

Gas radiation model for reheating furnaces

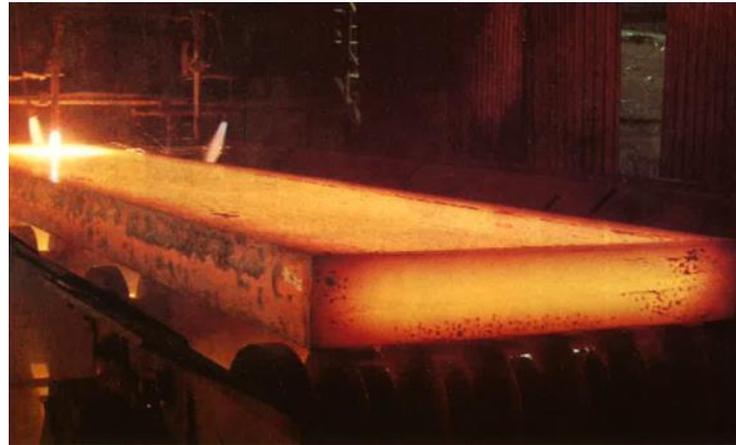
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Background

- Modelling of gas radiation is needed for calculations of stock temperatures in furnace simulations and in process control when there is infrared radiative gases
- Swerea MEFOS, together with IFE (Norway) and Jernkontoret, have developed the software STEELTEMP[®] that e.g. calculates heat transfer from gas and wall to stock in reheating furnaces
- The furnace control system FOCS, delivered by PREVAS, has the same calculation models for e.g. heat transfer

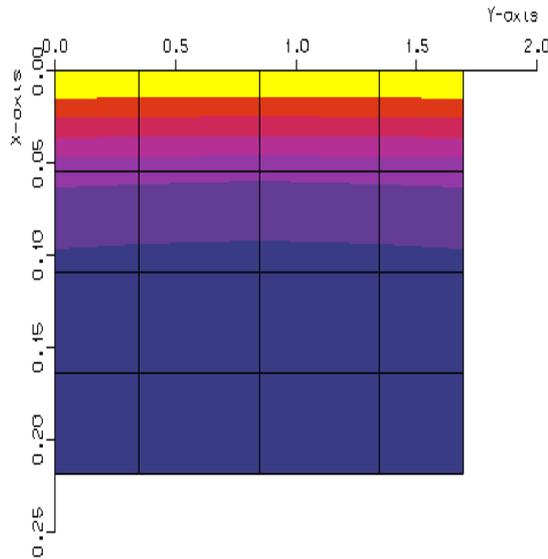
STEELTEMP[®] 2D

- STEELTEMP[®] 2D is a software using mathematical models for heat transfer analysis and temperature calculations for a number of different processes:
 - Casting
 - Cooling
 - Heating
 - Flat rolling
 - Open-die forging
 - Quenching
- STEELTEMP[®] 2D increases the control of the slab temperature and the process, which give a more efficient production with a higher product quality.



STEELTEMP[®] 2D

- Temperatures and heat densities are calculated in stocks with rectangular or circular cross sections
- Composite structures can be analysed and temperature gradients in the stocks can be minimized



Important parameters in gas radiation modelling

- ϵ_g = Emissivity of furnace gases
 - Near zero for protective gases, e.g. N_2 and H_2
 - Very important for oxyfuel fired furnaces with high levels of water vapour and carbon dioxide
- A_g = Absorptivity
 - Near zero for protective gases, e.g. N_2 and H_2
 - Very important for oxyfuel fired furnaces with high levels of water vapour and carbon dioxide
 - Function of surface temperature in addition to the same parameters as for gas emissivity
- τ_g = Transmissivity
 - $\tau_g = 1 - A_g$
 - Near 1 for protective gases

Model for radiation heat exchange in a furnace room

The radiation heat exchange between the flue gas (CO₂, H₂O and SO₂), the walls, roof and the stock, respectively is described by the model

$$\varphi_s = \frac{\sigma \varepsilon_s}{1 - (1 - \varepsilon_s)(1 - A_{gs})} (\varepsilon_g \Theta_g^4 - A_{gs} \Theta_s^4) + \sigma \varepsilon_{sw} (\Theta_w^4 - \Theta_s^4) = \varphi_{g,s} + \varphi_{w,s}$$

where

ε_s = emissivity of stock [-]

