AGENZIA NAZIONALE
PER LE NUOVE TECNOLOGIE, L'ENERGIA
E LO SVILUPPO ECONOMICO SOSTENIBILE

CLUB CAST3M
Paris 29-11-2012

Conceptual design of concrete thermal energy storage system for small size concentration solar plants.

(Overview on CAST3M application for the analysis of components for solar plants employing molten salts)

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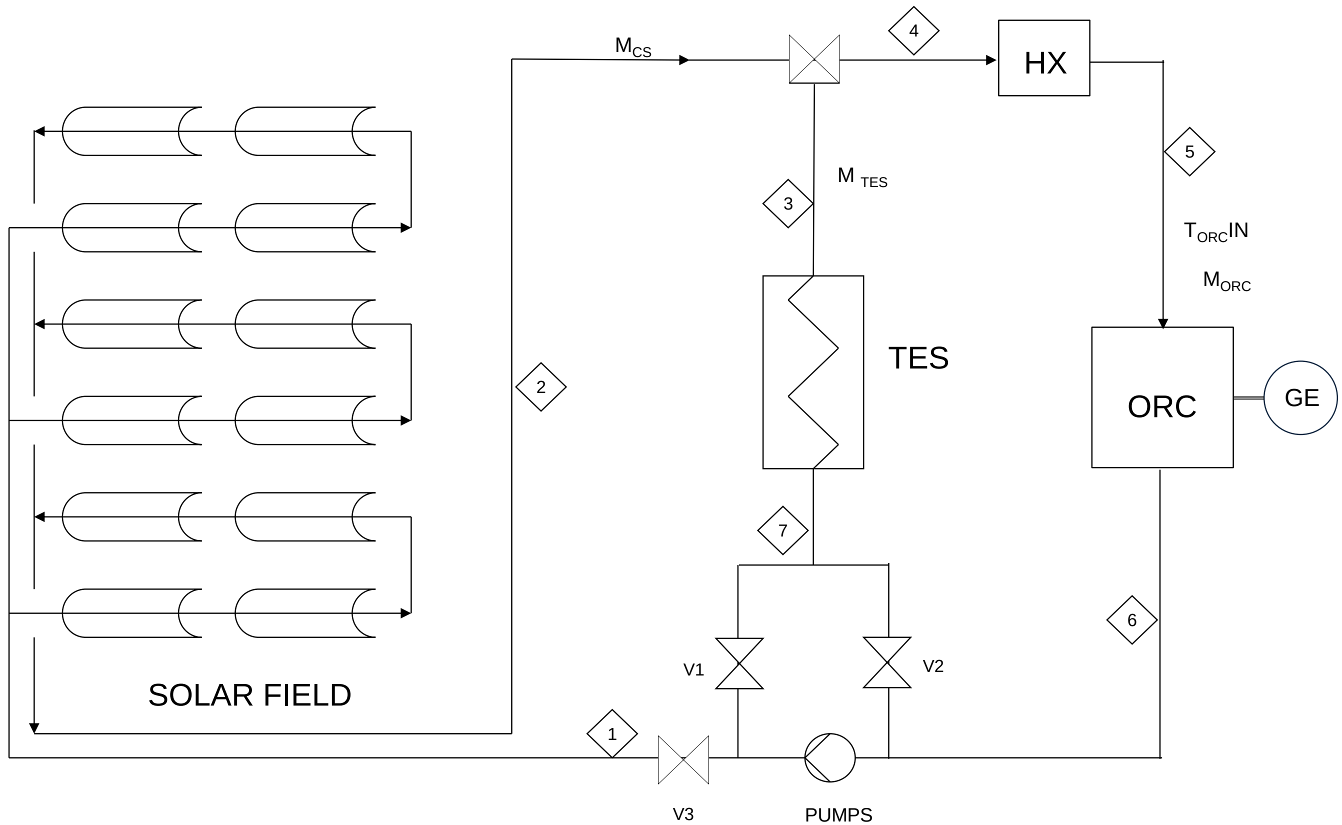
Objectives of the SOLTECA project

- Sensible heat storage in a specially developed concrete mix
- Modular storage system, not cast in situ, reduction in the degassing time at start up.
- Working temperature between 120 e 300 °C, able to operate a ORC power block
- Cost containment - (between 20-30 € / kWh_th), (not expensive O&M costs).
- Small plants with peak power (0.5 to 5 MWe), more placeable in the territory

The project is funded by the Cassa di Risparmio di Trento E Rovereto (CARITRO)

Scheme of the available solar plant with concrete TES



General scheme

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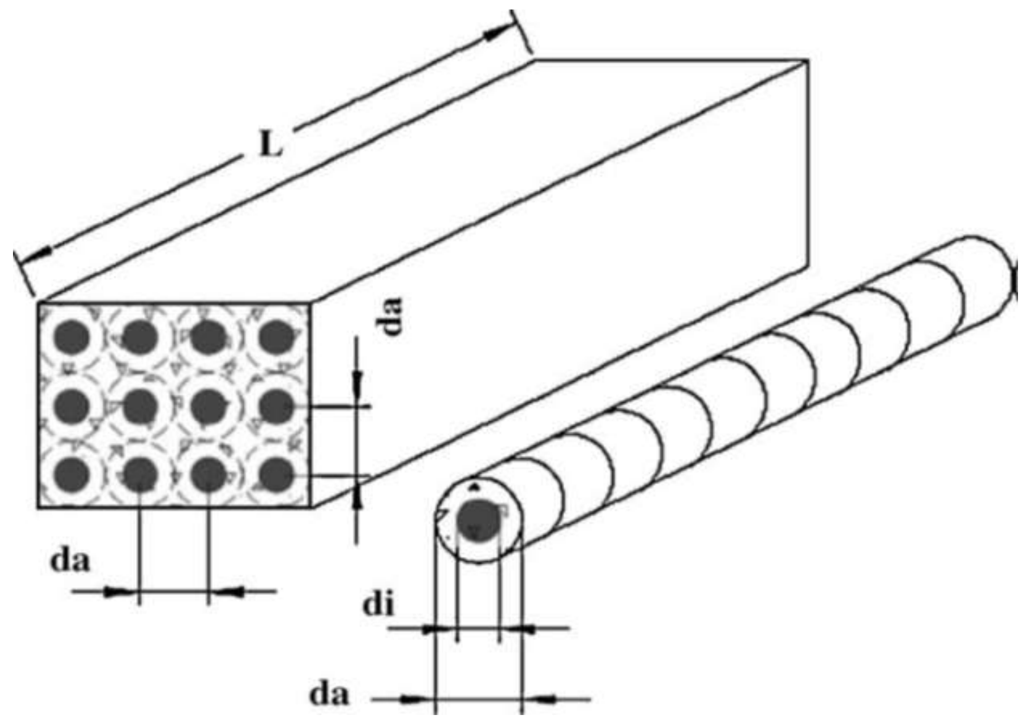
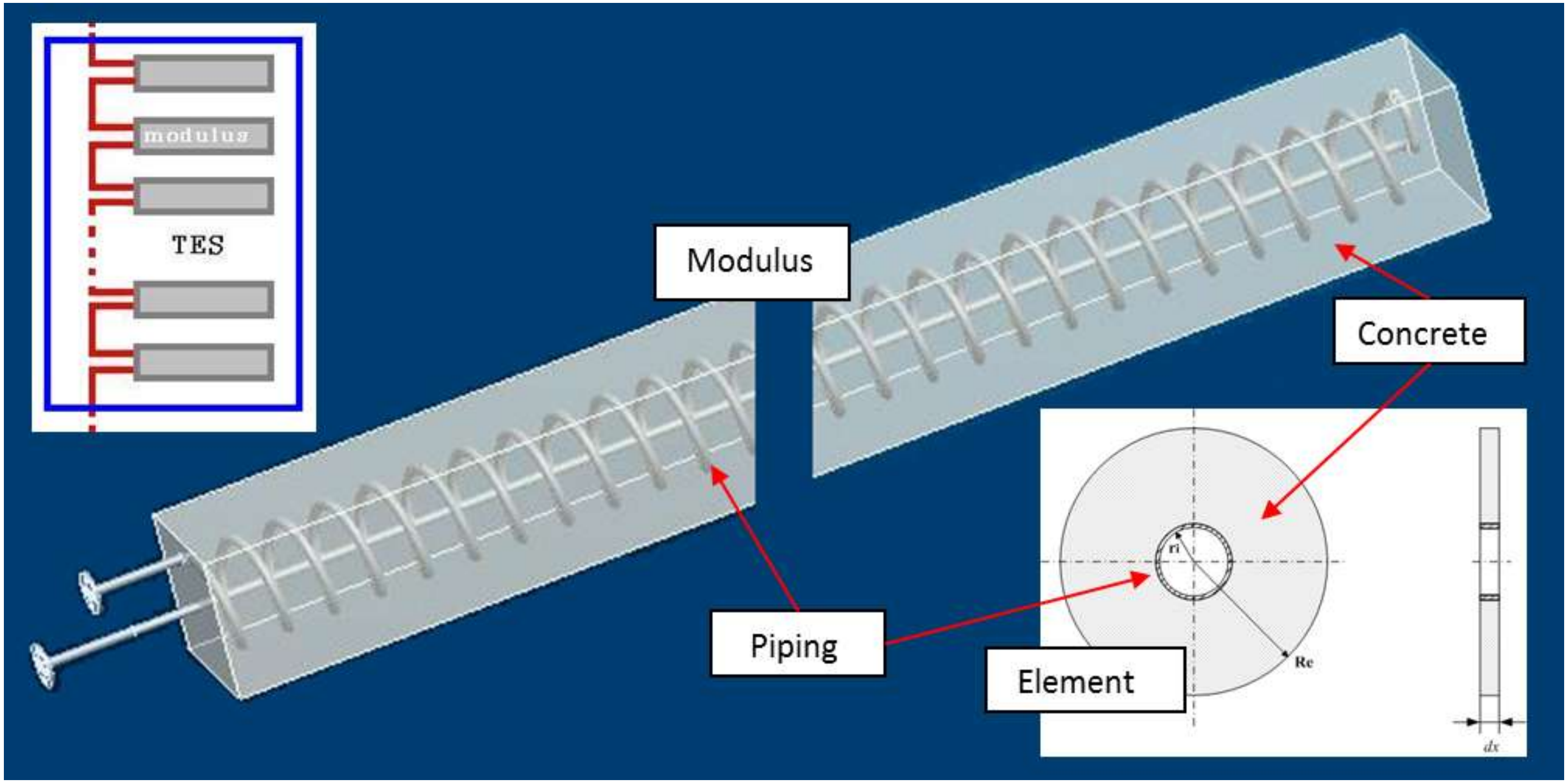


Element-Module-System Scheme



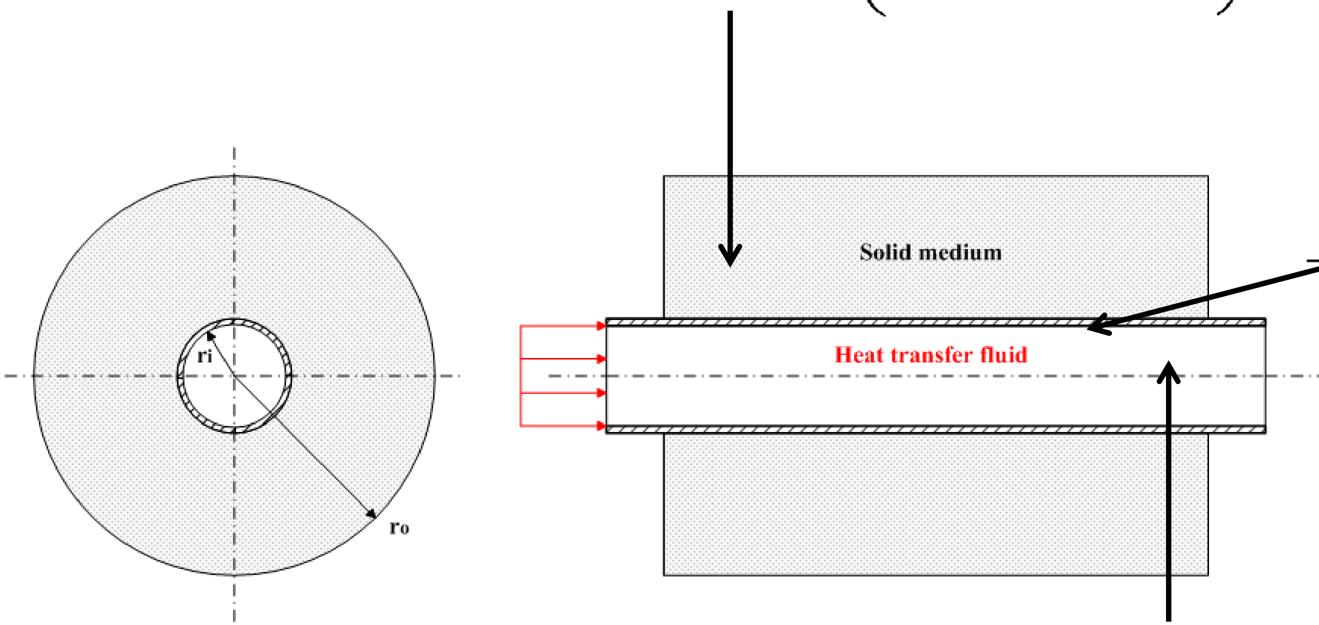
Economic and Physical Features of Solid Storage Media

Storage medium	Temperature		Average density (kg/m^3)	Average heat conductivity (W/m K)	Average heat capacity (kJ/kg K)	Volume specific heat capacity (kWh_t/m^3)	Media costs per kg ($US\$/kWh_t$)	Media costs per kWh_t ($US\$/kWh_t$)
	Cold (°C)	Hot (°C)						
Sand-rock-mineral oil	200	300	1700	1.0	1.30	60	0.15	4.2
Reinforced concrete	200	400	2200	1.5	0.85	100	0.05	1.0
NaCl (solid)	200	500	2160	7.0	0.85	150	0.15	1.5
Cast iron	200	400	7200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7800	40.0	0.60	450	5.00	60.0
Silica fire bricks	200	700	1820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1200	3000	5.0	1.15	600	2.00	6.0

Material	High temperature concrete
Density at 200 °C [kg/m^3]	2700
Specific heat capacity at 200 °C [J/kg K]	910
Thermal conductivity at 200 °C [W/m K]	1.0
Coefficient thermal expansion at 200 °C [$10^{-6}/K$]	9.3
Capacity [kWh_t/m^3 K]	0.68

TES: Physical Model

$$\rho c_p \cdot \frac{\partial T_s}{\partial t} = k_s \cdot \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} \right)$$

