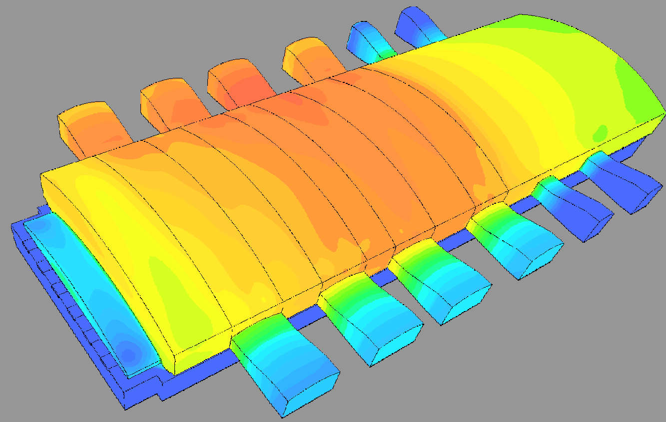
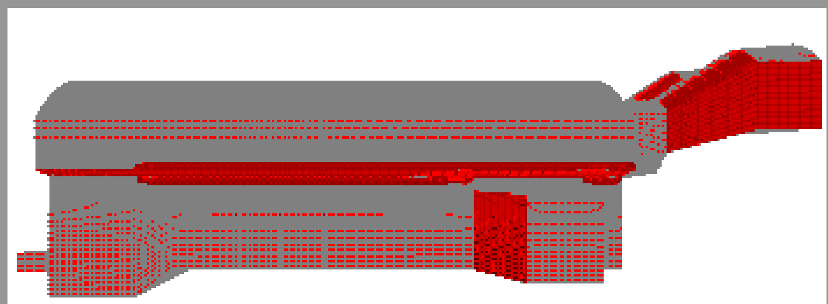
Concepts for energy & emission friendly glass melting