ε_g = emissivity of gas [-]

ε_{sw} = radiation heat exchange factor between walls, roof and stock, respectively [-]

Θ_s = stock temperature [K]

Θ_g = gas temperature [K]

Θ_w = wall temperature [K]

The absorptivities of CO₂ and H₂O gas to radiation are given by

$$A_{gs} = \left(\frac{\Theta_g}{\Theta_s} \right)^{0.65} * \varepsilon_{g_{CO_2}} \left(\Theta_s, s * p_{CO_2} \frac{\Theta_s}{\Theta_g} \right)$$

and

$$A_{gs} = \left(\frac{\Theta_g}{\Theta_s} \right)^{0.45} * \varepsilon_{g_{H_2O}} \left(\Theta_s, s * p_{H_2O} \frac{\Theta_s}{\Theta_g} \right)$$

where

s = thickness of the gas layer [-]

p_{xi} = partial pressure of the flue gas component x_i [atm]

For calculation of the gas emissivity, as a function of the gas temperature, the partial pressure of CO₂, H₂O and SO₂ and the gas layer thickness, analytical expressions derived by K. Schack are used. These expressions are based on the accurate gas radiation measurements made by Hottel and Egbert in 1942.

The radiation exchange factor between the walls, roof and the stock is given by

$$\varepsilon_{sw} = \varepsilon_s \varepsilon_w \tau_g \beta_{sw} + \Delta \varepsilon_{sw}, \quad \beta_{sw} = \sum_{k=1}^N \frac{1}{2} (\sin \beta'_k - \sin \beta_k)$$

where

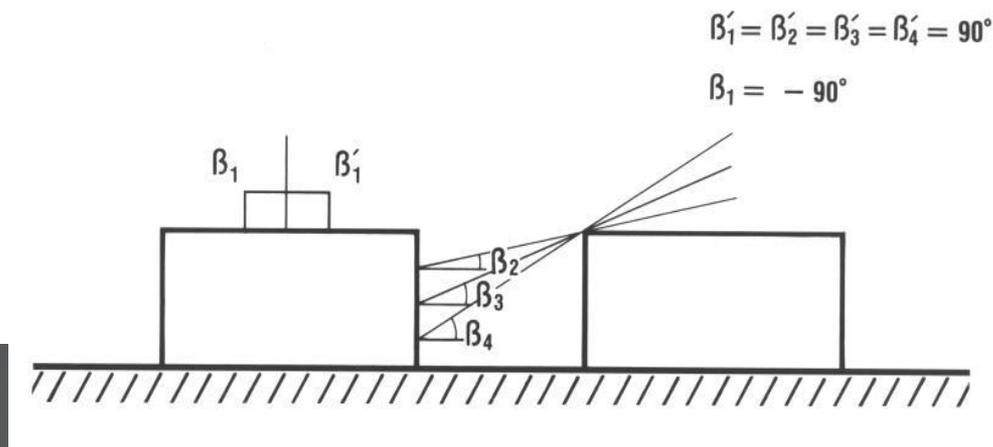
ε_w = emissivity of wall [-]

τ_g = transmissivity of gas

β_{sw} = view factor from the walls and roof to the stock [-]

