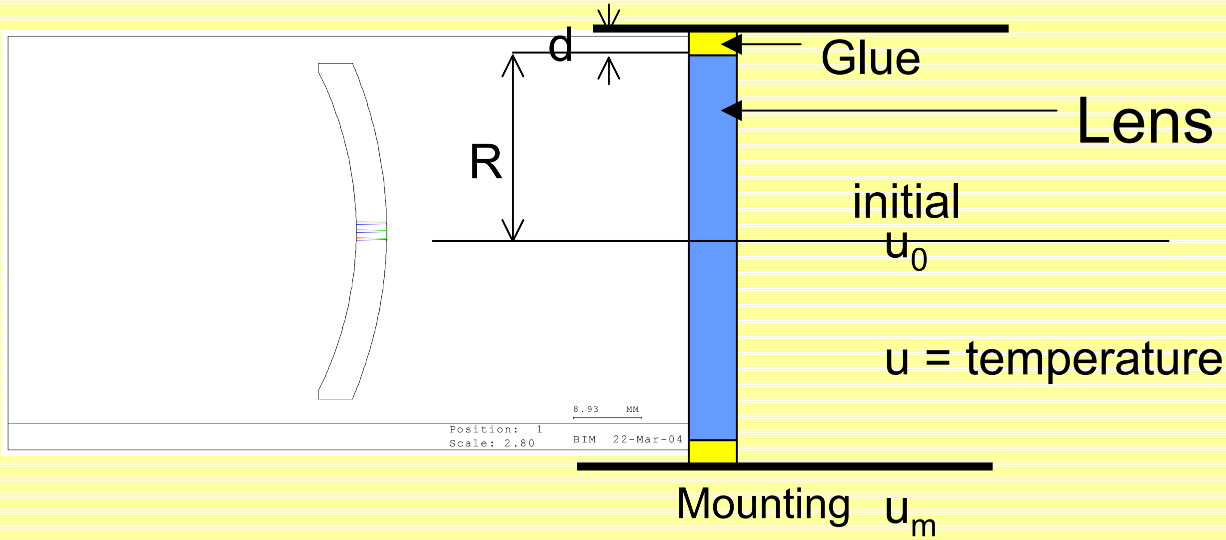
Non stationary: Thermal Management

Questions

- How do thermal gradients influence the optical performance?
- When does the lens reach full performance, e.g. a lens at –20 °C is brought into a surrounding of +25 °C?
- How to thermally speed up to reach the fully operational state?

Mathematical Modeling

- Realistic modeling using
  - Each lens is modeled as a cylinder
  - But with the material parameter of the glass body κ
  - And the mechanical interface glass to mounting d



Differential Equation

$$\frac{\partial u}{\partial t} = \kappa \cdot \Delta u = \kappa \cdot \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r^2}\frac{\partial^2 u}{\partial \varphi^2} + \frac{\partial^2 u}{\partial z^2} \right]$$

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Material Parameters

$$\begin{cases} \kappa = \dfrac{\lambda}{c\rho} : \text{ heat conductivity } [\mathrm{m^2 s^{-1}}] \\ \lambda : \text{ thermal conductivity } [\mathrm{W m^{-1} K^{-1}}] \\ c : \text{ specific heat } [\mathrm{J\,kg^{-1} K^{-1}}] \\ \rho : \text{ density } [\mathrm{kg\,m^{-3}}] \end{cases}$$

	N-LASF41	N-LF5	
λ	0.790	1.060	$\mathrm{W\,m^{-1}K^{-1}}$
c	490	810	$\mathrm{J\,kg^{-1}K^{-1}}$
ρ	4930	2570	$\mathrm{kg\,m^{-3}}$
$\kappa = \lambda/(c\,\rho)$	$3.3 \cdot 10^{-7}$	$5.1 \cdot 10^{-7}$	$\mathrm{m^2 s^{-1}}$

Normalized Parameters

Characteristic time

Characteristic thickness

$$\tilde{r} = \frac{r}{R}, \quad T = \frac{R^2}{\kappa}, \quad \tilde{t} = \frac{t}{T}, \quad \tilde{D} = \frac{D}{R}, \quad \tilde{u}(\tilde{r}, \varphi, z; \tilde{t}) = \frac{u(r, \varphi, z; t) - u_m}{u_m - u_0}$$

Normalized radius

Normalized time

Normalized temperature

Mechanical interface

$$D = d \cdot \frac{\lambda}{\lambda_{\text{glue}}}$$

d = glue thickness

Simplifying Assumptions

- (i) The lens only exchanges heat with the mounting
- (ii) The temperature of the lens is constant in the direction of its optical axis (*no z-dependence*)
- (iii) The mounting is radially symmetric (*no φ-dependence*)
- --
- (iv) The mounting keeps its temperature independently of the quantity of heat it must deliver to the glass

or

- (iv') The mounting holds the heat flux constant independently of the temperature of the glass