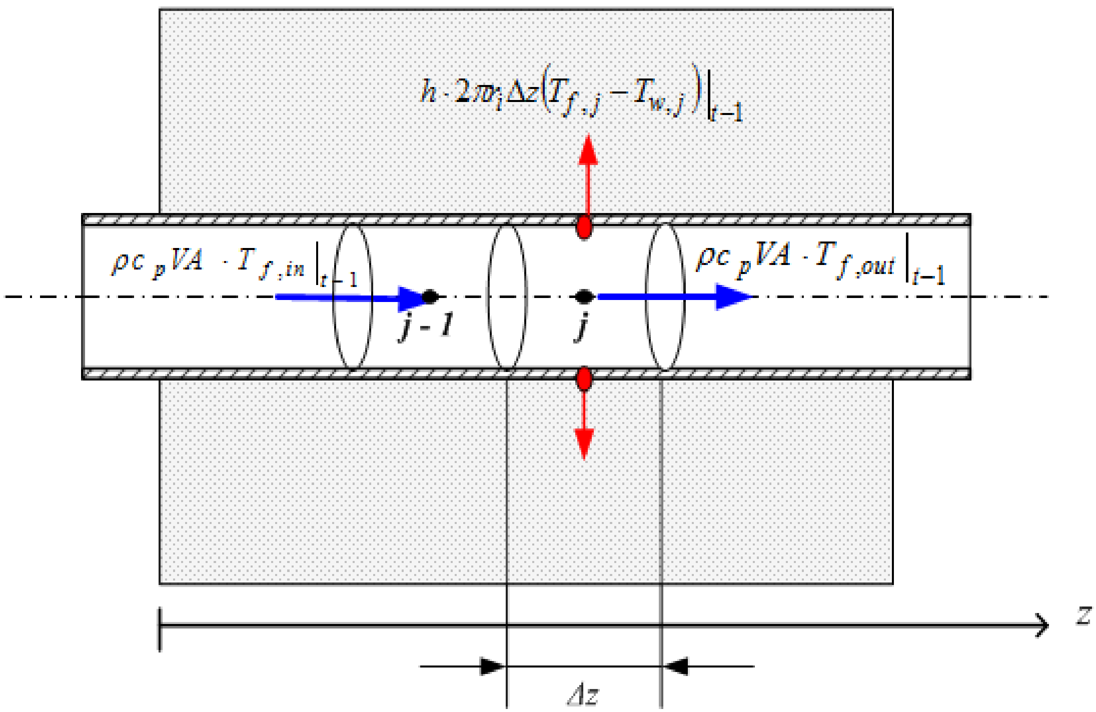


$$-k_s \frac{\partial T_s}{\partial r} = h \cdot (T_f - T_{s,w})$$

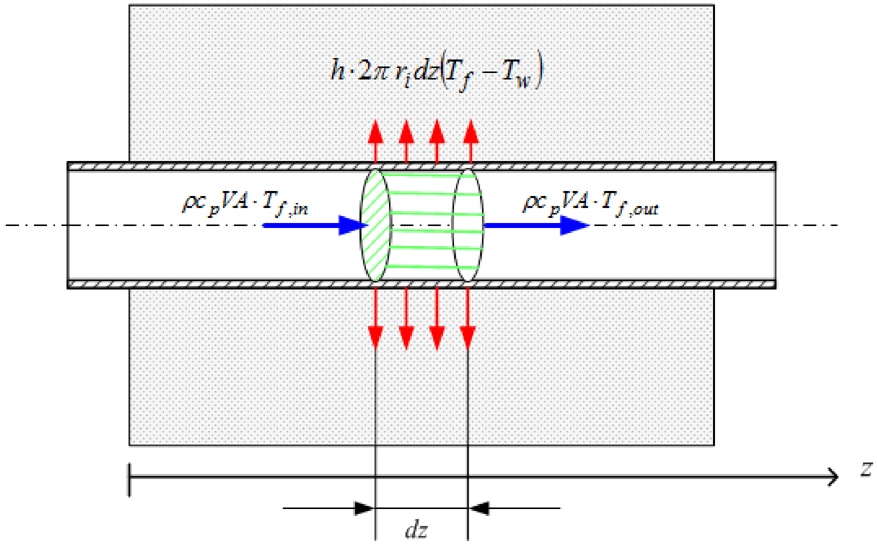
$$\rho c_p V A \cdot \frac{\partial T_f}{\partial z} - h \cdot 2\pi r_i (T_f - T_{s,w}) = \rho c_p A \cdot \frac{\partial T_f}{\partial t}$$

Nonstationary Model

$$T_{f,j}\big|_{t} = V\frac{\Delta t}{\Delta z}\cdot\left(T_{f,j-1} - T_{f,j}\right)\big|_{t-1} - 2\pi\cdot r_i\Delta z\frac{h\cdot\Delta t}{\rho c_p A\Delta z}\left(T_{f,j} - T_{w,j}\right)\big|_{t-1} + T_{f,j}\big|_{t-1}$$



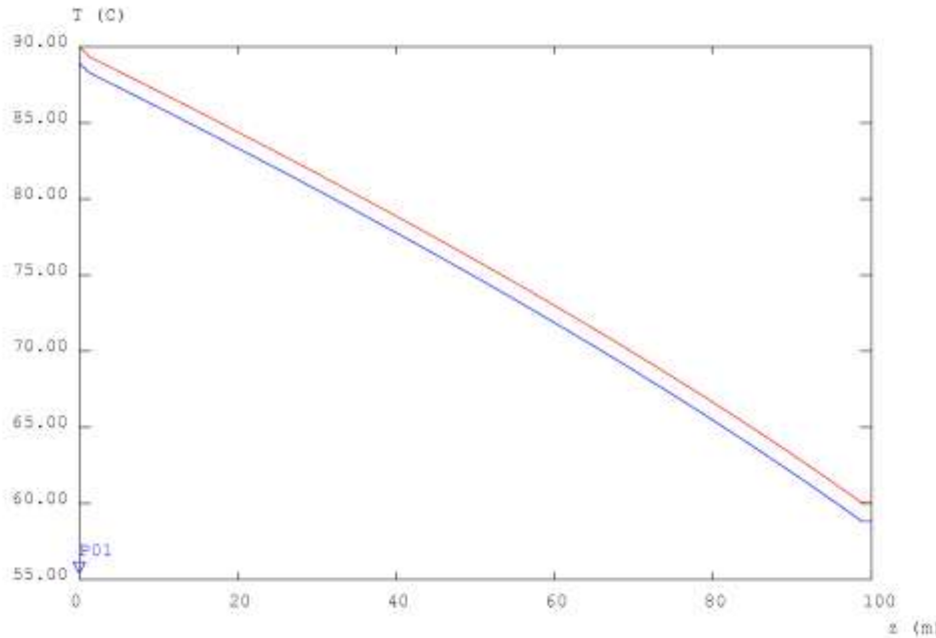
Semi – Steady State Model



$$\frac{dT_f}{dZ} = 4\frac{Nu}{Pe}\left(T_w - T_f\right) \xrightarrow{\int} T_f$$

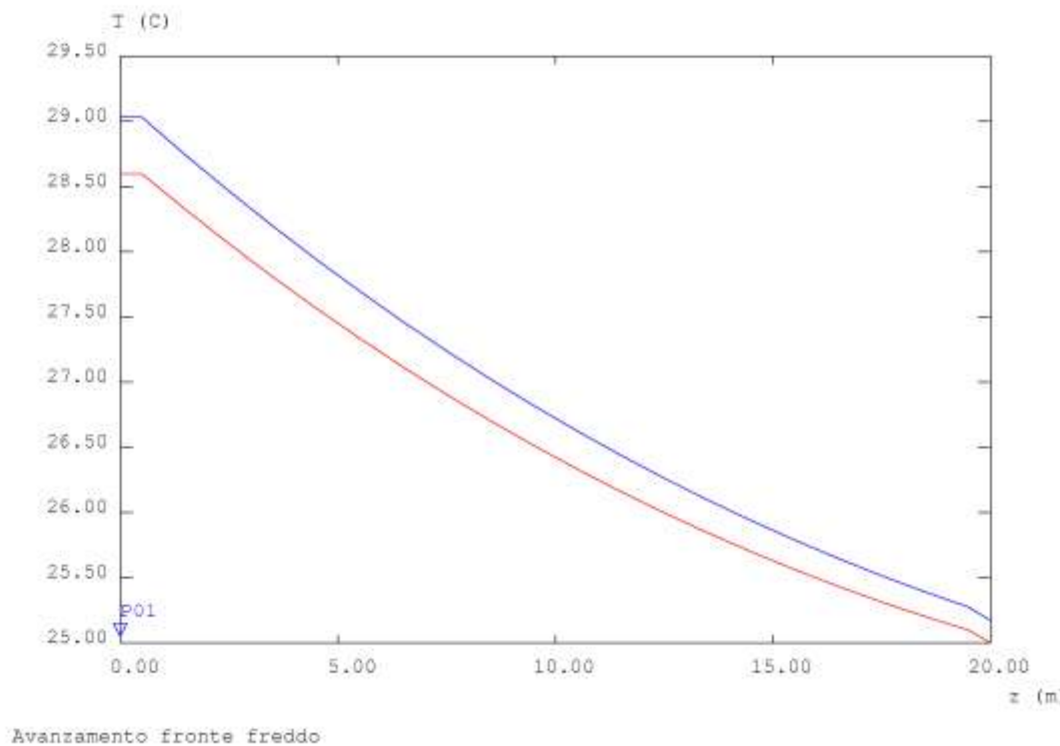
Fengwu Bai

Nonstationary Model: Charging Phase

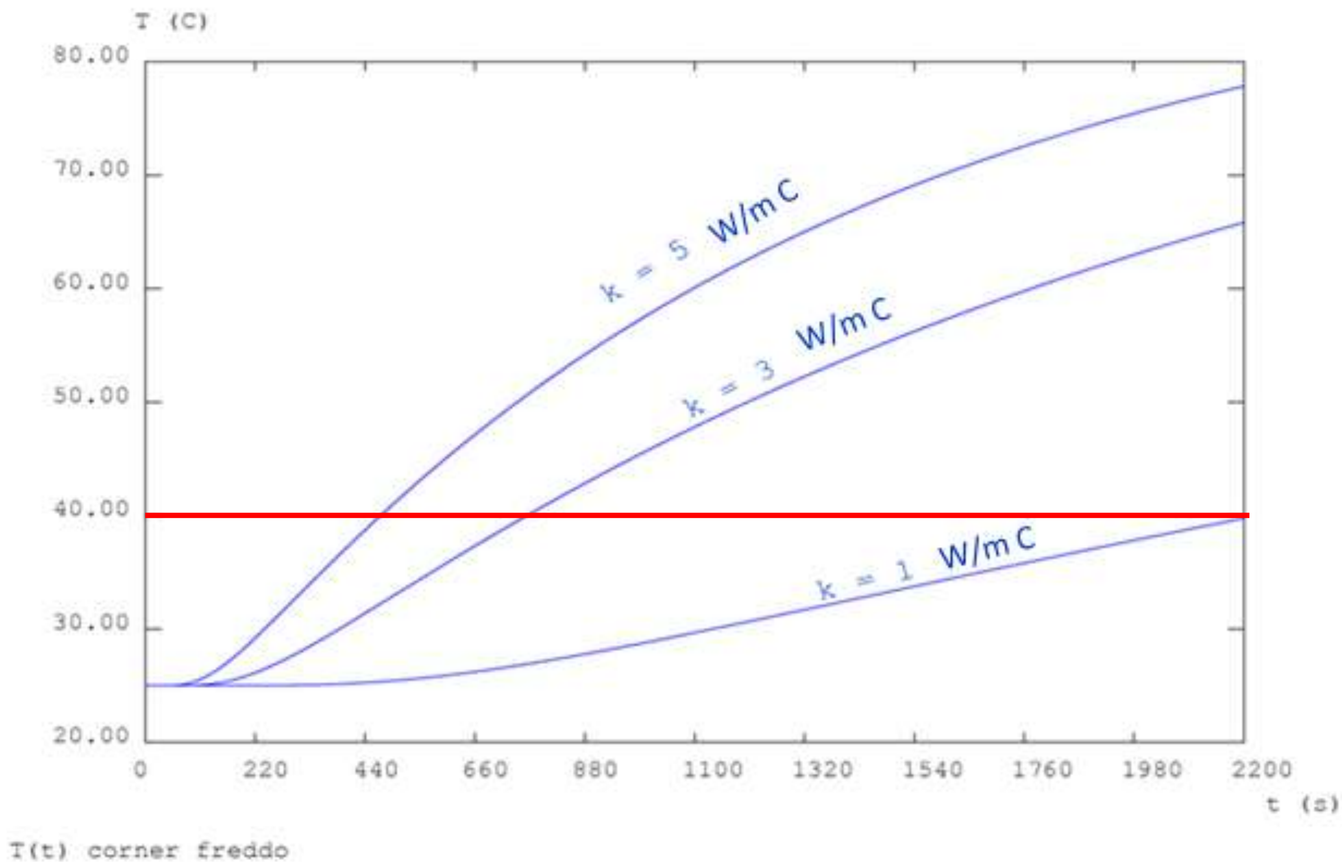


Profili di T fluido e parete

Nonstationary Model: Discharging Phase



Effect of Thermal Conductivity on the Charge Time

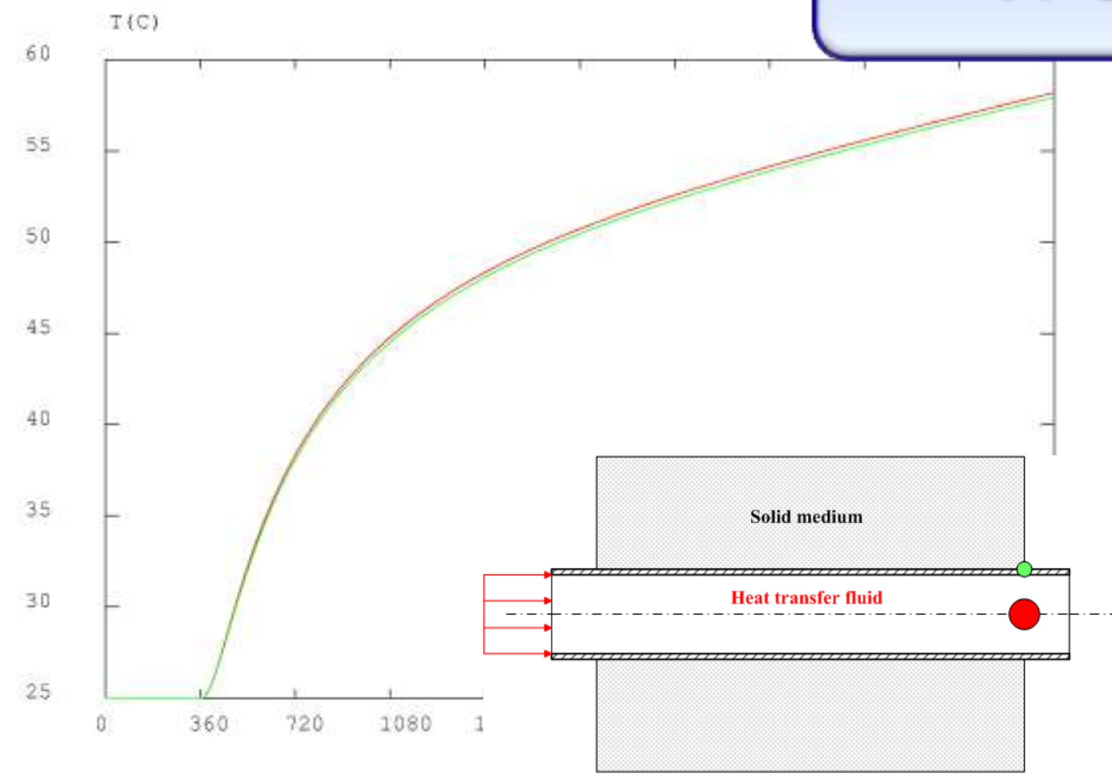


NON-STATIONARY MODEL: application to a realistic case

Time of charging = 1h

Channel L

Tf exit

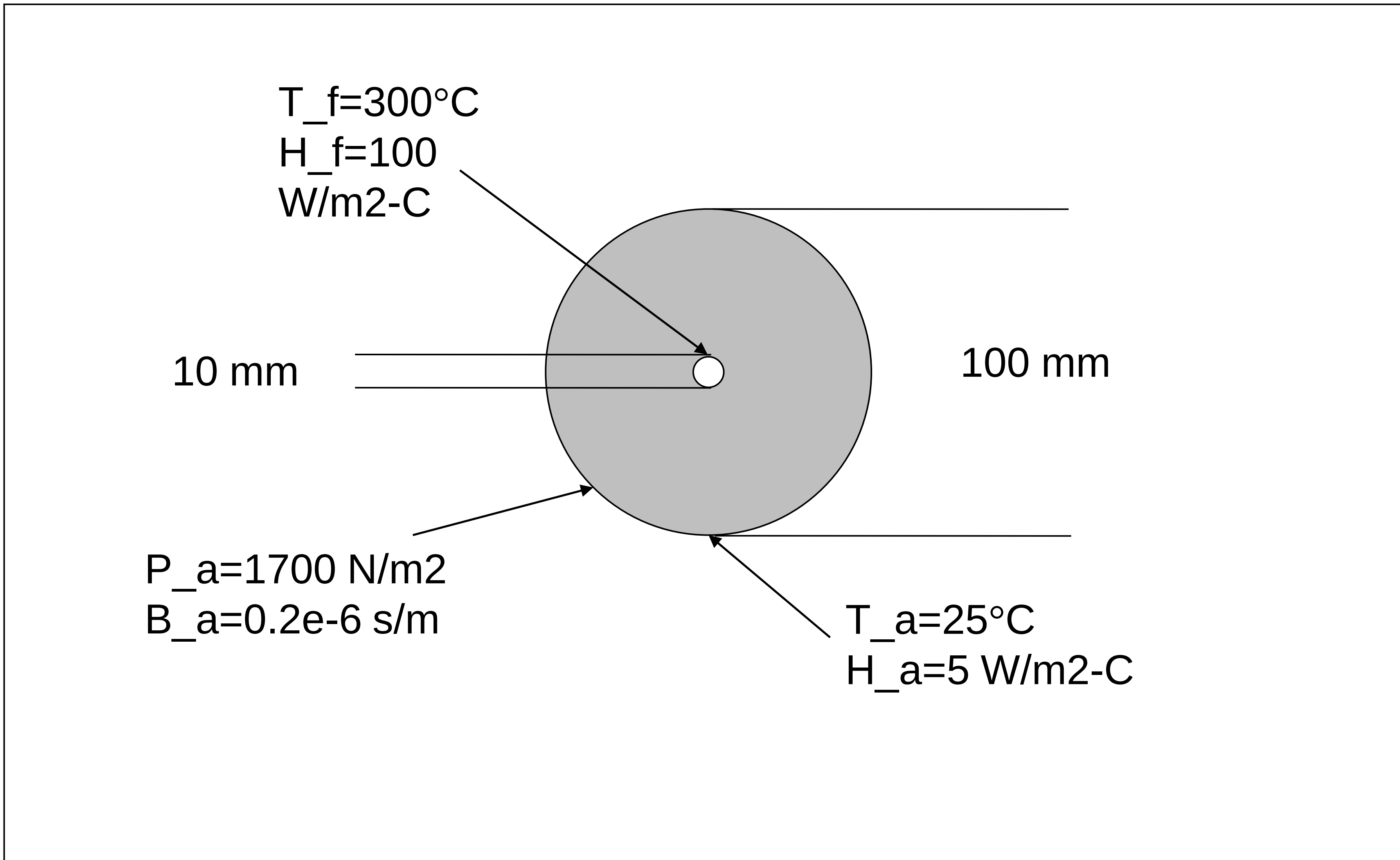


Andamento temporale Tf sezione uscita (L= 400 m)