Evolution or Revolution in Glass Melting

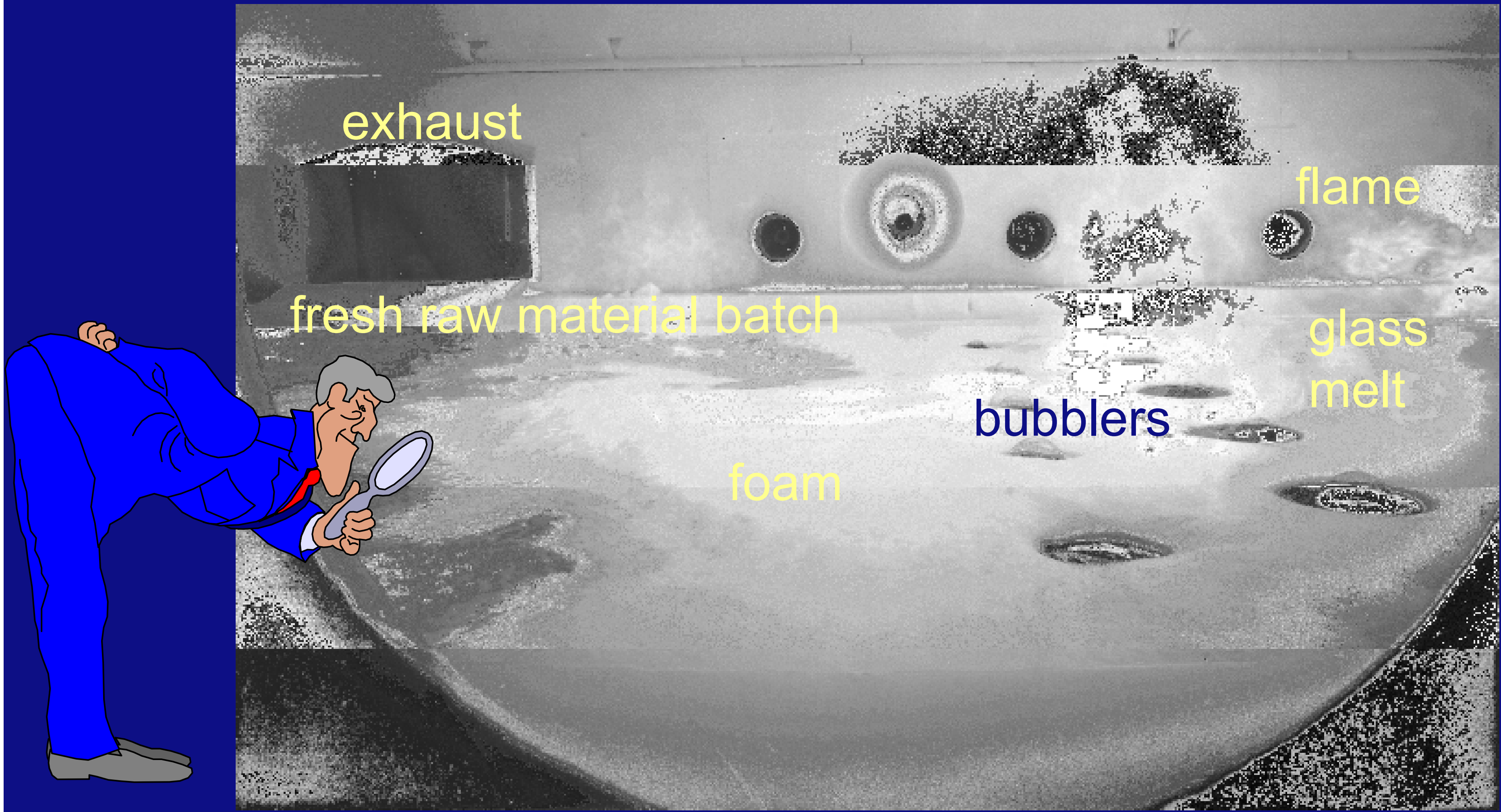
Ruud Beerkens

CelSian Glass & Solar TNO





The difficulty to observe the glass melting process….



Approaches

- Glass quality – dedicated laboratory tests
  - Optimum melting
  - Optimum fining conditions

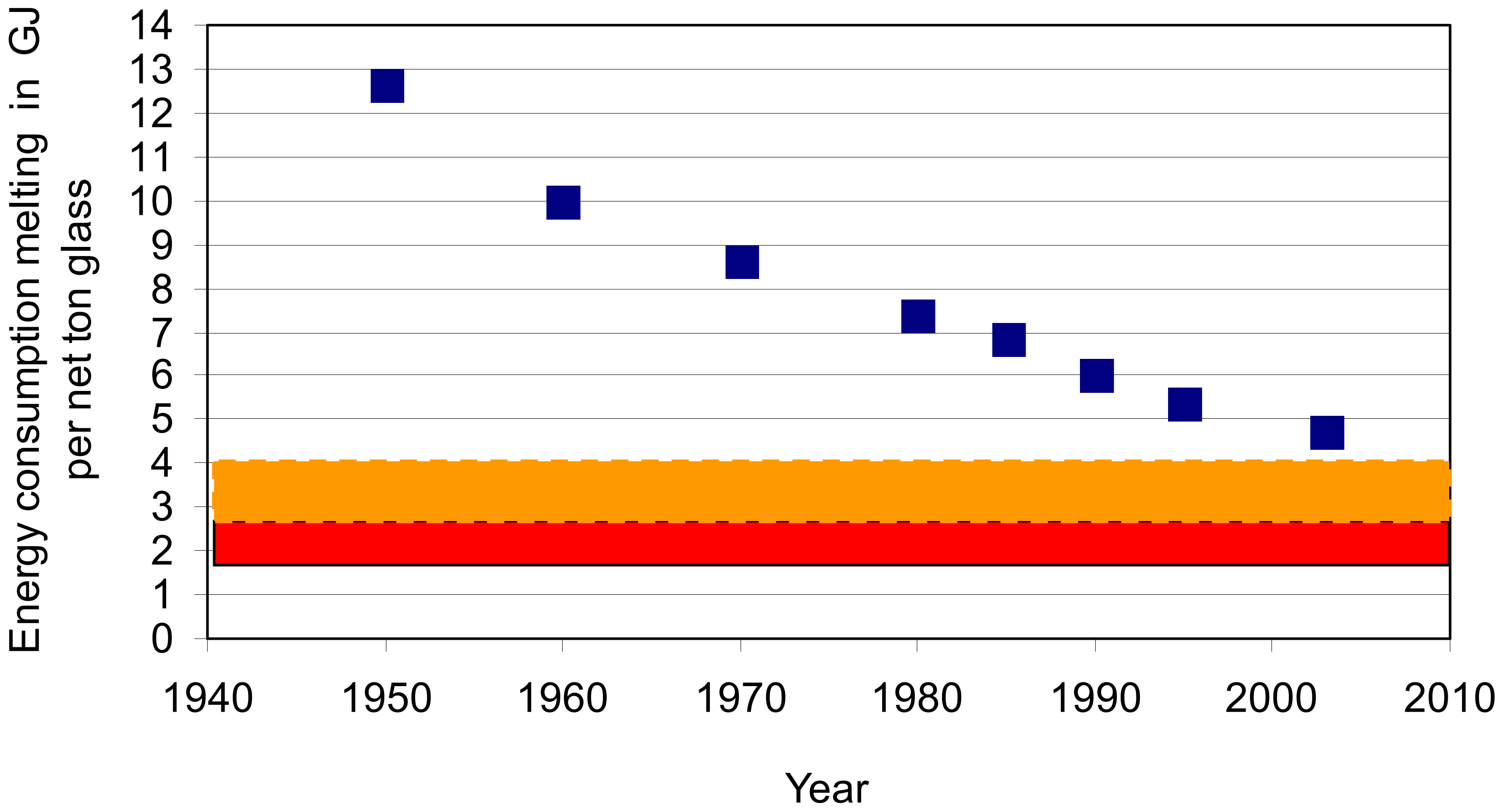
- Energy Efficient (Container) Glass Furnace
  - Low NOx emissions
  - Normal glass quality
  - Highest energy efficiency