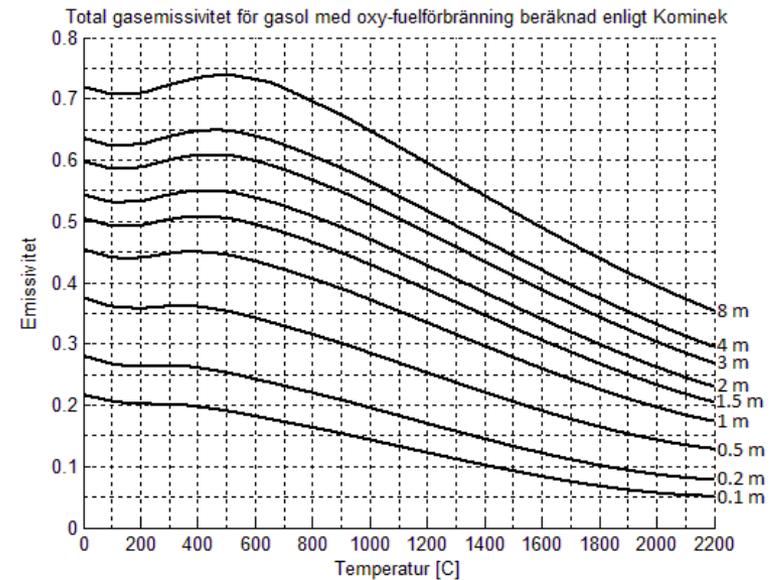
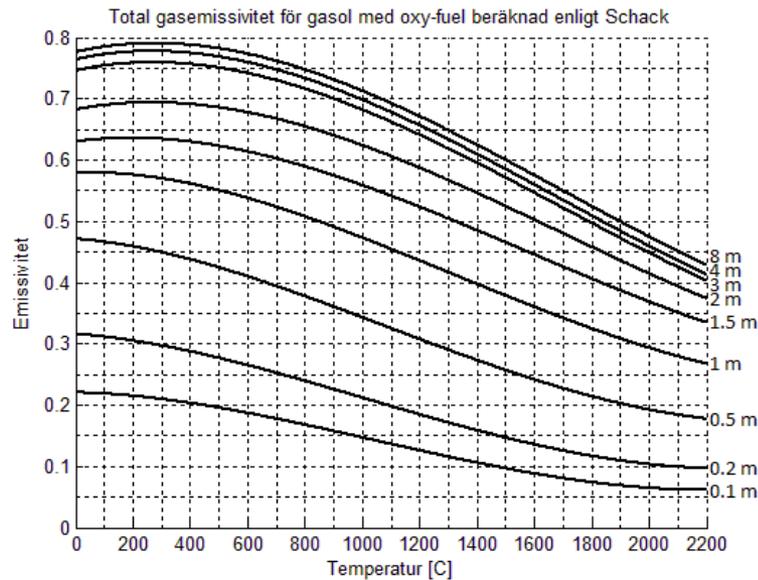
$\Delta \varepsilon_{sw}$ = correction factor for flame radiation [-]

In the program the view factors and the gas layer thicknesses are calculated automatically from geometrical data describing the location of the stock with neighbours in the furnace. The users can also give their own values of the gas layer thicknesses.



Total gas emissivity – oxyfuel fired propane

Adaptions of Schack vs Kominek from Hottel's data



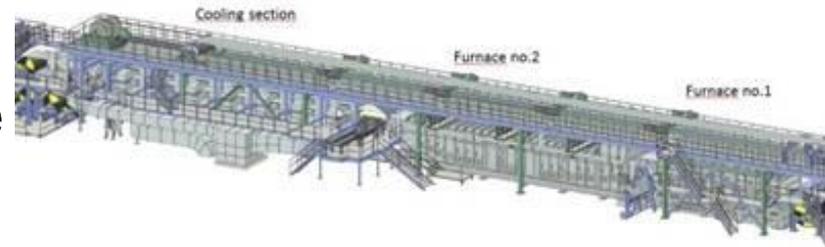
The graphs show emissivity for different gas layer thickness.

Gas layer thickness = $1.76 \times$ distance (between infinite parallel surfaces)

Gas radiation modelling in the industry

- Continuous heat treatment furnaces

- e.g. Outokumpu KBR with oxyfuel firing needs accurate gas radiation modelling



- Small batch furnaces with protective gas – heat transfer modelling of heating and cooling but no gas radiation modelling
- STEELTEMP heat transfer modelling can be used in many different furnaces

User-Friendly Excel Interfaces for SteelTemp

- SteelGen

SteelGen 2D v3.1 - 010

Heating: Simple heating model

Rolling: No rolling

Stock data: Rectangular

Initial temperature: 20 °C

Material: 5, SIS 1312

Region and mesh definition

Zone	Size mm	HTC (W/m ² °C)	Top	Bottom
1	50	3500	3000	
2	40	3500	3000	
3	20	6000	3500	
4	40	3500	3000	
5	50	3500	3000	
Sum	200			