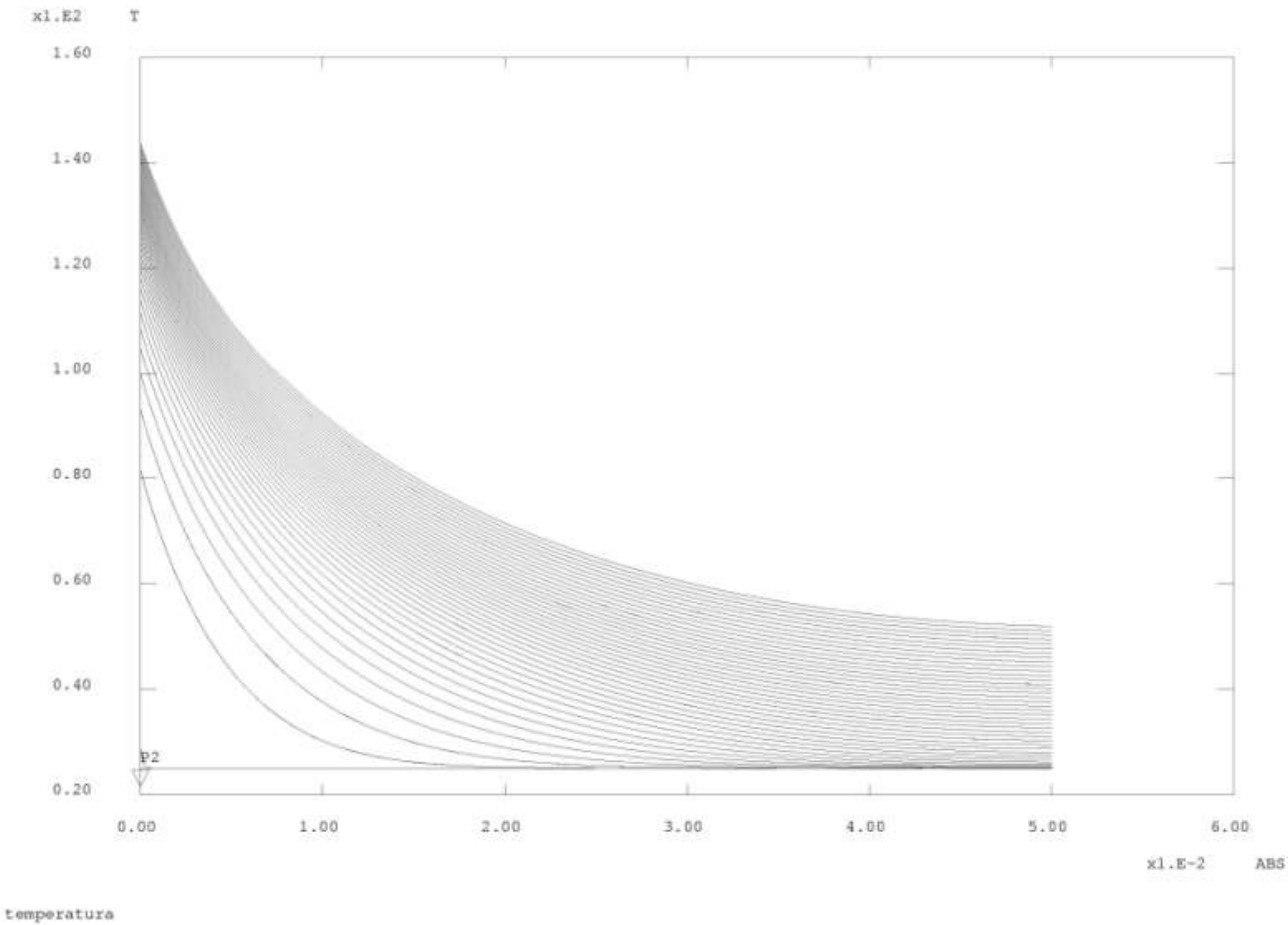
t(s)

T corners esterni L= 400 m

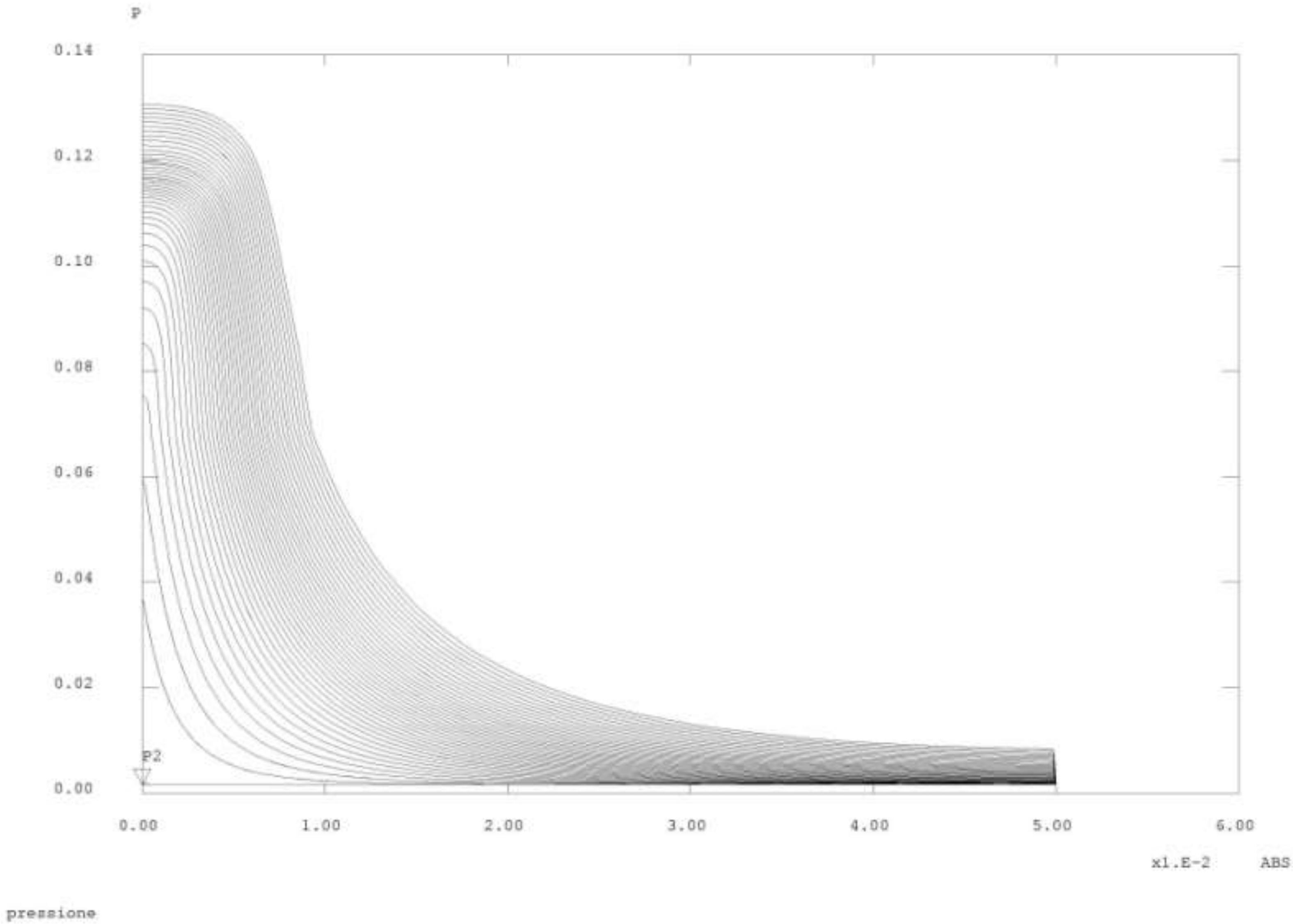
Schematic of the storage modulus HTCTRAN simulation with thermo-hygrometric boundary condictions



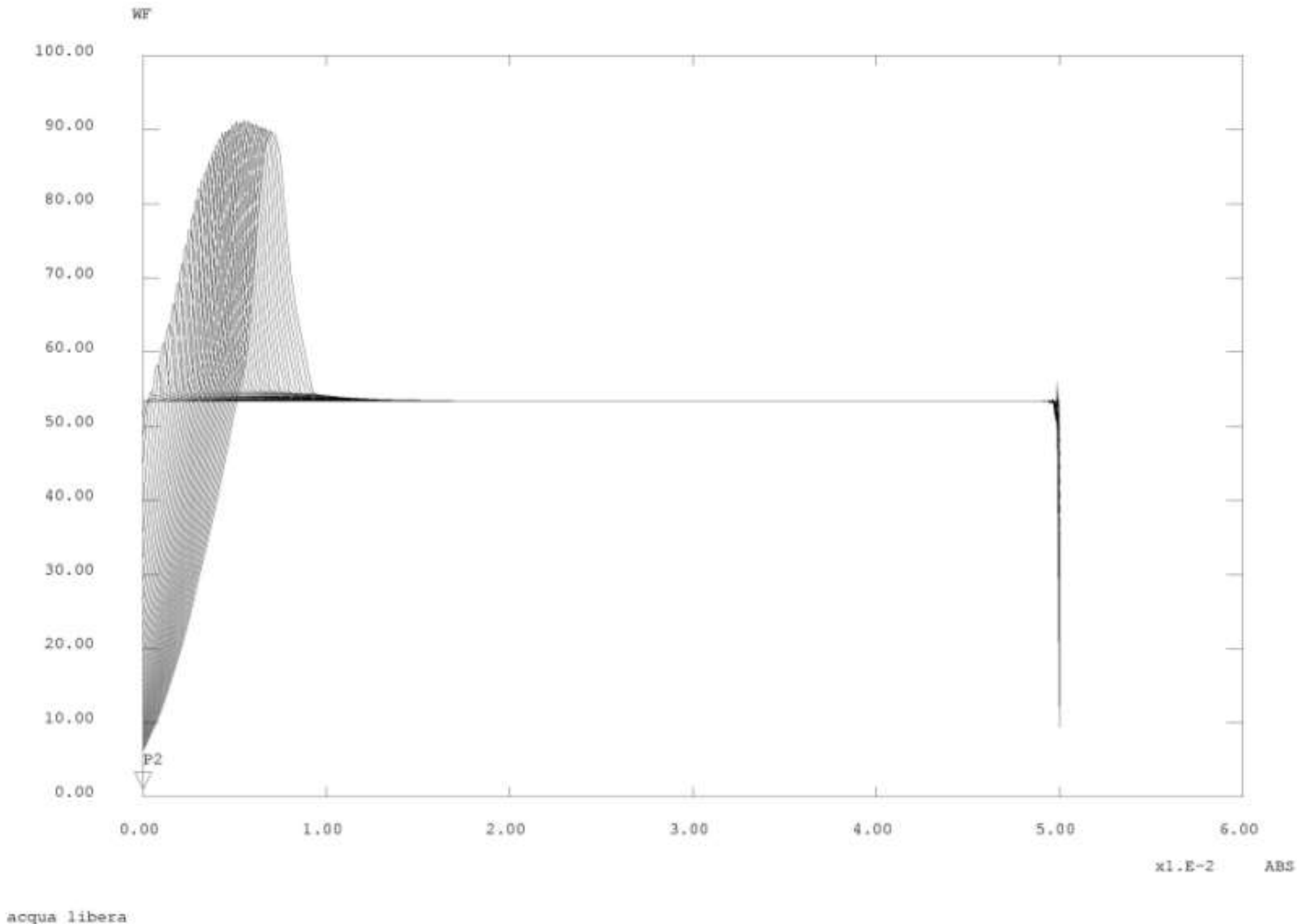
Radial Temperature at various time steps



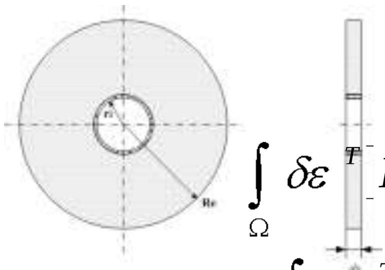
Radial vapour pressure (MPa) at various time steps.



Radial water content (Kg/m3) at various time steps.



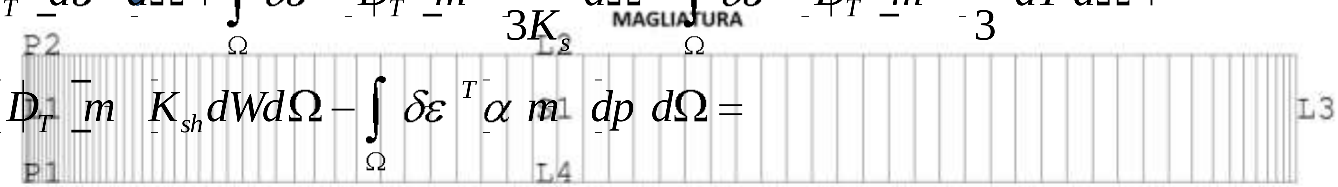
HTCTRAN - mechanical elastic coupling

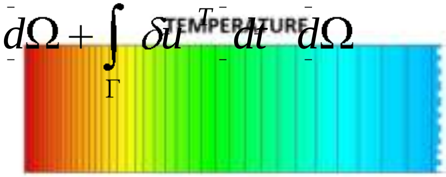


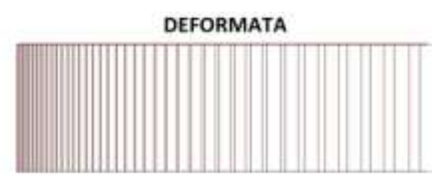
$$\int_\Omega \delta\underline{\varepsilon}^T \underline{\underline{D}}_T \, d\underline{\varepsilon} \, d\Omega + \int_\Omega \delta\underline{\varepsilon}^T \underline{\underline{D}}_T \underline{m} \frac{dp}{3K_s} d\Omega - \int_\Omega \delta\underline{\varepsilon}^T \underline{\underline{D}}_T \underline{m} \frac{\beta_s}{3} dT \, d\Omega +$$

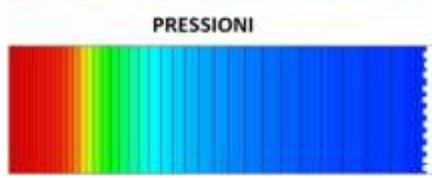
$$+ \int_\Omega \delta\underline{\varepsilon}^T \underline{\underline{D}}_T \underline{m} \, K_{sh} dW d\Omega - \int_\Omega \delta\underline{\varepsilon}^T \alpha \, \underline{m} \, dp \, d\Omega =$$

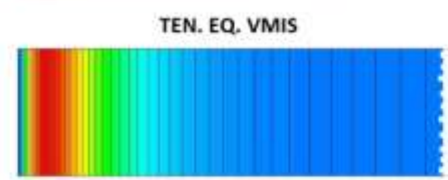
$$= \int_\Omega \delta\underline{u}^T d\underline{b} \, d\Omega + \int_\Gamma \delta\underline{u}^T d\underline{t} \, d\Omega$$