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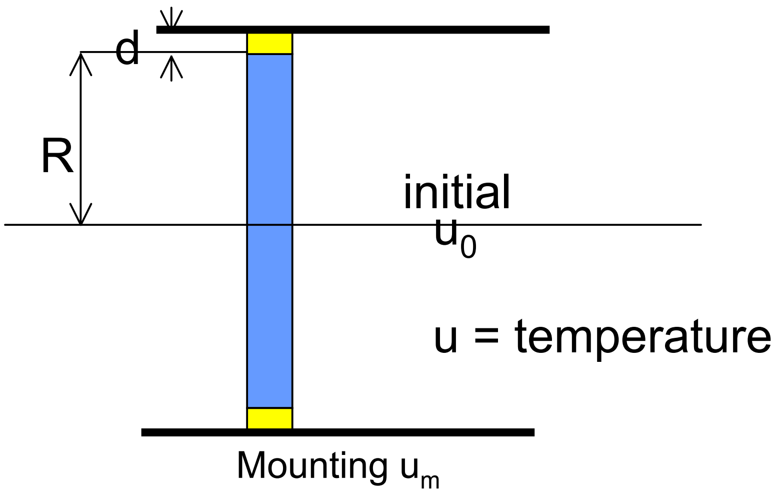
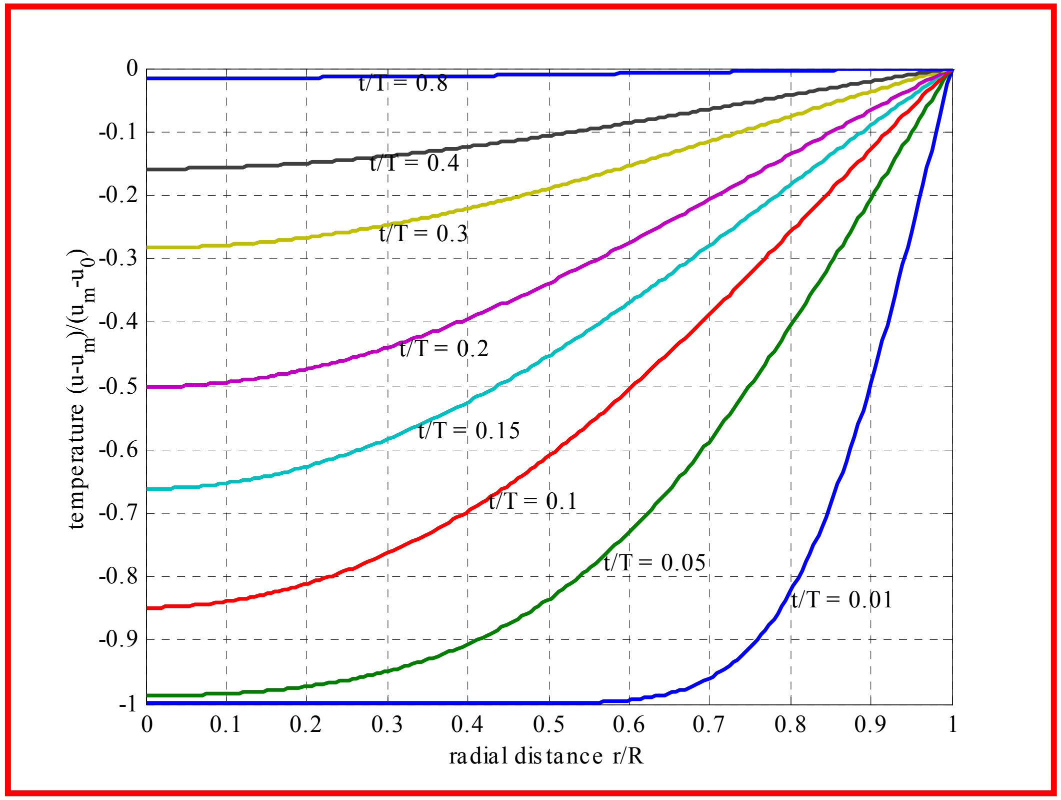
Heat Diffusion with constant Mounting Temperature

Boundary conditions

$$u(r,0) = u_0$$

$$D \cdot \frac{\partial u}{\partial r}(R,t) + u(R,t) = u_m$$





Solution

$$\tilde{u}(\tilde{r},\tilde{t}) = \sum_{j=1}^{\infty} \frac{-2\, e^{-k_j^2 \tilde{t}}}{(\tilde{D}^2 k_j^2 + 1) \cdot k_j J_1(k_j)} J_0(k_j \tilde{r})$$