- QuenchTemp

QuenchTemp5.1.xls

Quenching: Cooling line, Step hardening

Transport: Scale breaker

After quenching

Time from furnace: 66 s

HTC: 20000 °C

Time: 1 s

Time: 60 s

Roller table speed: 1 m/s

Length: 4 mm

Coolant temperature: 8 °C

Temperatures: A: 41, B: 5, C: 77

Zone	Size mm	HTC (W/m ² °C)	Top	Bottom
1	50	3500	3000	
2	40	3500	3000	
3	20	6000	3500	
4	40	3500	3000	
5	50	3500	3000	
Sum	200			

Temperature dependent HTC

Temp. °C	Factor
10	20
60	20
110	2.5
400	2.5
600	1
900	1

- New on-line version of STEELTEMP is under development

STEELTEMP 2D - Manager (Stl1.pct)

File Input Presen Run View Tools Help

STEELTEMP
Edition 2D - February 2005

STEELTEMP 2D - Run (Stl1.pct)

Type of calculation
GENERAL MODEL RUNNING

Iter Time (h:m:s)
0 6 H 4 M 12.09

Stock temp (OC)	Top zone (OC)	Btm zone (OC)
A 1182.7	Gas 1223.7	Gas 1223.7
B 1200.6	Wall 1201.2	Wall 1201.2
C 1173.9		

Choose
 Spec Data Restart Continue
 Stop Quit

Oxide scale calculation

22
23
24
25
26
27
28
29
30
31

Main input / SHM RF / Temp curve / T

Skriv en fråga för hjälp

100%

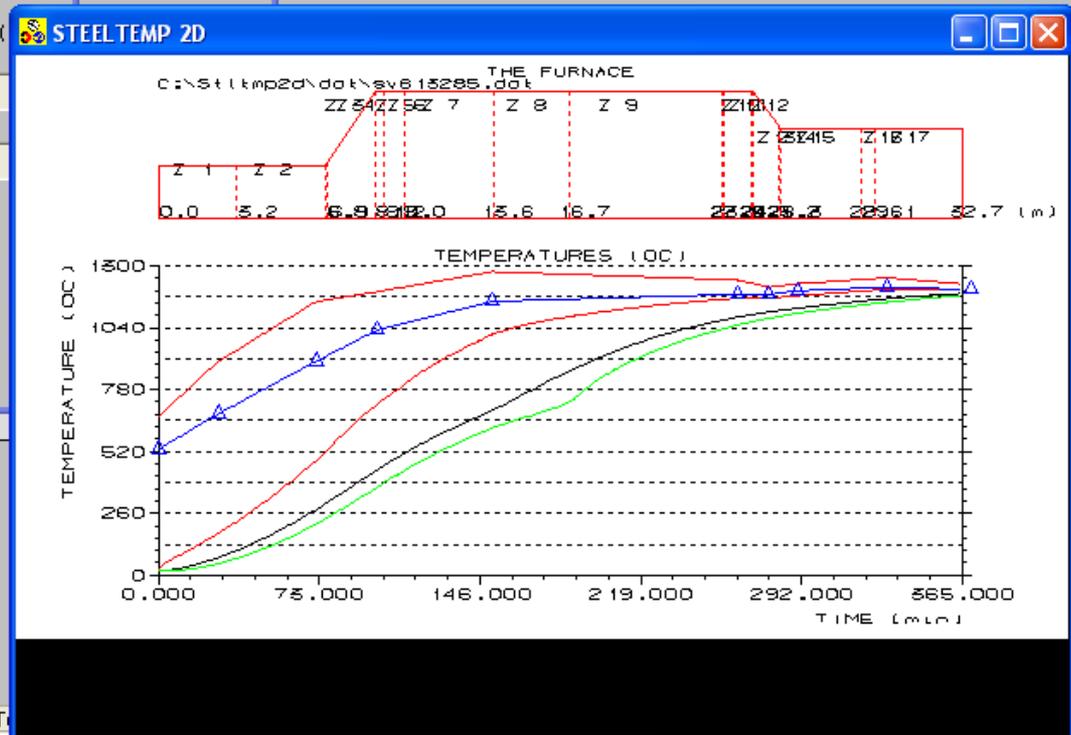
H I J K L M N O

input file Run STEELTEMP Show diagram Show heatbalance

No gradients

File: Sv613285 (Syntax: Test6)