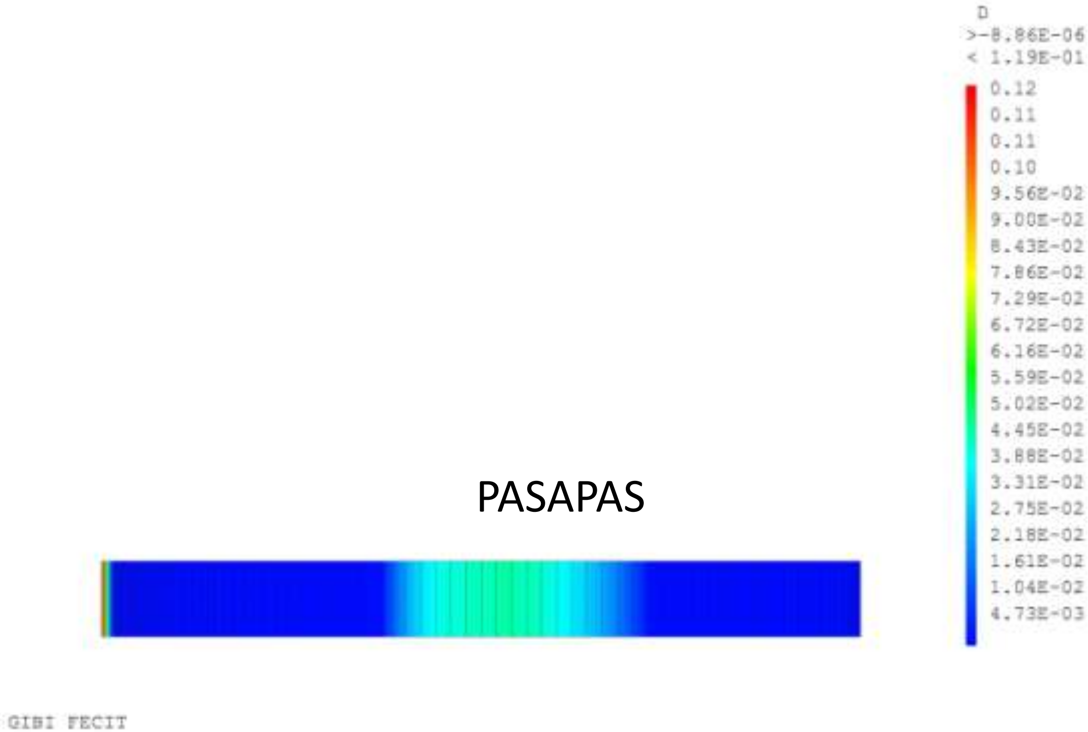


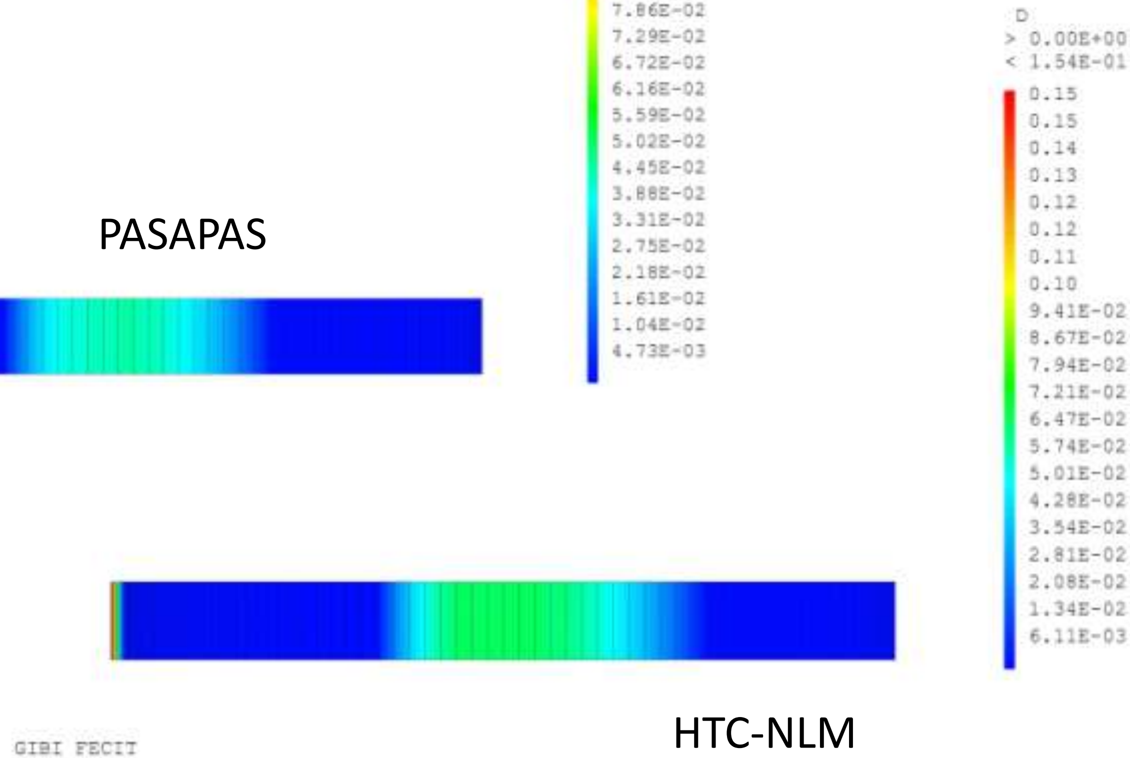




HTCTRAN – non-linear coupling

PASAPAS

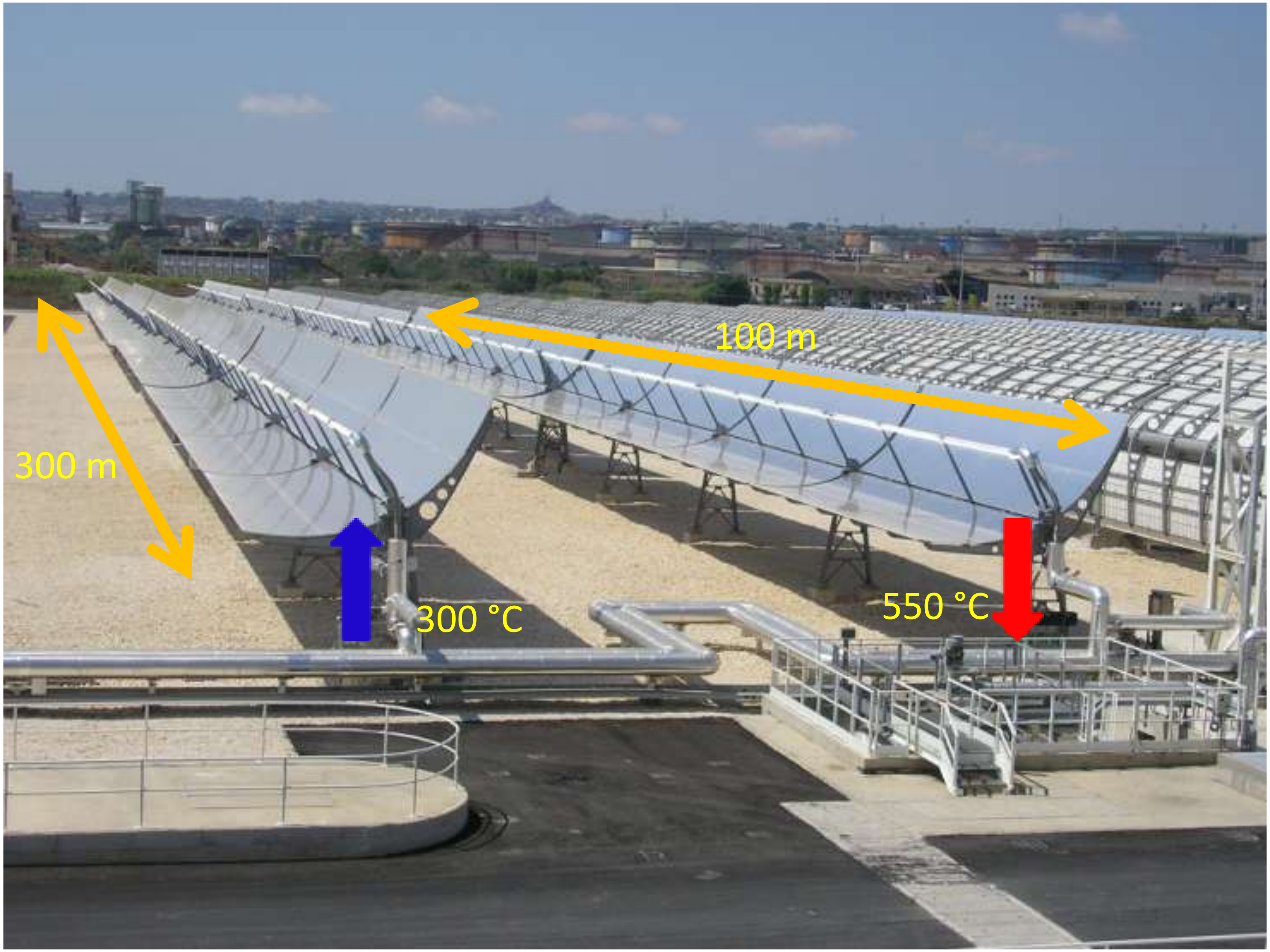




HTC-NLM

Concrete TES Test Apparatus

ENEL ARCHIMEDE Plant : Parabolic Trough Loop



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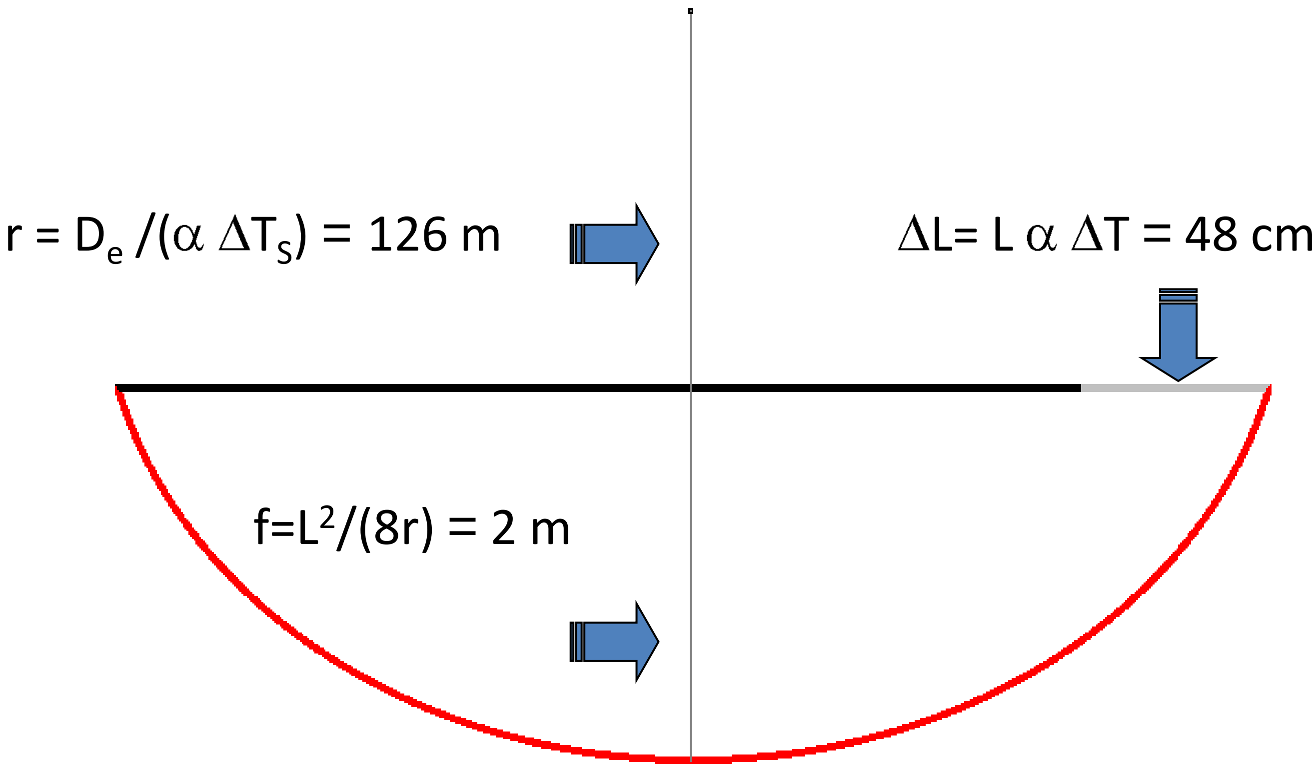
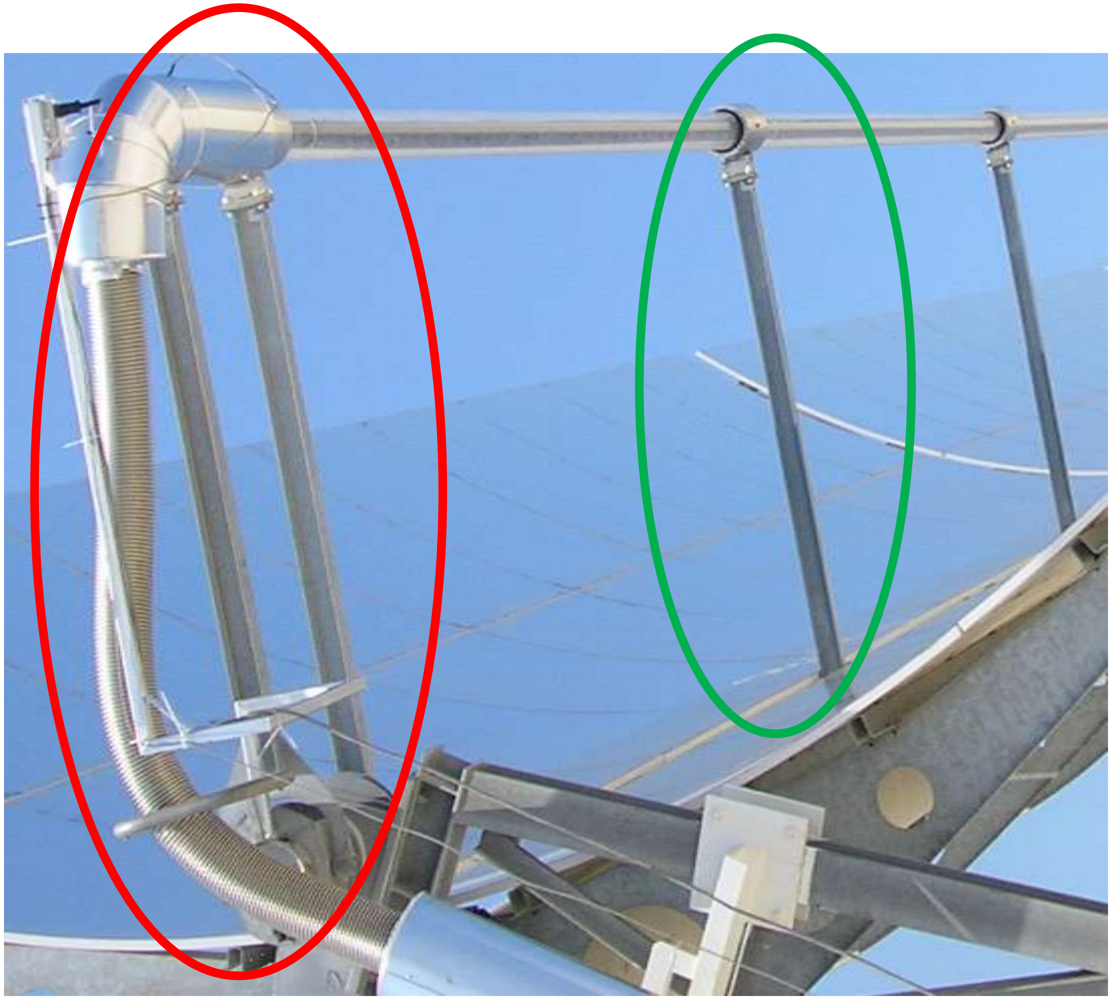
Free Thermal deformation in Priolo Receiver Line