$$\tilde{D} \cdot k_j \cdot J_0'(k_j) + J_0(k_j) = 0$$

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Characteristic Times

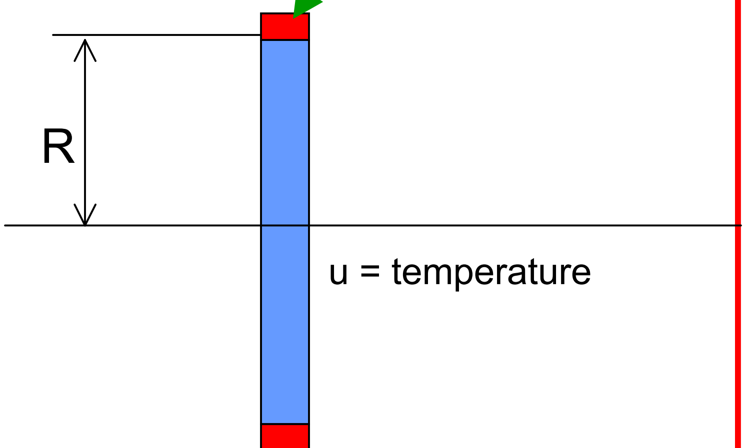
	N-LASF41	N-LF5	
λ	0.790	1.060	$W\ m^{-1}K^{-1}$
c	490	810	$J\ kg^{-1}K^{-1}$
ρ	4930	2570	$kg\ m^{-3}$
$\kappa = \lambda/(c\ \rho)$	$3.3 \cdot 10^{-7}$	$5.1 \cdot 10^{-7}$	m^2s^{-1}
R	0.05	0.025	m
$T = R^2 / \kappa$	2.1	0.34	h

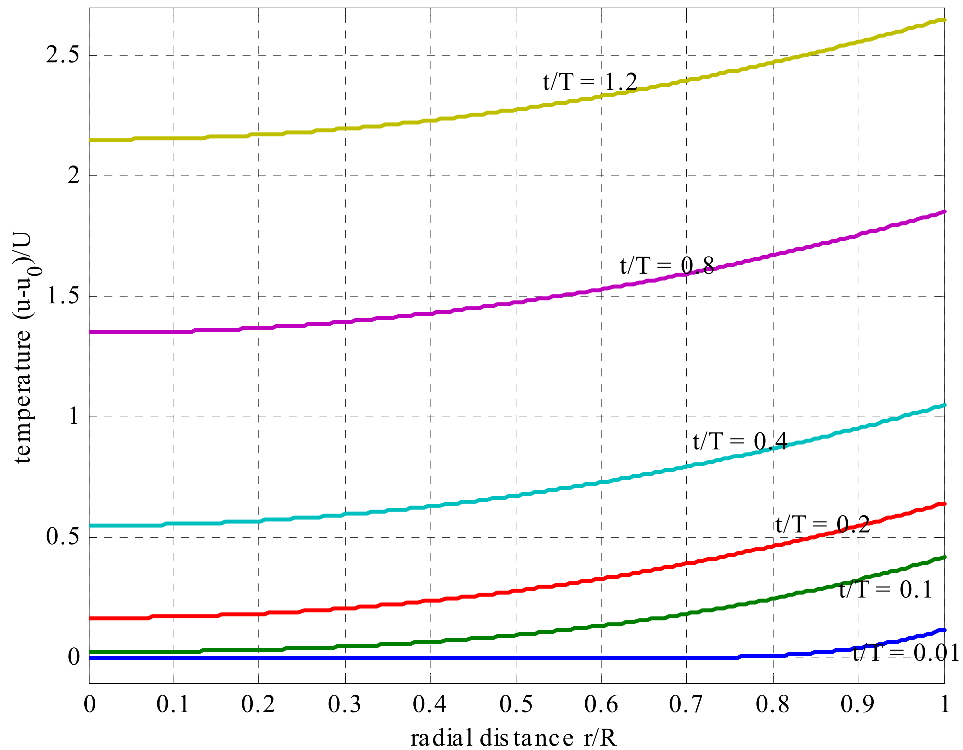
Constant Heat Flux

Boundary conditions

$$u(r,0) = u_0$$

$$\lambda \cdot \frac{\partial u}{\partial r}(R,t) = q$$





Solution

$$\tilde{u}(\tilde{r},\tilde{t}) = \frac{\tilde{r}^2}{2} + 2\tilde{t} - \frac{1}{4} - \sum_{j=1}^{\infty} \frac{2e^{-k_j^2 \tilde{t}}}{k_j^2 J_0(k_j)} J_0(k_j \tilde{r})$$