Path: C:\Stltmp2d\dat (Syntax: C:\Stltmp2d\dat)



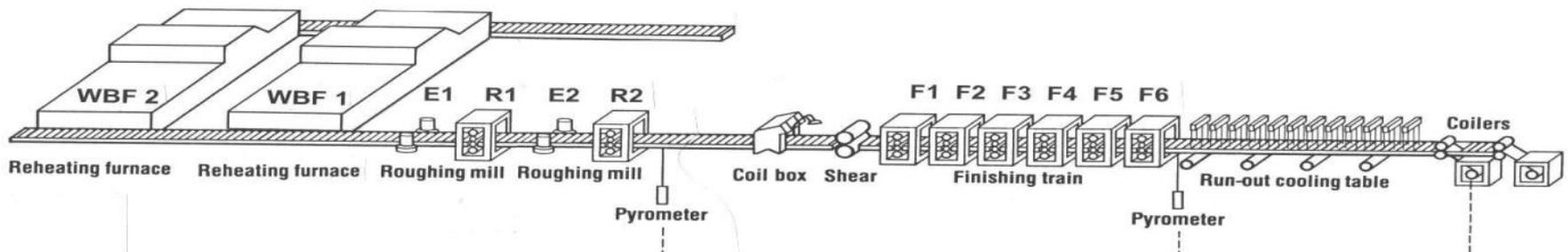
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eratures

Flue gas calculation with oxygen enrichment

- Flue gas flow is calculated in each furnace zone using:
 - Chemical analysis of fuel
 - Fuel flow of up to four different fuels
 - Air flow
 - Oxygen
- Calculations normally start in the soaking zone but arbitrary flue gas flow is possible
- Flue gas composition is calculated for each zone

Microstructure model as DLL in STEELTEMP[®] 2D

- User-defined microstructure model can be used in STEELTEMP[®] 2D
- Process and microstructure data can be defined and results plotted in STEELGEN 2D



Microstructure data in STEELTEMP[®] 2D

- General microstructure data:
 - Steel composition in weight per cent
 - Fraction of microstructure constituents (austenite, ferrite, perlite, cementite, bainite, martensite)
 - Fraction recrystallized austenite, grain sizes of recrystallized and non-recrystallized austenite
 - Grain deformation parameters
 - Nucleation densities
- The variables can be plotted in STEELGEN 2D
- User-defined variables

Sheet for microstructure data

StlGen2D32-001_Demo_SSAB - Microsoft Excel

Arkiv Start Infoga Sidlayout Formler Data Granska Visa Utvecklare Tillägg

Arial 10

Klistra in Urklipp Tecken Justering Tal Villkorsstyrd formatering Formatera som tabell Cellformat Infoga Ta bort Format Sortera och filtrera Sök och markera Redigering

C5 0,067

Steel composition		Microstructure parameters, input		Microstructure variables as function of time, output	
Element	wt%	Parameters DDGRAIN(1)-DDGRAIN(10)		Variables DAUST(1)-DAUST(9)	
C	0,067	Fraction recrystallized austenite	1	Fraction rec. austenite	
Si	0,017	Grain size of recrystallized austenite	20 μm	Grain size rec. aust.	μm
Mn	0,312	Grain size of non-recrystallized austenite	20 μm		Don't plot
P	0,015	Initial grain size	1000	True strain	
S	0,007	Reheating temperature	1100	Critical strain	Plot
Cr	0,043	Cooling rate since the deformation is finishe	21		Don't plot
Ni	0,036	DDGRAIN(7)	0	Grain size ferrite	
Mo	0,006	DDGRAIN(8)	0	Yield strength	Right y-axis
Cu	0,054	DDGRAIN(9)	0	Tensile strength	Right y-axis
Ni	0,0067	DDGRAIN(10)	0		
Nb	0,001				
V	0,001				
Ti	0,001	The parameters DDGRAIN(4)-DDGRAIN(10) can be used as optional input by the user.			
Al	0,029				
B	0				
Zr	0				
W	0				
As	0				
Sb	0				
Sn	0,005				