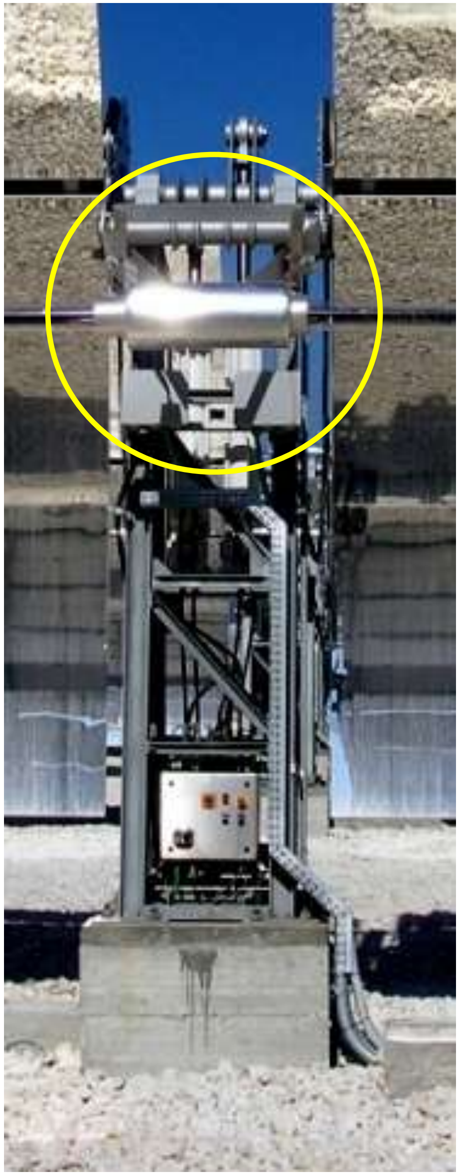
$T_0 = 20$ $\Delta T_S = 30$ C $\Delta T = 530$ C L = 48 m



$$M_{th} = E\,J_x / r = E J_x \alpha \cdot \Delta T_{cf} / D_e \quad \Rightarrow \quad \sigma_{th-\max} = E\,R_e / r = \tfrac{1}{2} E \alpha \cdot \Delta T_{cf}$$

Receiver Line Supports





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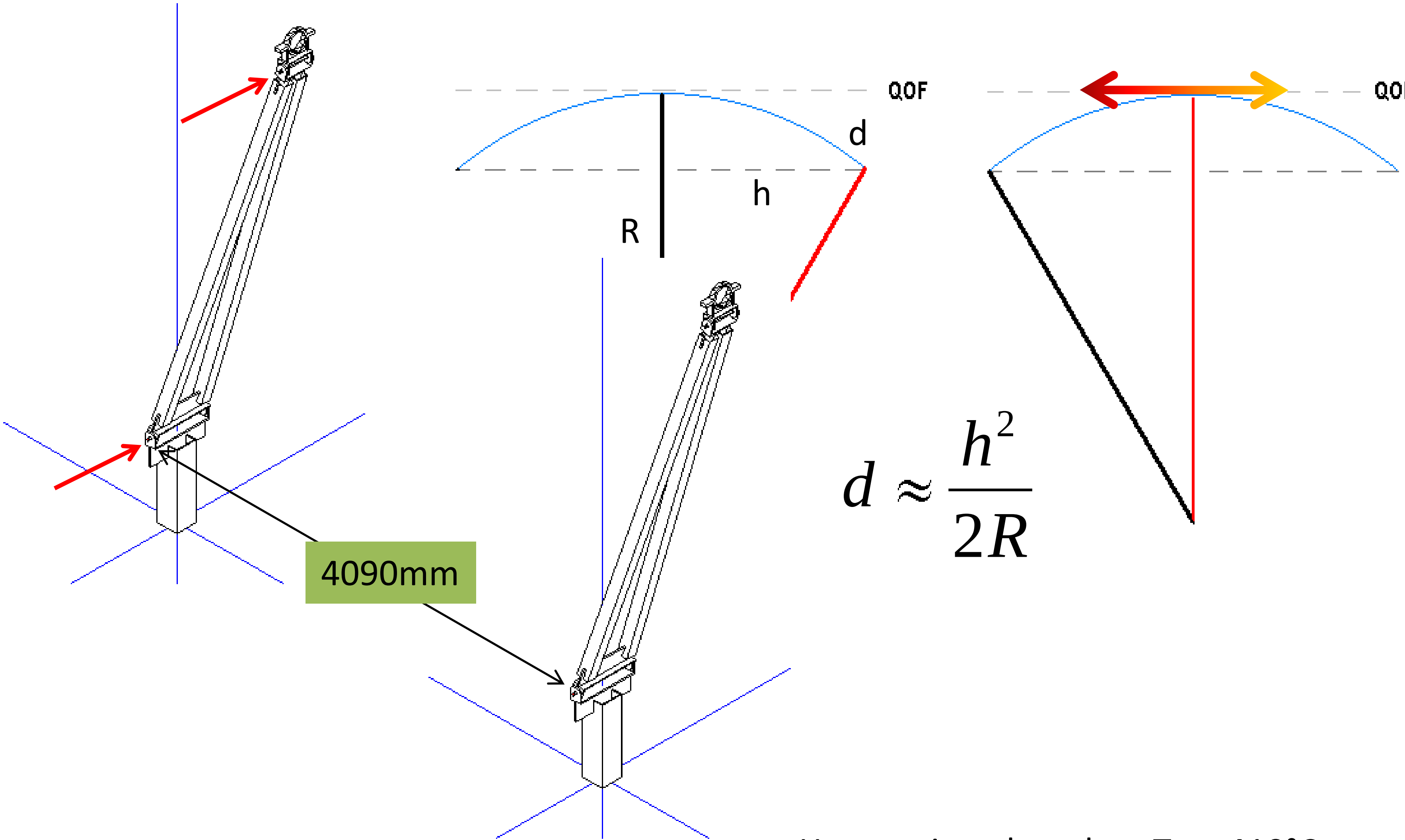
Receiver Support Kinematics