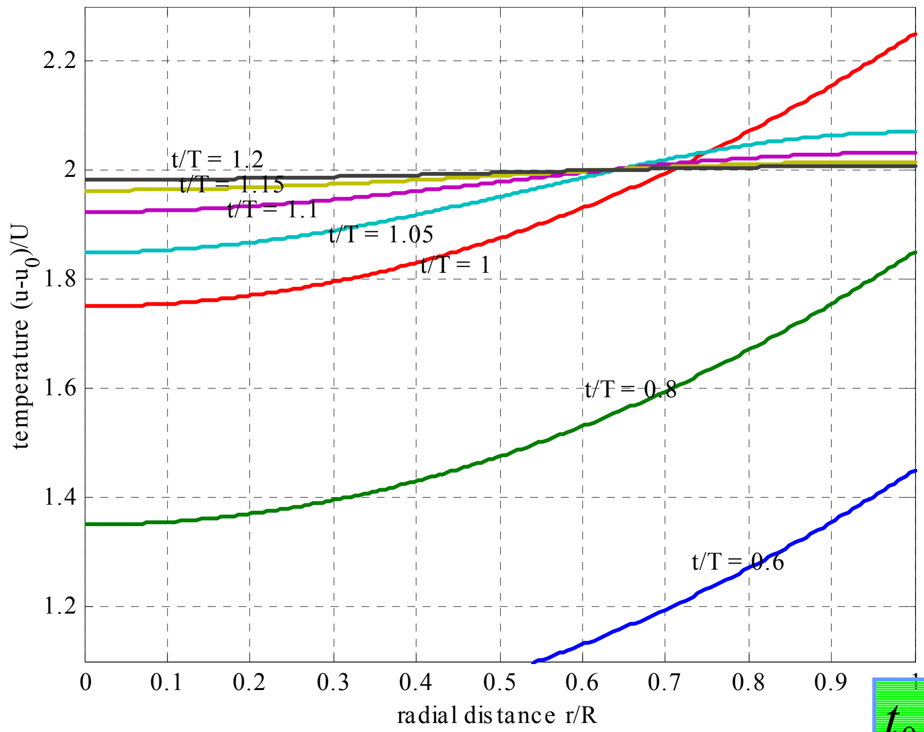
$$U = \frac{qR}{\lambda}, \quad \tilde{u}(\tilde{r},\tilde{t}) = \frac{u(r,t) - u_0}{U}$$

Turning the Heat Flux 'on and off'

Boundary conditions

$$u(r,0) = u_0$$

$$\lambda \cdot \frac{\partial u}{\partial r}(R,t) = \begin{cases} q, & 0 < t \le t_0 \\ 0, & t > t_0 \end{cases}$$



$t_0 = T$

Solution

$$\tilde{u}(\tilde{r},\tilde{t}) = \begin{cases} \dfrac{\tilde{r}^2}{2} + 2\tilde{t} - \dfrac{1}{4} - \displaystyle\sum_{j=1}^{\infty} \frac{2e^{-k_j^2\tilde{t}}}{k_j^2 J_0(k_j)} J_0(k_j\tilde{r}), & \tilde{t} < \tilde{t}_0 \\ 2\tilde{t}_0 + \displaystyle\sum_{j=1}^{\infty} \frac{2}{k_j^2 J_0(k_j)} \left(1 - e^{-k_j^2\tilde{t}_0}\right) e^{-k_j^2(\tilde{t}-\tilde{t}_0)} J_0(k_j\tilde{r}), & \tilde{t} > \tilde{t}_0 \end{cases}$$

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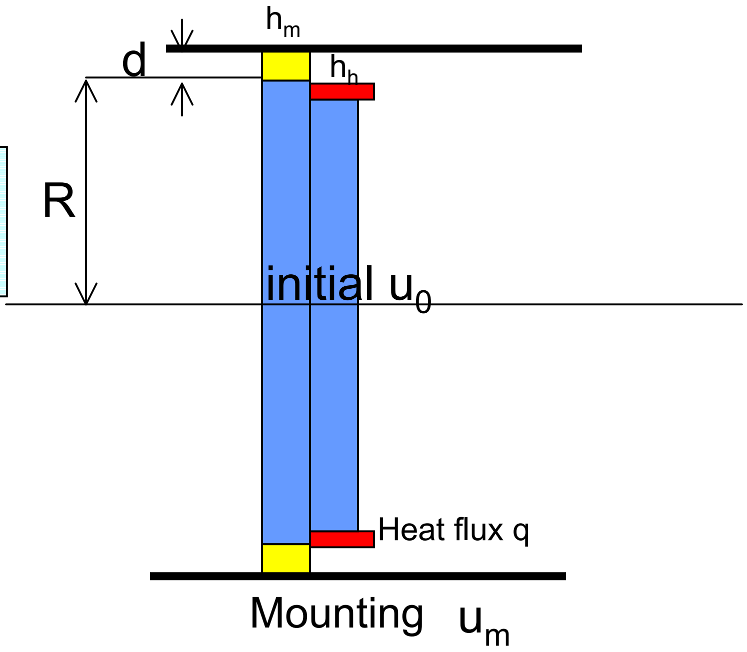
Heating a Part of the Cylinder Mantle

Boundary conditions

$$u(r,0) = u_0$$

$$d\,\frac{\lambda}{\lambda_{\text{glue}}}\frac{h_L}{h_m}\cdot\frac{\partial u}{\partial r}(R,t) + u(R,t) - \left(u_m + H(t_0 - t)\cdot q\,\frac{h_h}{h_m}\frac{d}{\lambda_{\text{glue}}}\right) = 0$$