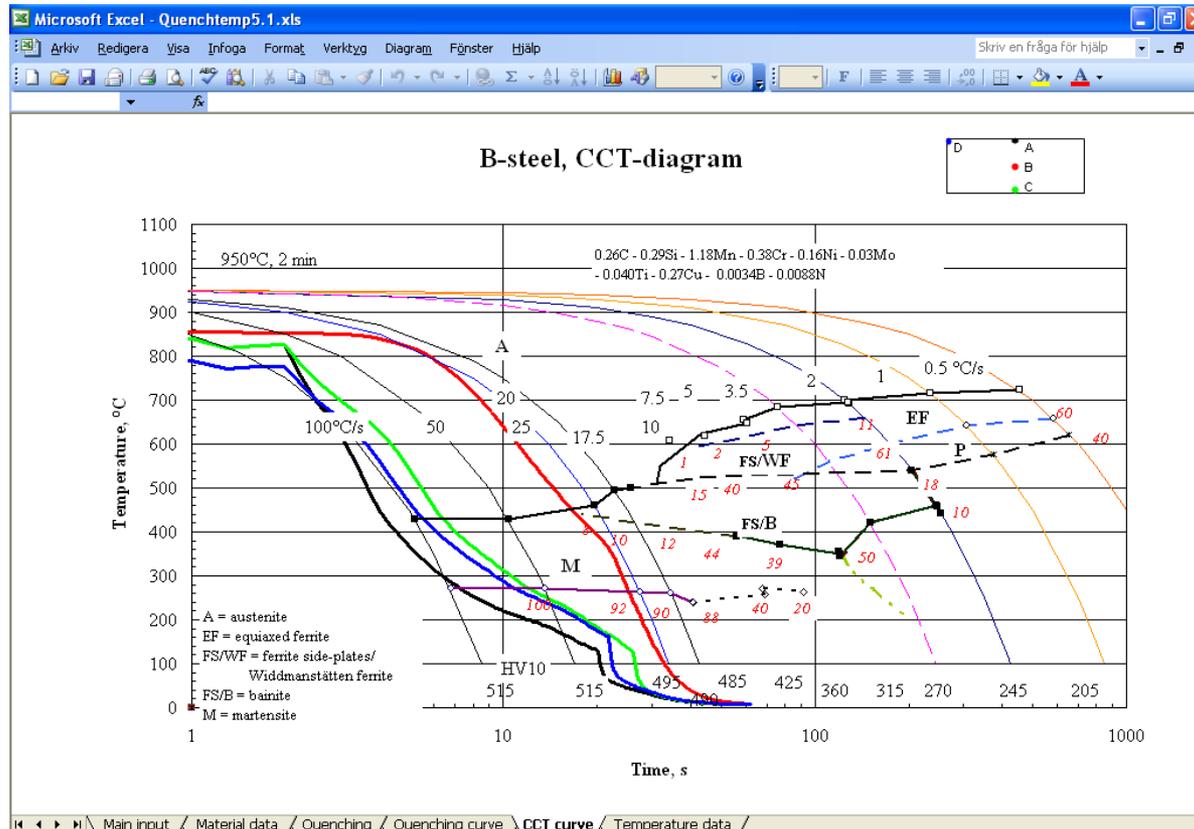
The name of the variables DAUST(3)-DAUST(9) can be changed by the user, cf. sheets "Grain curve", "Strain curve" and "Daust curve".

The variables DAUST(8) and DAUST(9) can be plotted on left or right y-axis or, optionally, not plotted at all. The last option also applies to DAUST(3), DAUST(5) and DAUST(6).

Main input **Microstruc** Measured temp SHM RF Temp curve Temp data Phase curve Phase

Klar 100%

Cooling Cycles in STEELTEMP[®] using Quenchttemp



Summary of calculations in STEELTEMP®

- Temperature calculations of heat transfer with gas radiation and wall radiation in arbitrary flue gas atmosphere
- Calculations of microstructure after heat treatment for processes including heating and cooling
- STEELTEMP calculations can be applied for online process control in FOCS in cooperation with PREVAS



Thank you for your attention!

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