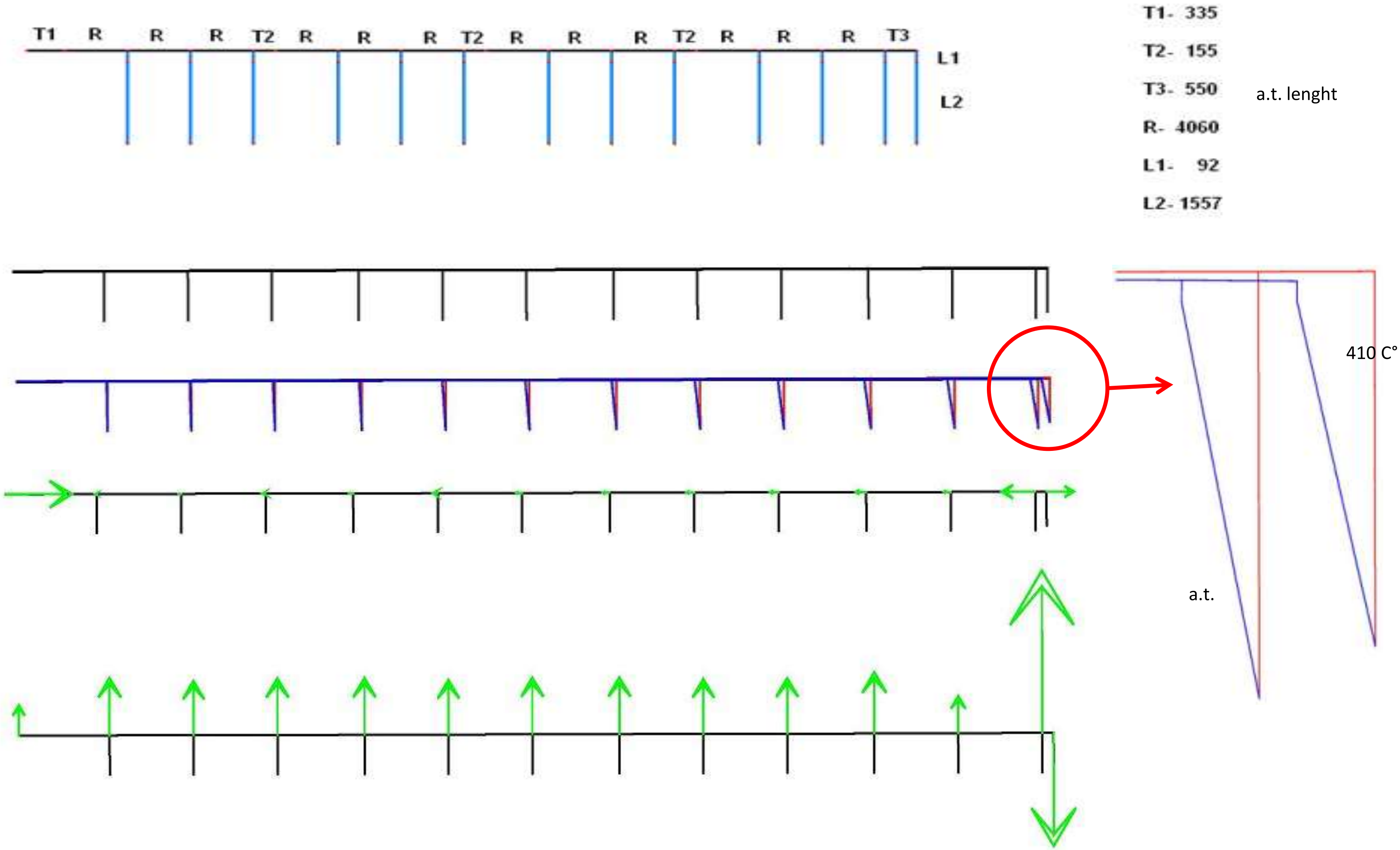


$$d \approx \frac{h^2}{2R}$$

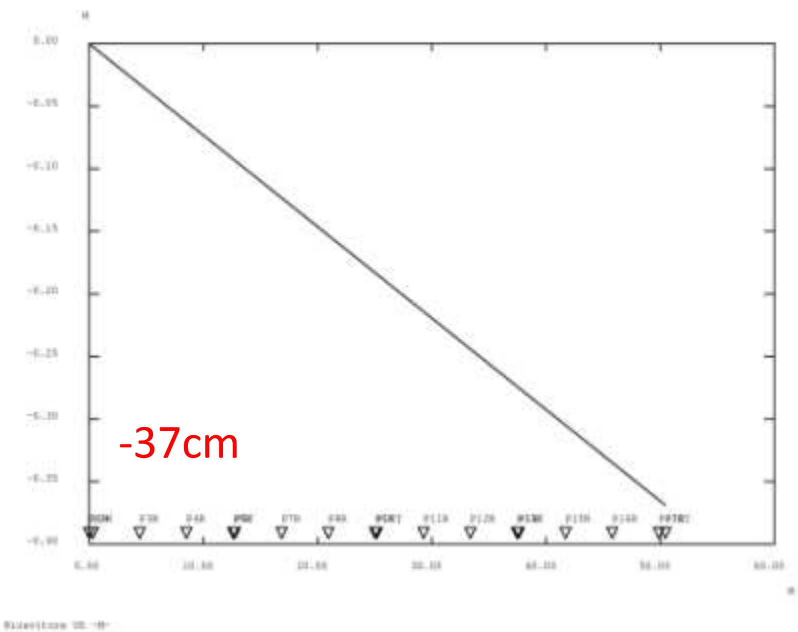
Cold receiver length
4060mm

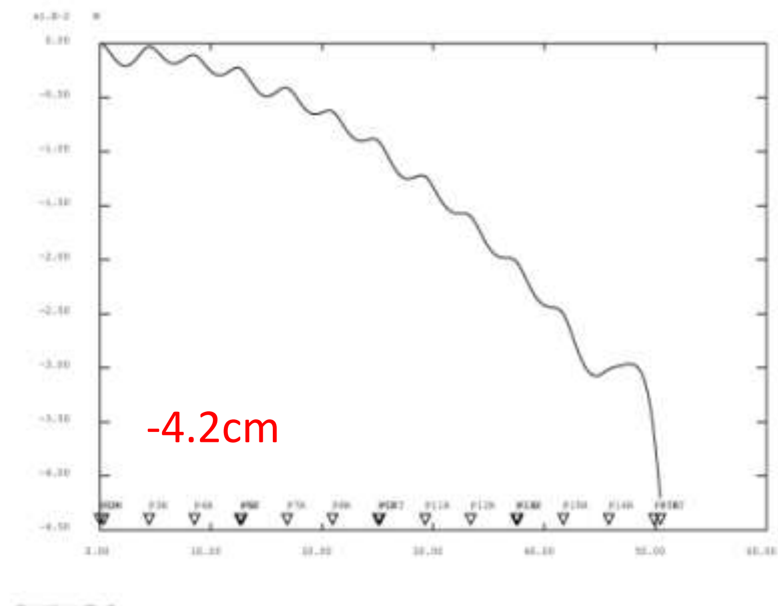
Hot receiver length at Tm y410°C
4090mm

Receiver line schematic, mesh, deformation profile, reactions

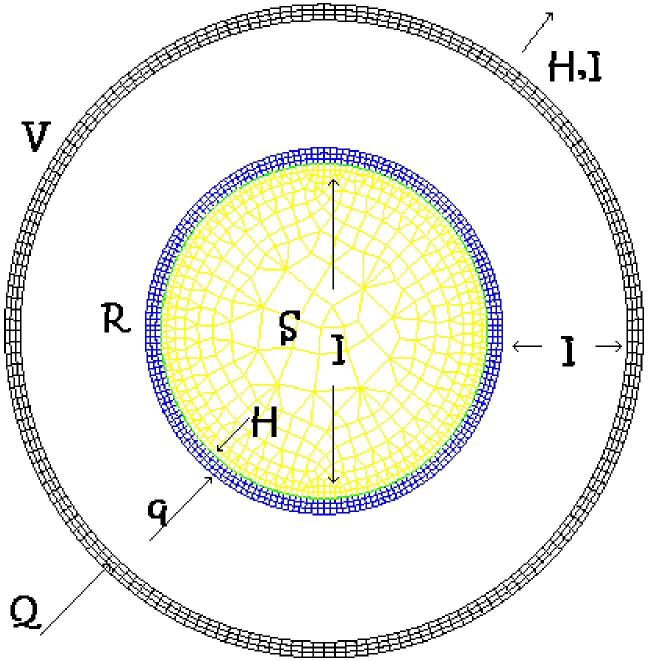


Receiver line contraction and deflection





Mass flow and tracking stop accident



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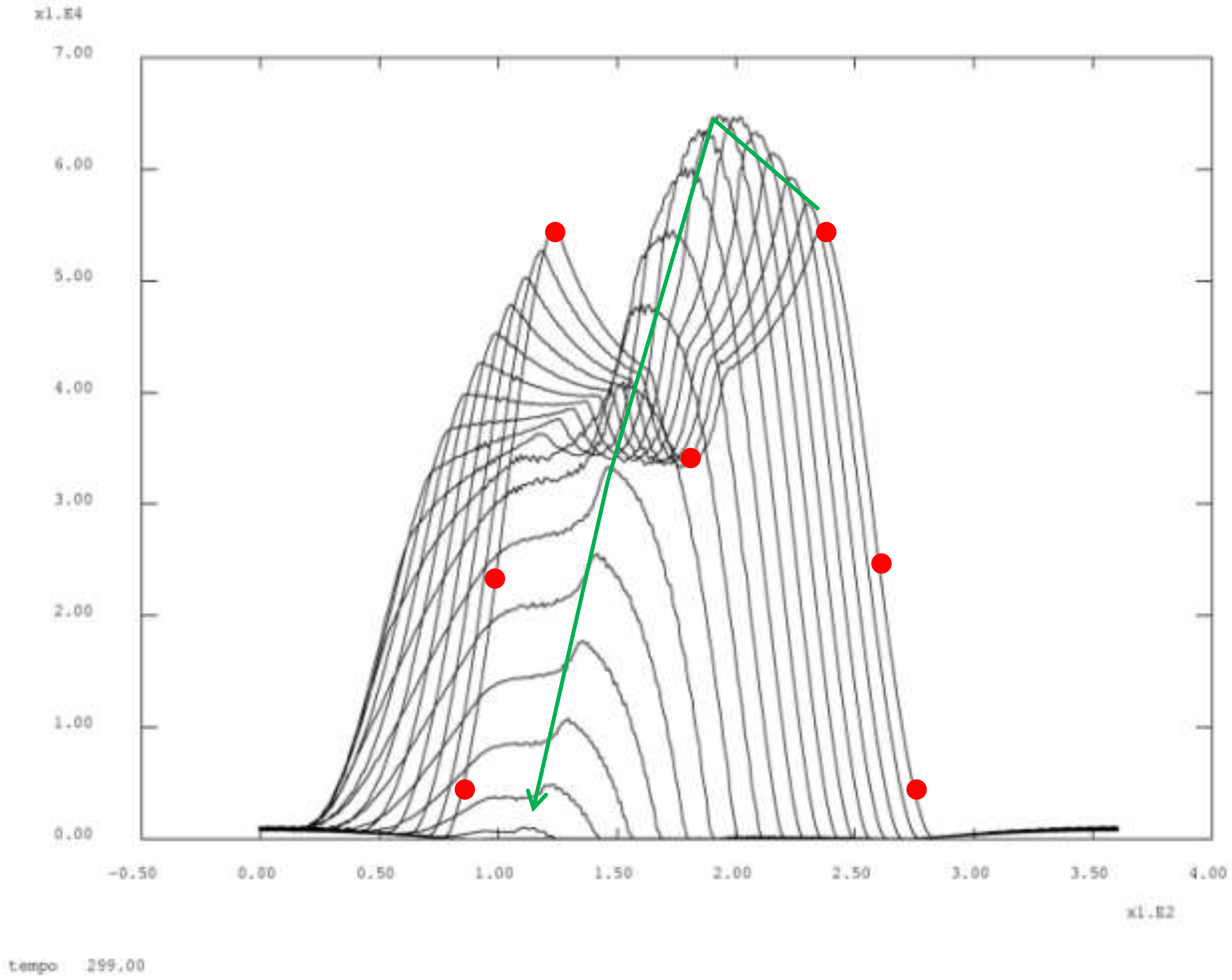
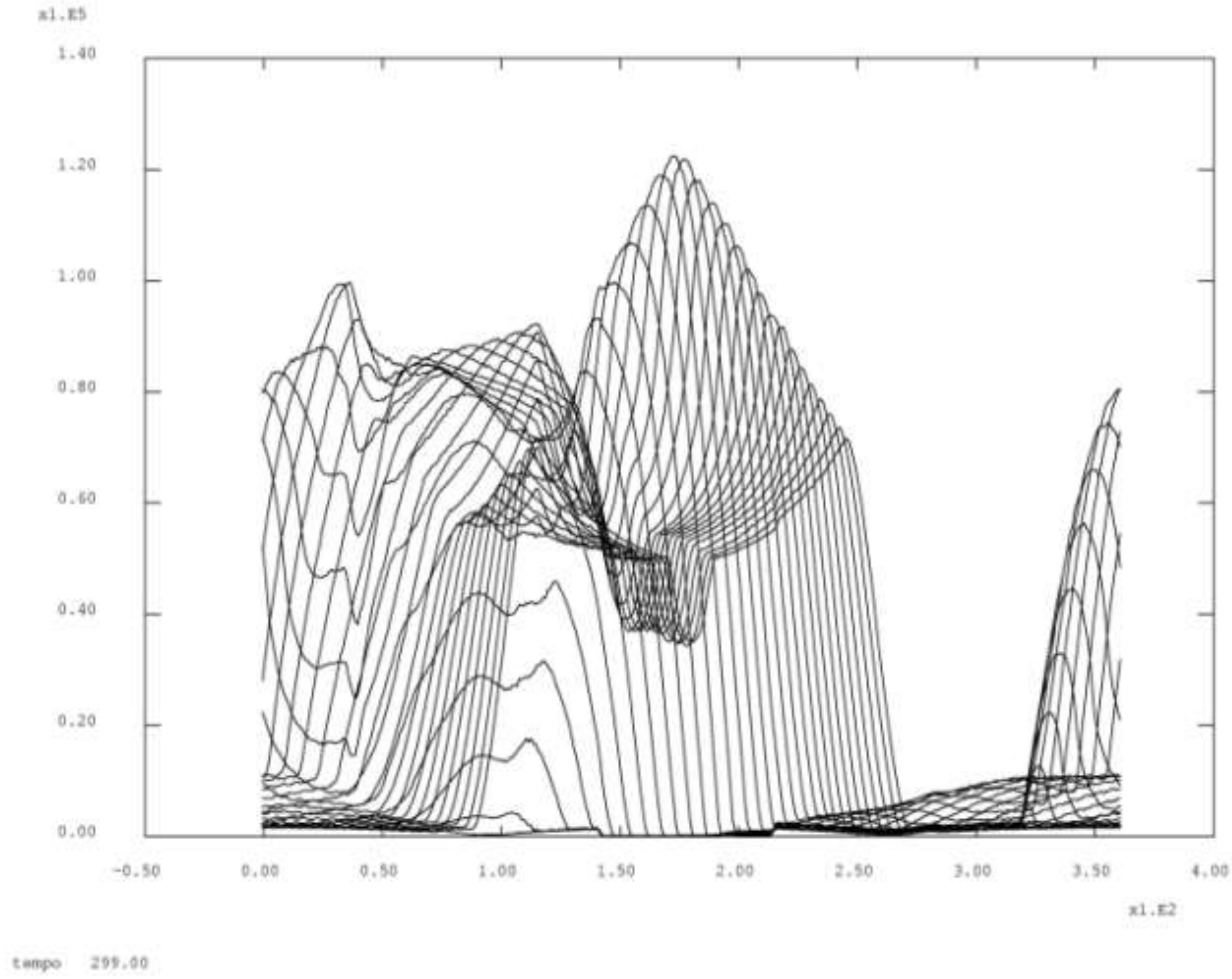
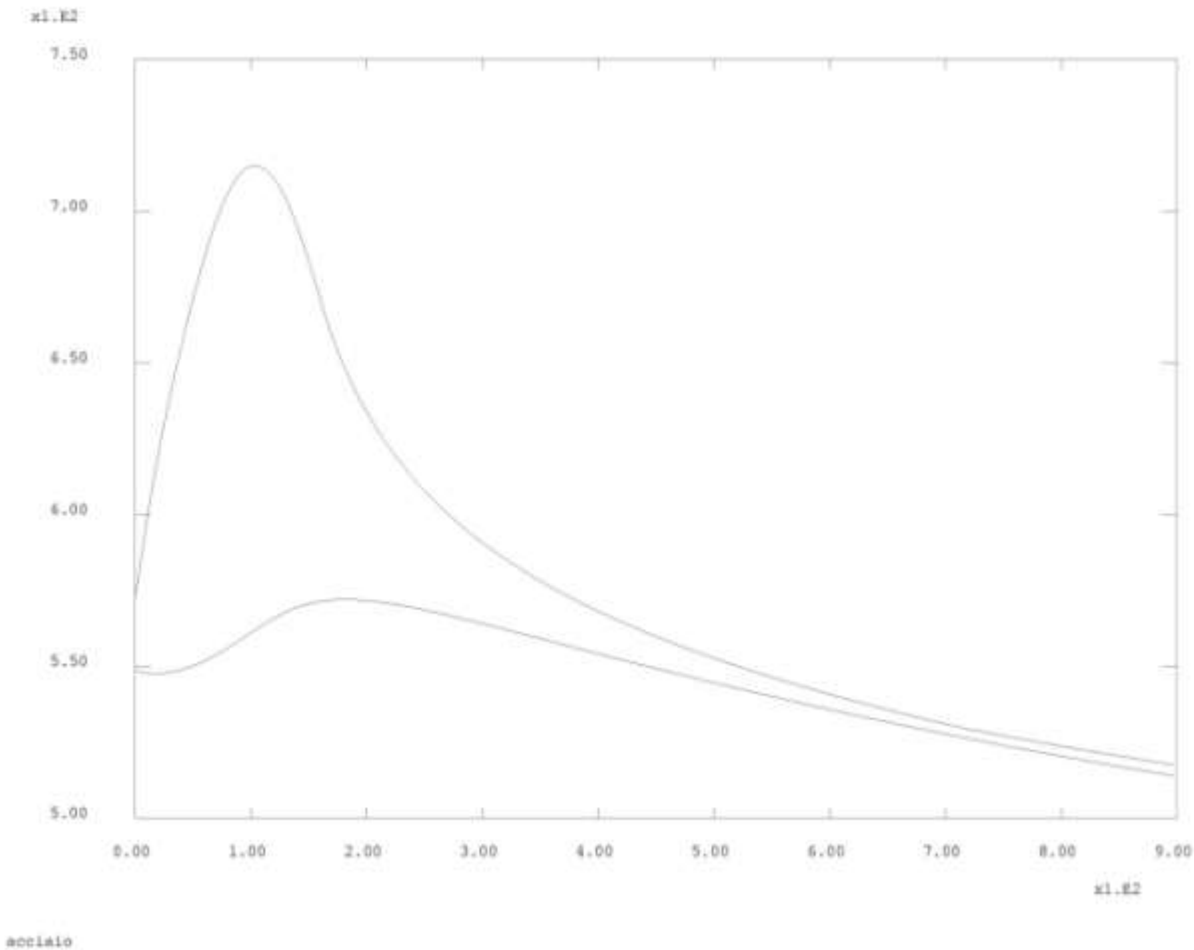
Flux distribution on receiver surface



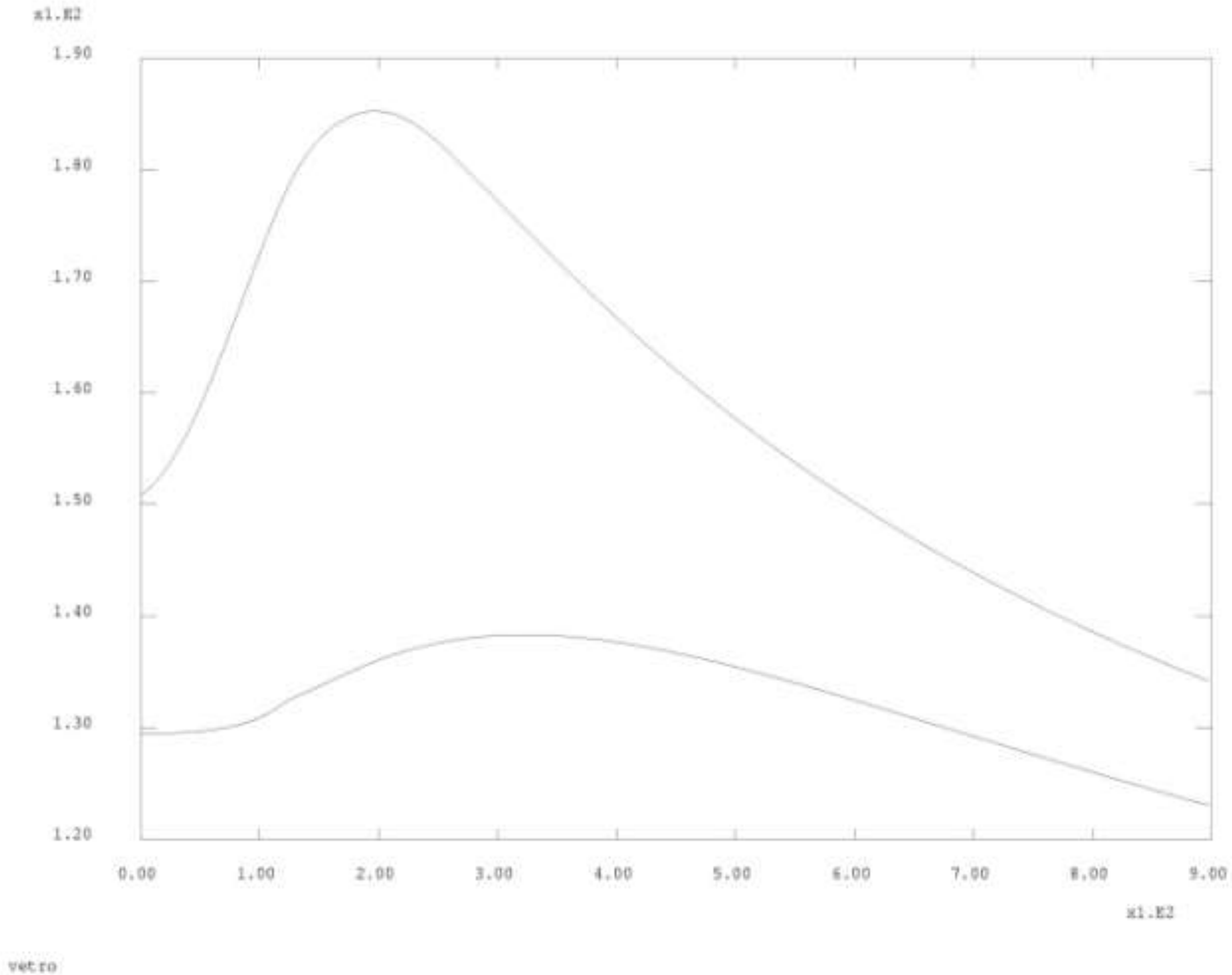
Heat released in the glass



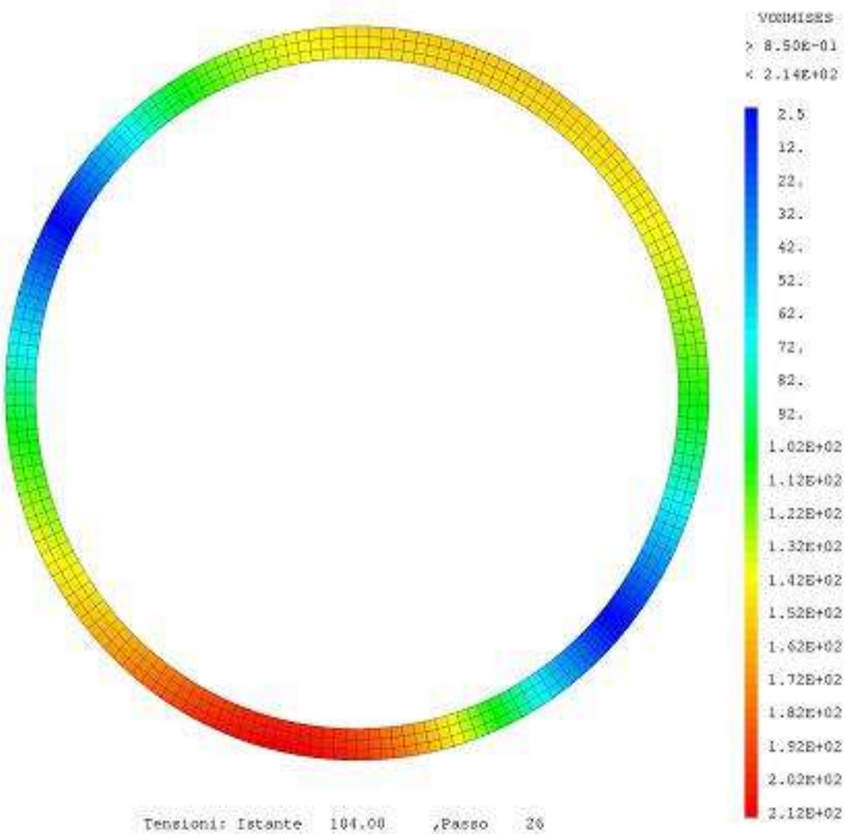
Maxi-mini temperature evolution in receiver