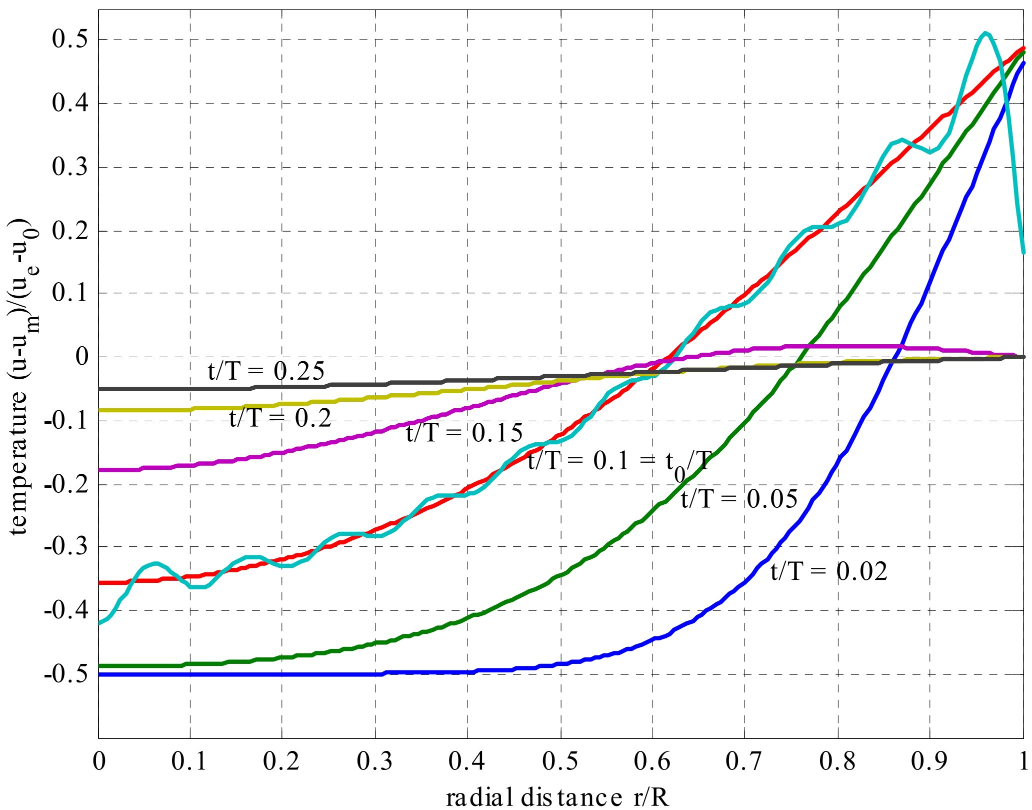
$$\tilde{u}(\tilde{r},\tilde{t}) = \frac{u(r,t) - u_m}{u_e - u_0}$$

$$u_e := u_m + q\,\frac{h_h}{h_m}\frac{d}{\lambda_{\text{glue}}}$$

Solution

$$\tilde{u}(\tilde{r},\tilde{t}) = \begin{cases} \gamma - \displaystyle\sum_{j=1}^{\infty} \frac{2\,e^{-k_j^2\tilde{t}}}{(\tilde{D}^2 k_j^2 + 1)\cdot k_j J_1(k_j)} J_0(k_j\tilde{r}), & \tilde{t} \le \tilde{t}_0 \\ \displaystyle\sum_{j=1}^{\infty} \frac{2}{(\tilde{D}^2 k_j^2 + 1)\cdot k_j J_1(k_j)} \cdot \left[\gamma\,e^{-k_j^2(\tilde{t}-\tilde{t}_0)} - e^{-k_j^2\tilde{t}}\right]\cdot J_0(k_j\tilde{r}), & \tilde{t} \ge \tilde{t}_0 \end{cases}$$

Heating a Part of the Cylinder Mantle



$$\tilde{D} = \frac{D}{R} = \frac{d}{R}\frac{\lambda}{\lambda_{\text{glue}}}\frac{h_L}{h_m}, \quad \tilde{u}(\tilde{r},\tilde{t}) = \frac{u(r,t)-u_m}{u_e-u_0}, \quad \gamma = \frac{u_e-u_m}{u_e-u_0}$$

$$u_e := u_m + q\frac{h_h}{h_m}\frac{d}{\lambda_{\text{glue}}}$$

t_0/T = 0.1, γ = 0.5, The wiggly line is for t/T = 0.1001 and shows the Gibbs phenomenon.