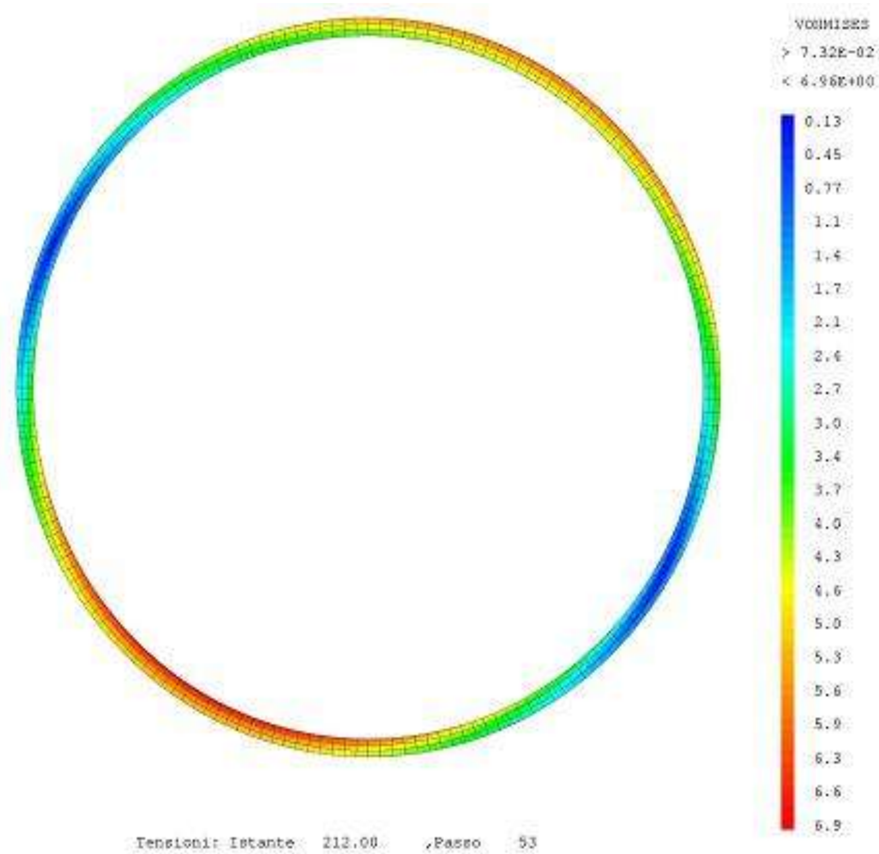


Maxi-mini temperature evolution in glass



von Mises in receiver and glass at maxi-Dt





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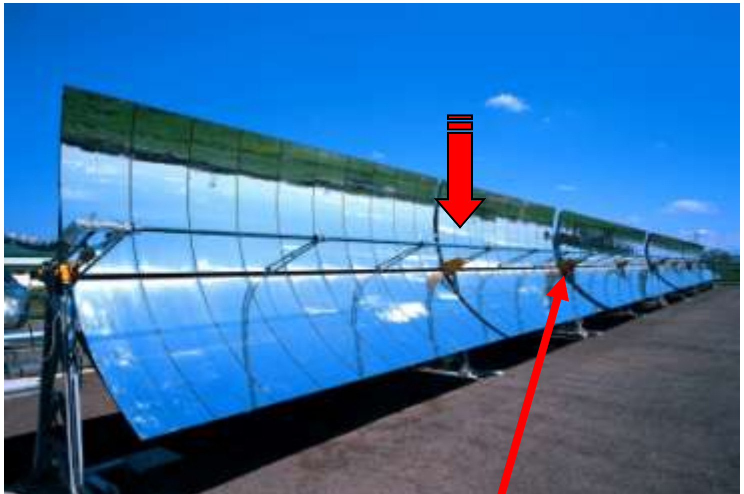
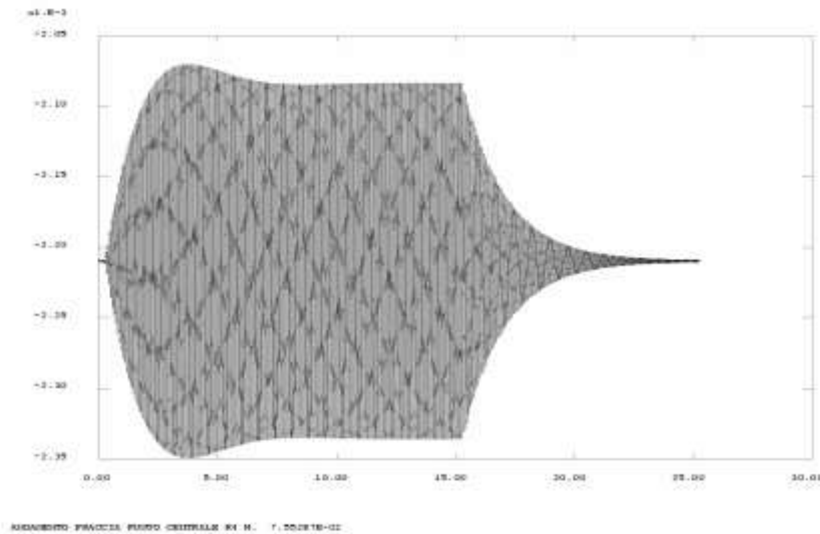
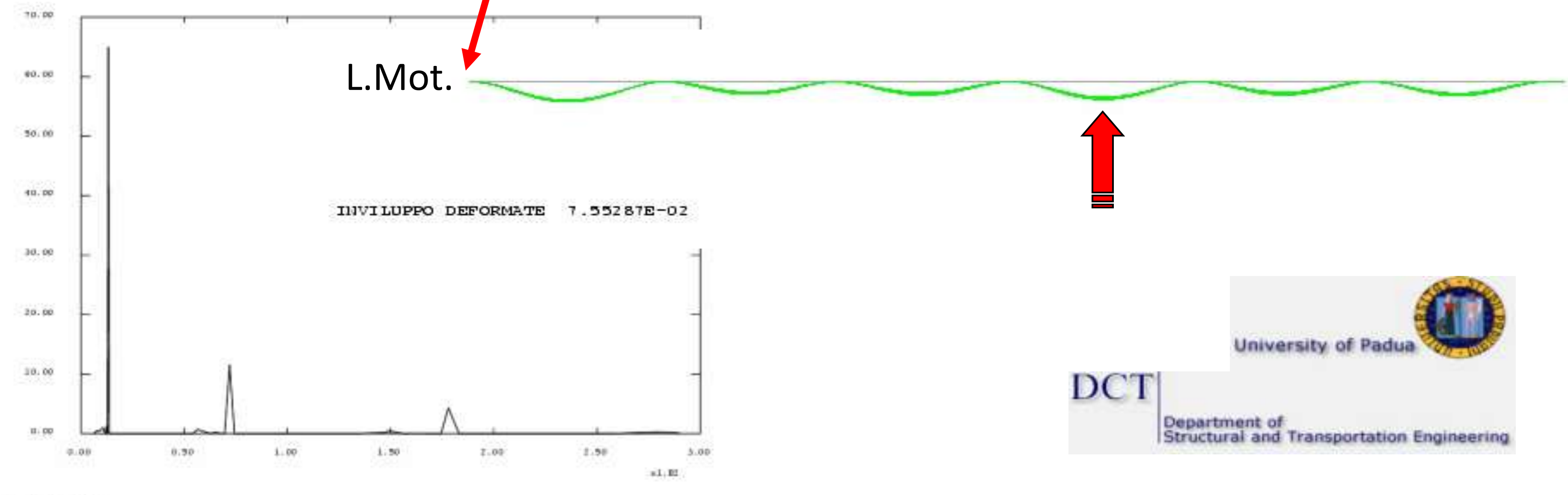
Receiver Vibration







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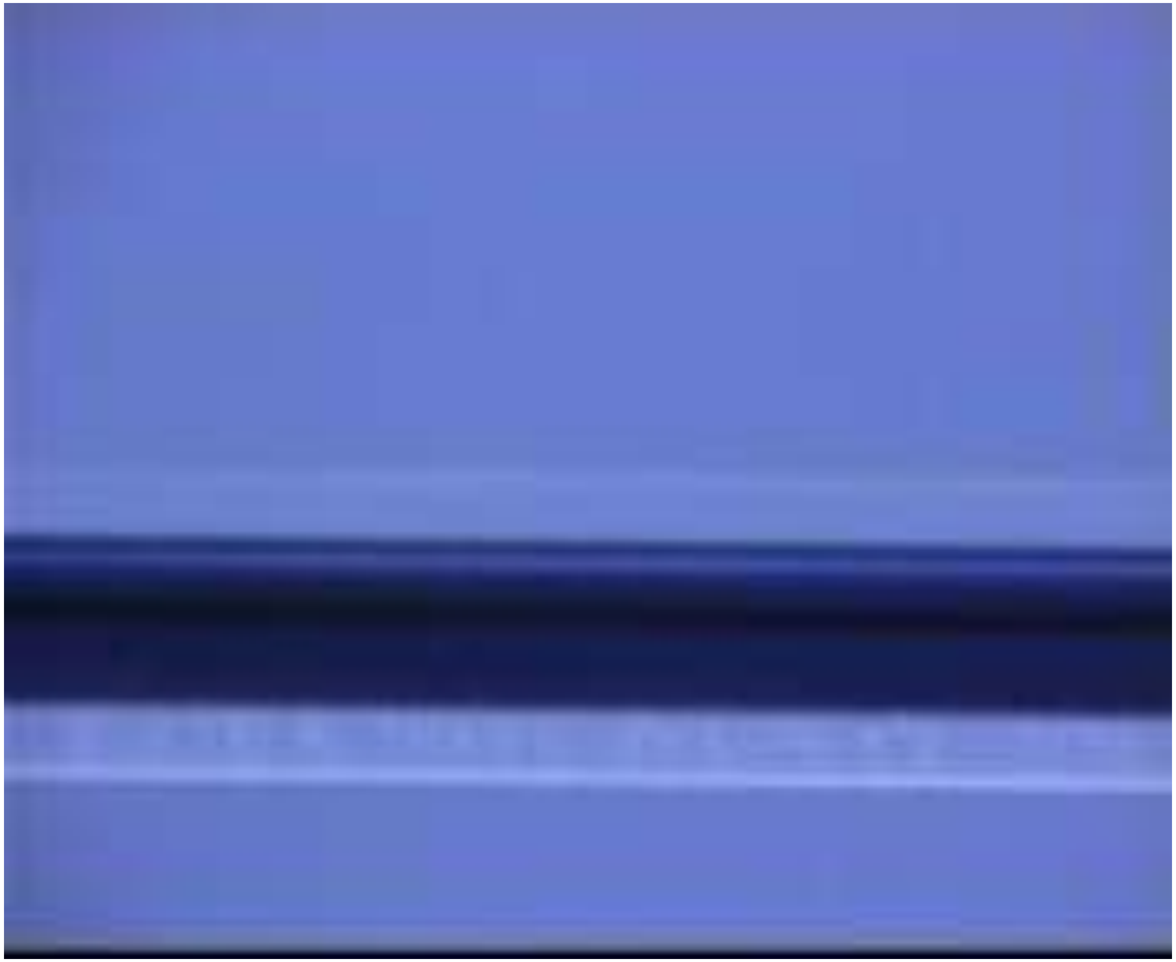
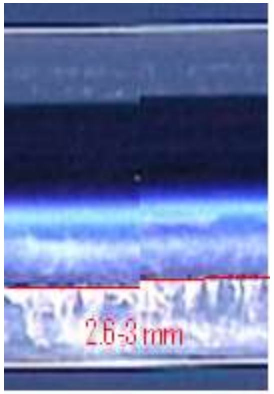




-Circulating fluid and defocused trough
-Trough focusing

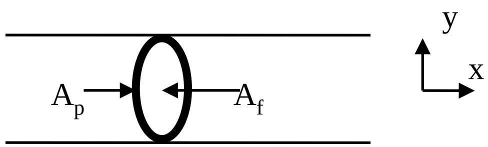
-Vibration amplitude-stabilized after about 2 min.

-Oscillation amplitude 2.6-3 mm

-Frequency 5.5-6 Hz

- The vibration stops after a minute from the defocusing

Governing Equation of Piping with Moving Fluid



$$EI\frac{\partial^4 y}{\partial x^4} + A_f(P_0 + \rho_f V_0^2)\frac{\partial^2 y}{\partial x^2} + 2\rho_f A_f V_0 \frac{\partial y}{\partial x \partial t} + (\rho_f A_f + \rho_p A_p)\frac{\partial^2 y}{\partial t^2} = 0$$

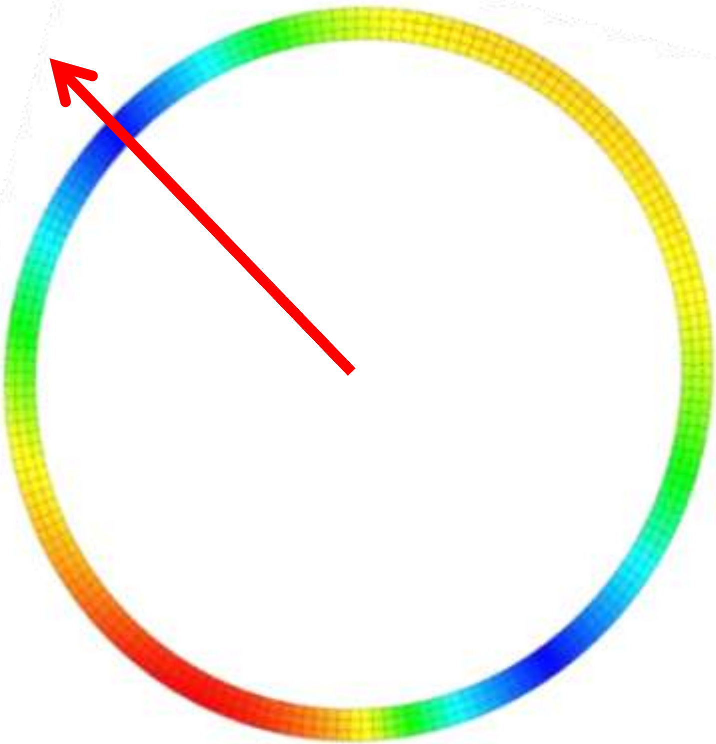
Physical interpretation of each term:

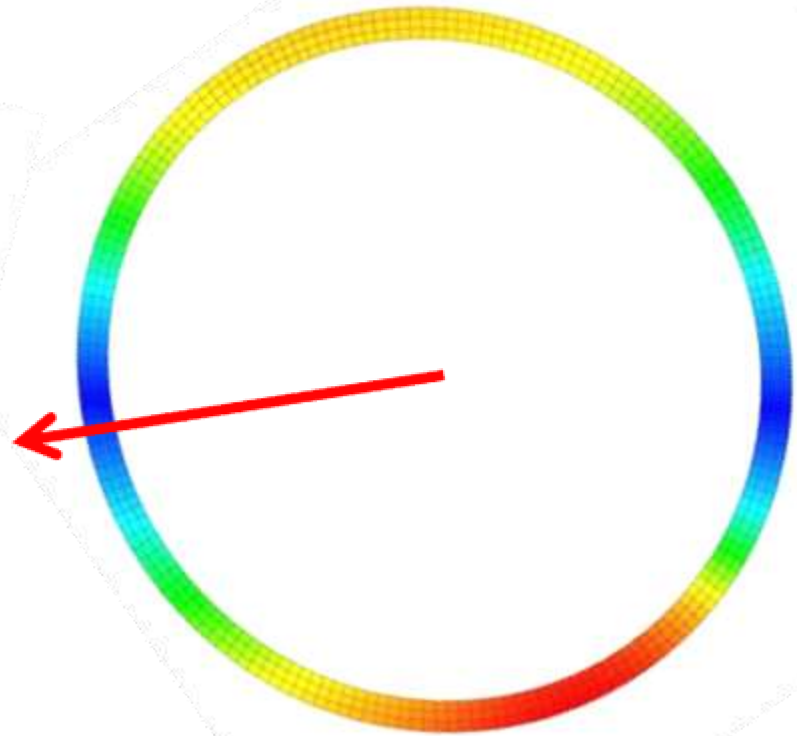
- 1- flexural restoring forces
- 2- centrifugal force of moving fluid and pressure force associated with radius of curvature $\Rightarrow r = \left[\partial^2 y/\partial x^2\right]^{-1}$
- 3- Coriolis force
- 4- inertia force of tube and fluid

$$M_T(x,t) = E\alpha \int_A (T - T_{env})\, y \, dA = EI\alpha \, \Delta T / D$$

$$M = -EI \frac{\partial^2 y}{\partial x^2} - M_T$$

T_{env} environment temperature
E modulus of elasticity
M_T thermal bending moment
y moment arm
x position along x-axis
α coefficient of thermal expansion



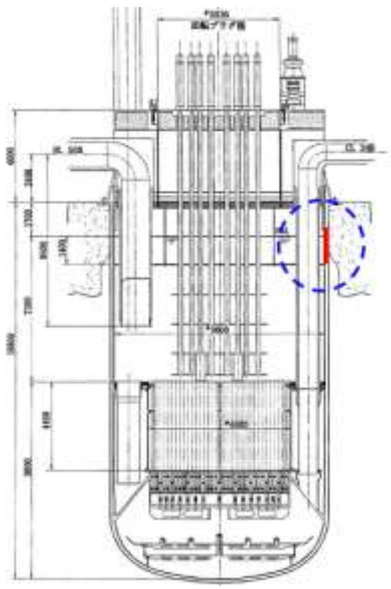


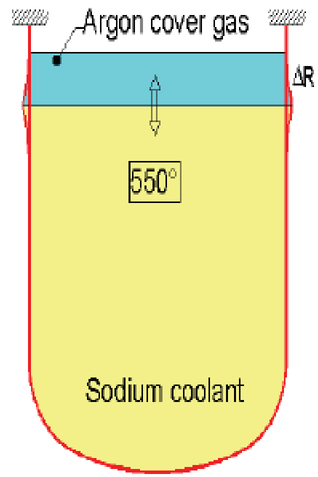
Mechanical effect of thermal-axial gradient in storage tank

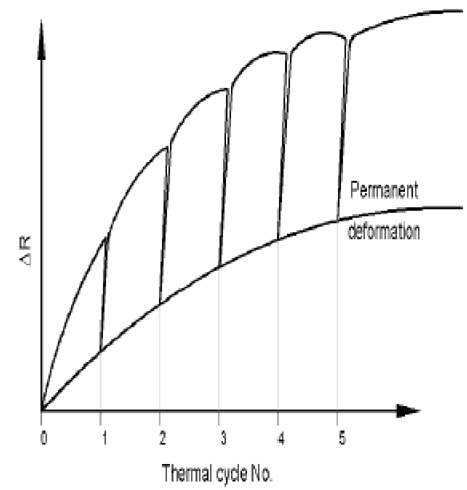
-Fatigue damage (double tank)