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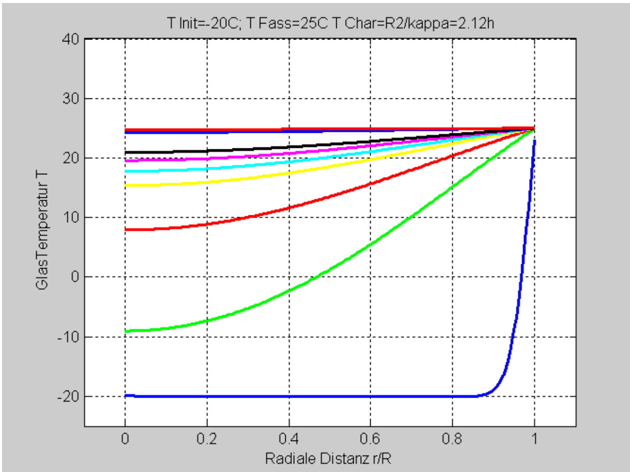
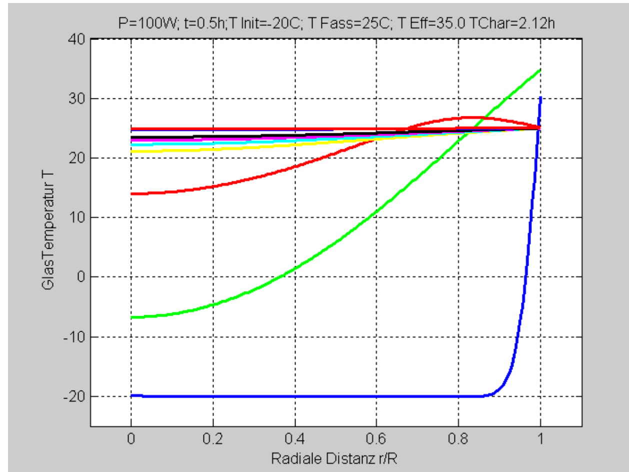
Example: Disc 100 mm Diameter; N-LASF41

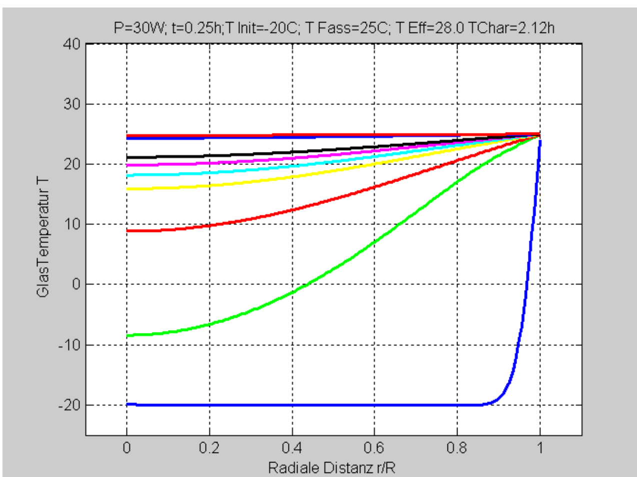
Diffusion



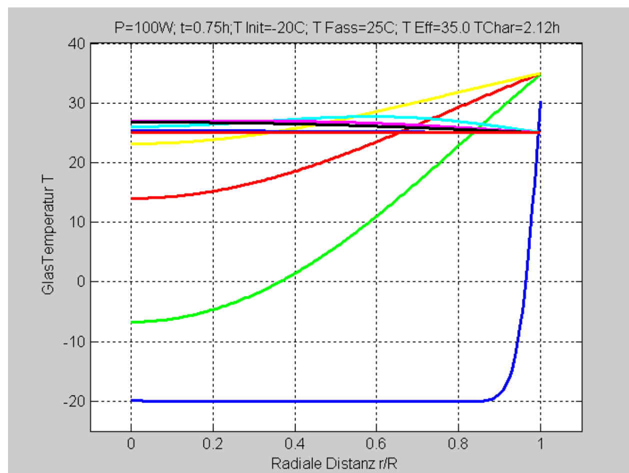
100 W / 30 min



30 W / 15 min



100 W / 45 min



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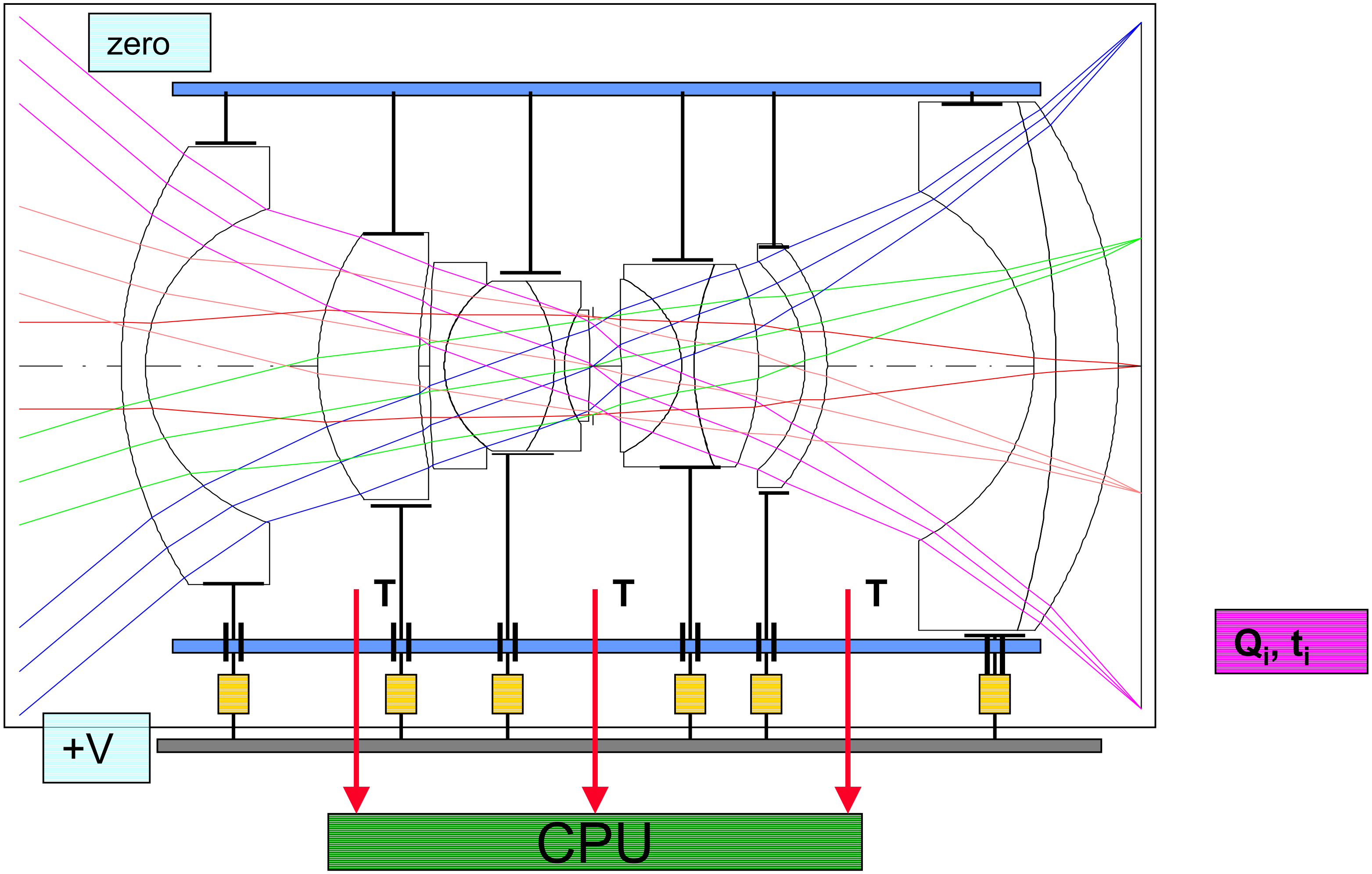
Hardware Concept: Individual Heating



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Summary

- Based on stationary athermalization
  - Measure temperature **T** inside and outside of objective
  - Compute for each lens **heat flux** $\mathbf{Q}_i$ and **heat duration** $\mathbf{t}_i$
    - e.g. so that all lens centers are at the same temperature after the same time

- We presented, under simplifying assumptions, an analytically closed theory
  - Invariant to material and geometry parameters
  - Applicable to many different boundary conditions

- Start procedure for fine tuning of $\mathbf{Q}_i$ and $\mathbf{t}_i$
  - Finite element modeling
  - Complicated ray tracing
  - Experimental verification

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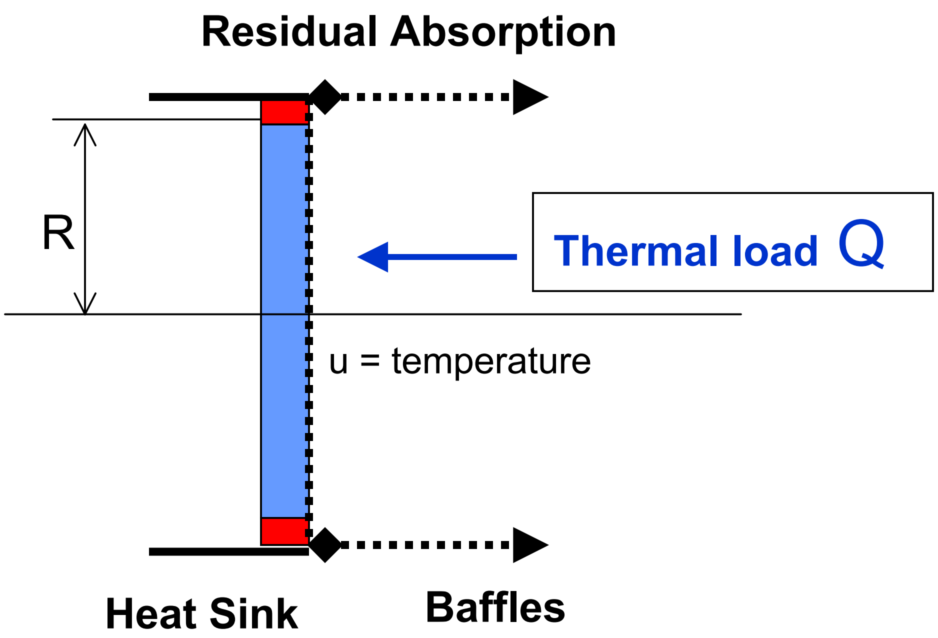
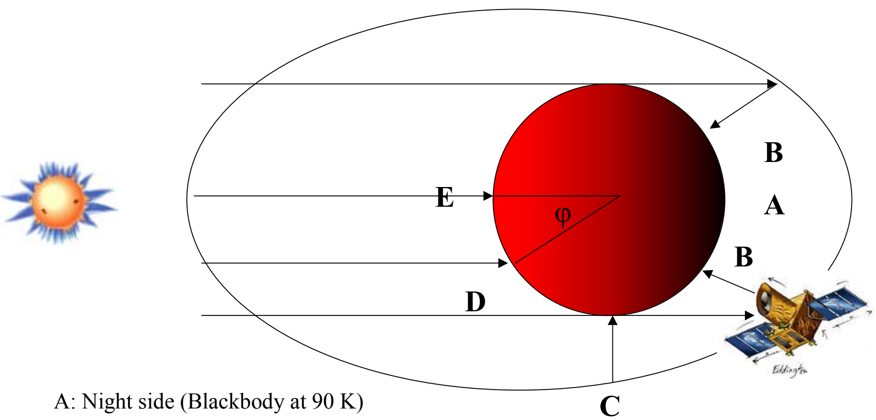
Heat Shield for Space Applications