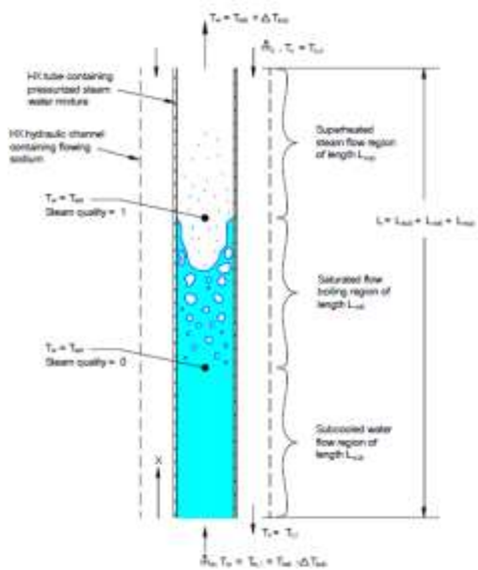
-Thermal Ratcheting (stratified tank)

Thermal Ratcheting due to axial gradient –MATTER Project







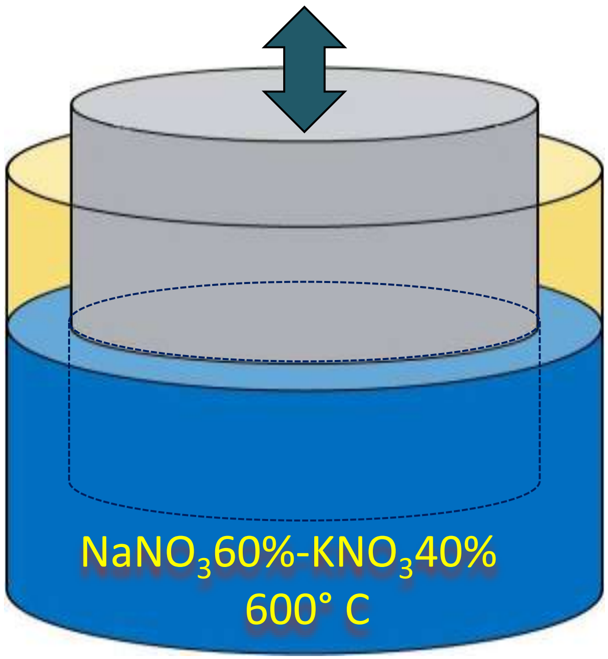


- Axial moving thermal gradient at sodium-free level

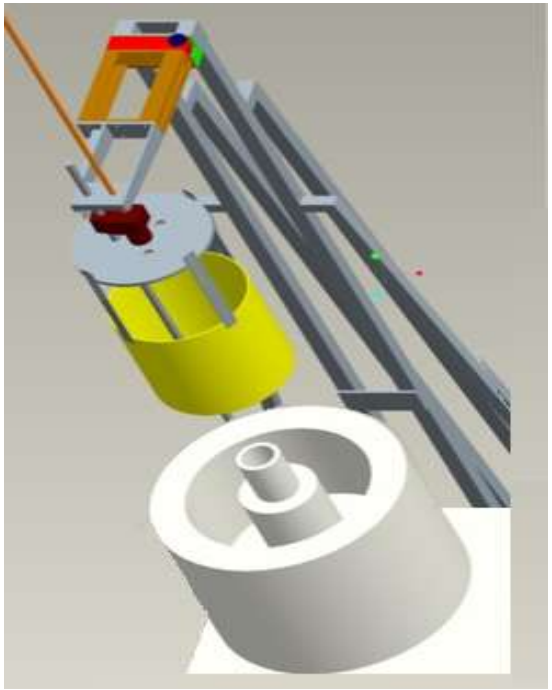
- Null-primary-stress condition

THERMAL RATCHETING FACILITY REALIZATION

P91 hollow cylinder

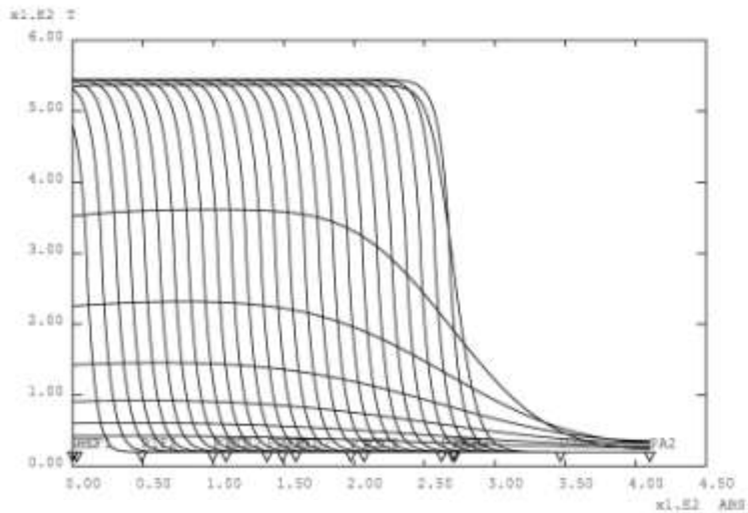


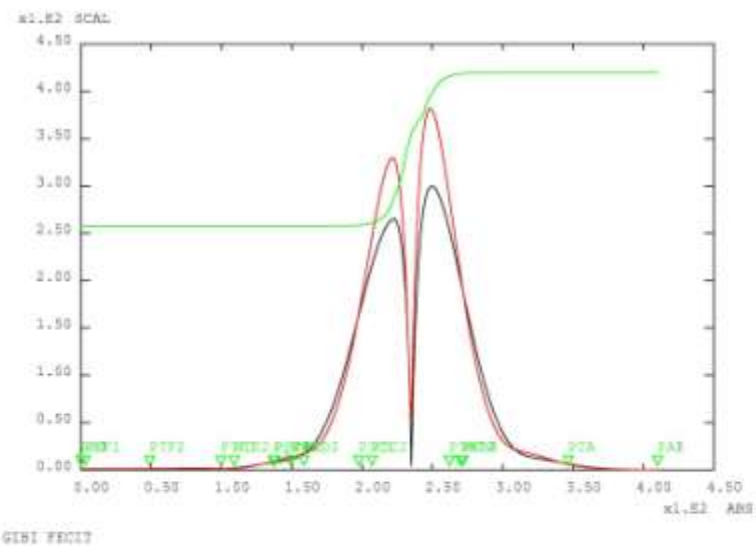
$NaNO_3$60%-$KNO_3$40%	
Thermal conductivity	0,56 W/m K
Specific heat	1550 J/kg K
Density	1700 kg/m^3
Viscosity	1 mPa sec
Melting Point	221°C

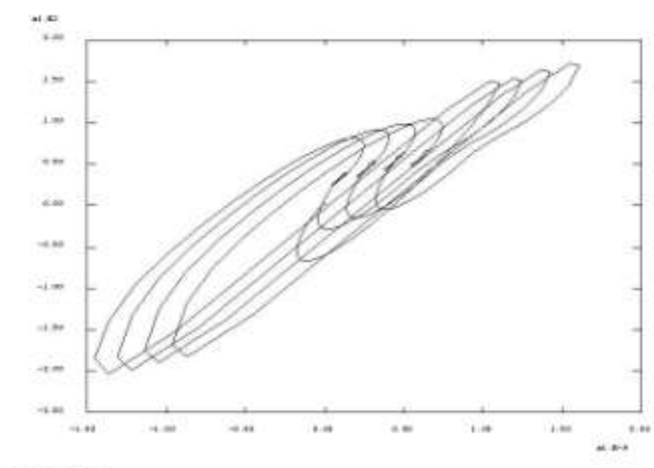


- Specimen speed during immersion
- Heat transfer coefficient
- Molten salts temperature (up to 600°C)
- Cylinder diameter and thickness

Performed Numerical Analysis

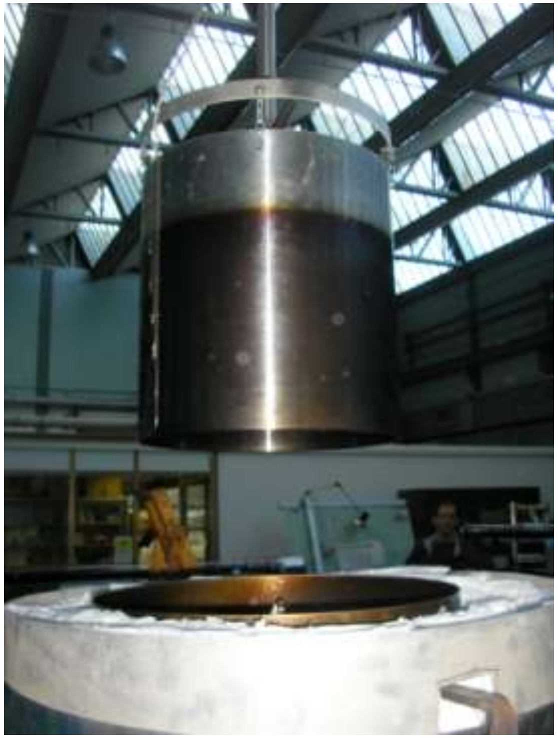




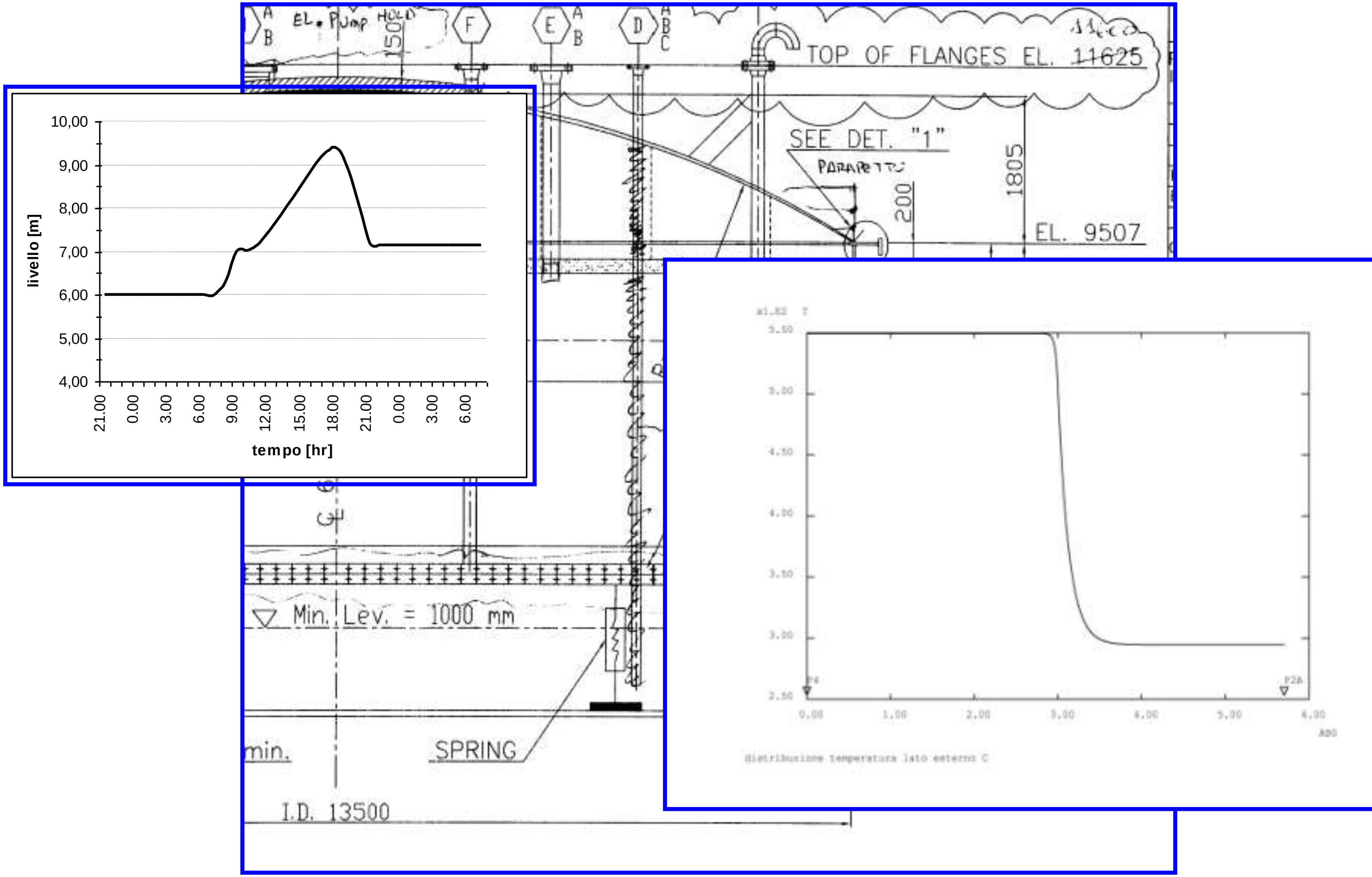


FIRST CYCLE 13-11-2012

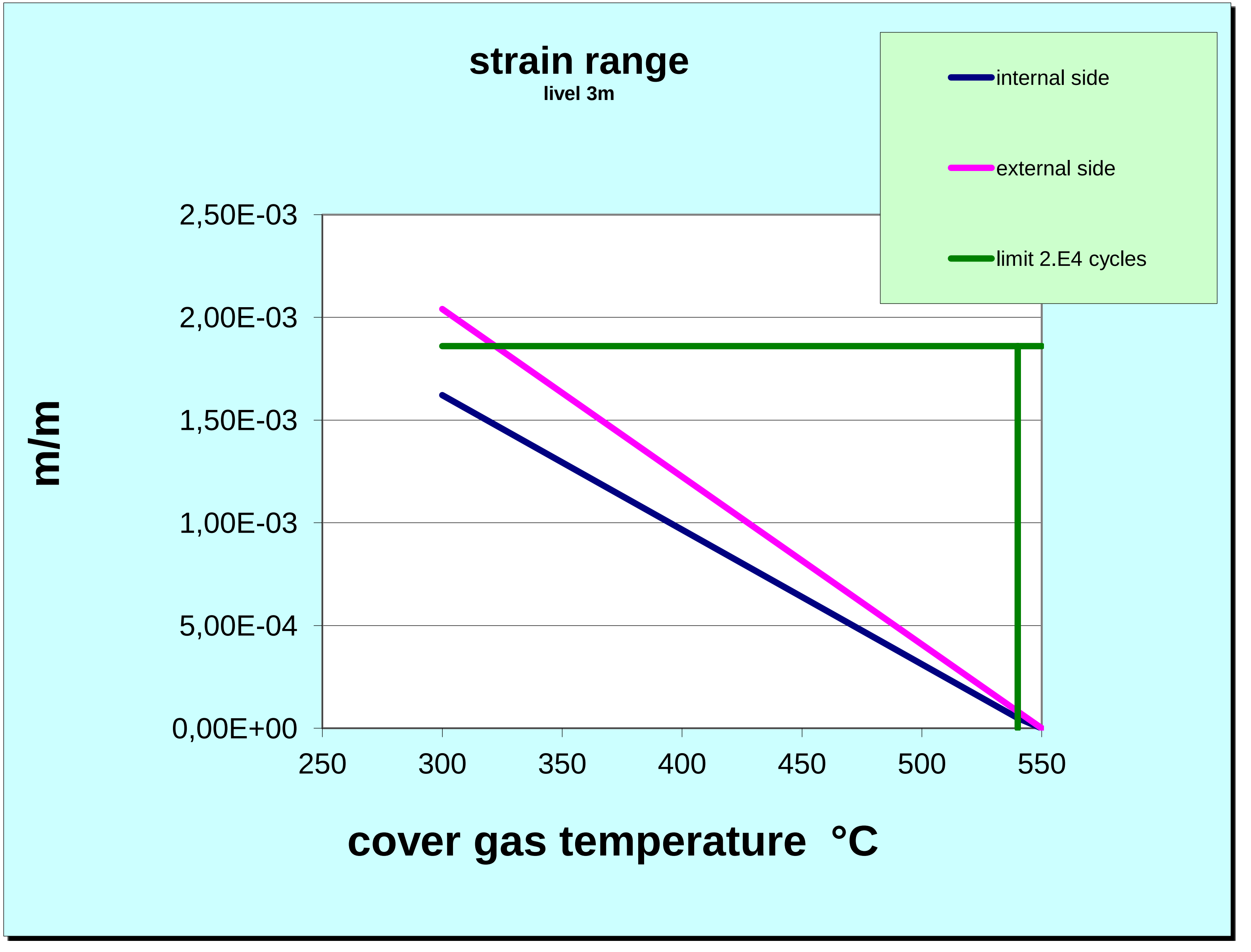




Fatigue due to level variation (ASME III NH T-1400)



Critical strain range



THANK YOU FOR YOUR KIND ATTENTION