A: Night side (Blackbody at 90 K)

B: Sunrise point

C: Polar point (Dawn of day)

D: Morning point

E: Zenith point (Blackbody at 688 K + albedo)

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Heating by Absorption in the Coating

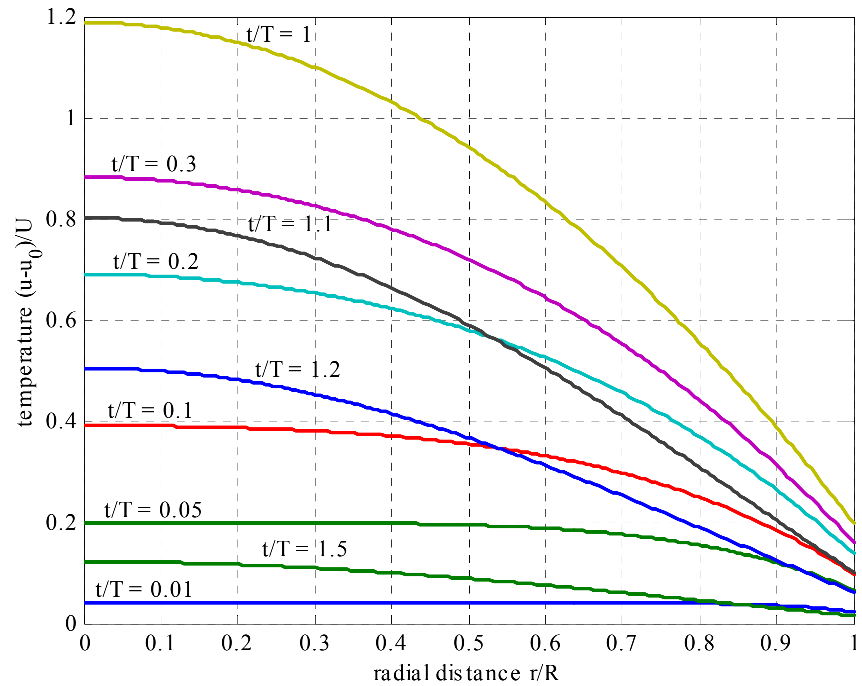
Boundary conditions

$$u(r,0) = u_0$$

$$D \cdot \frac{\partial u}{\partial r}(R,t) + u(R,t) = u_0$$

Equation with source term

$$\frac{\partial u}{\partial t} = \kappa \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{q}{\lambda h} H(t - t_0) \right]$$



$$t_0 = T, \quad D = R/10$$

Solution

$$\tilde{u}(\tilde{r},\tilde{t}) = \begin{cases} \frac{\tilde{q}}{4}(1 + 2\tilde{D} - \tilde{r}^2) - \sum_{j=1}^{\infty} \frac{2\tilde{q} e^{-k_j^2 \tilde{t}}}{(\tilde{D}^2 k_j^2 + 1) k_j^3 J_1(k_j)} J_0(k_j \tilde{r}), & \tilde{t} < \tilde{t}_0 \\ \sum_{j=1}^{\infty} \frac{2\tilde{q}}{(\tilde{D}^2 k_j^2 + 1) k_j^3 J_1(k_j)} \left(e^{-k_j^2(\tilde{t} - \tilde{t}_0)} - e^{-k_j^2 \tilde{t}} \right) J_0(k_j \tilde{r}), & \tilde{t} > \tilde{t}_0 \end{cases}$$

$$\tilde{u}(\tilde{r},\tilde{t}) = \frac{u(r,t) - u_0}{U}$$

$$U = \frac{qR}{\lambda}, \quad \tilde{q} = \frac{q}{R}, \quad \tilde{D} = \frac{D}{R}$$

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Concluding Remarks

- The procedure is extended to other applications
  - Stationary problem for spherical lens
- The mathematical theory is submitted to the journal
  - „American Mathematical Monthly“, B. Aebischer, May 2004
- The Presentation and the Matlab programs can be downloaded
  - http://www.leica-geosystems.com/**ctc/heat_conduction**