- Combination Energy Efficiency, LowNOx & High Glass Quality
- Application of **CFD models** for furnace design & operation

Specific energy consumption NL conventional container glass furnaces

red bar: range of theoretical low-limit based on thermodynamics for melting and heating of glass (1350 °C) for 100 % batch (upper range) and 100 % cullet (lower range)

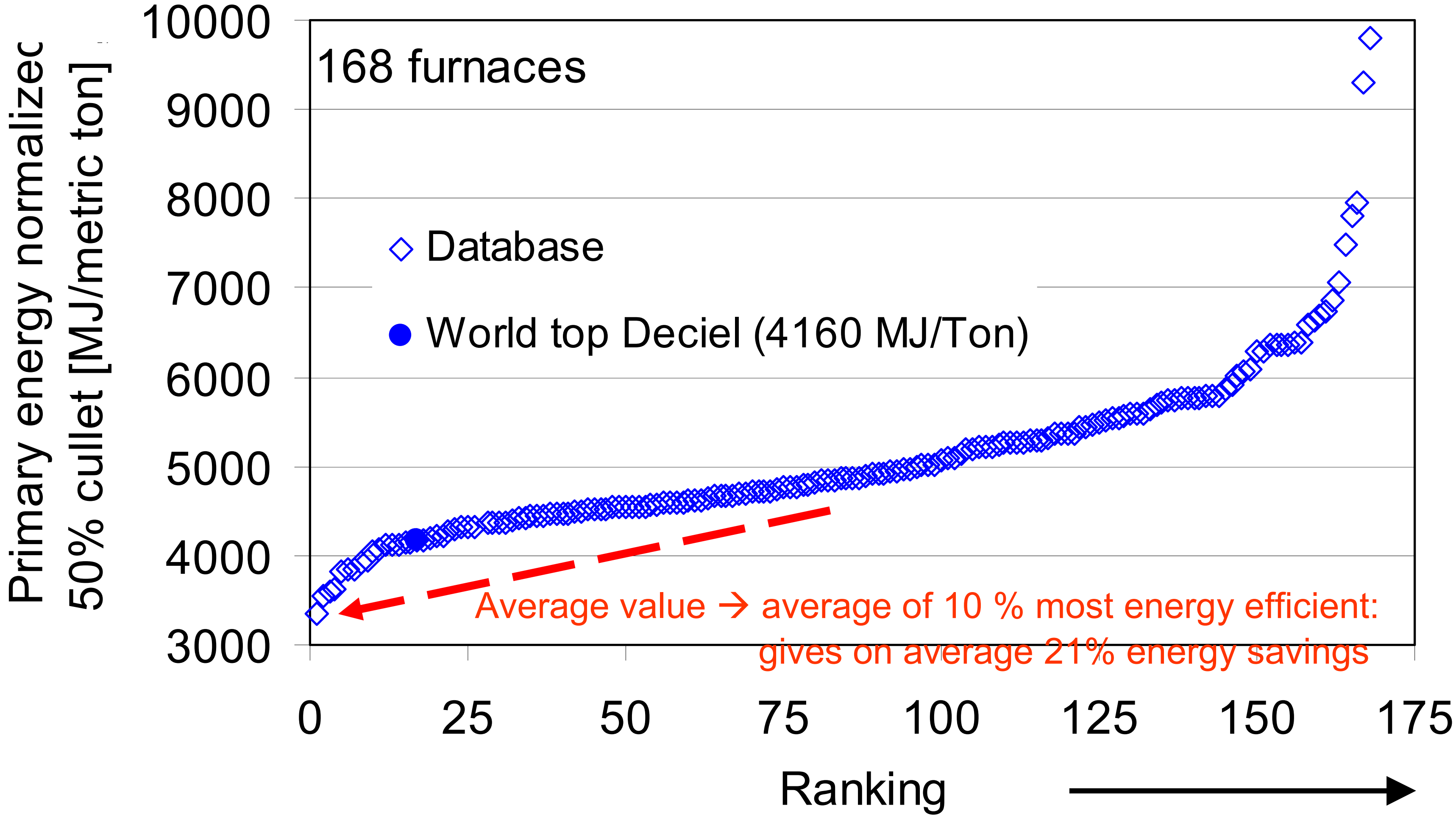
orange bar: best practical limits, no wall heat losses



100 % cullet ultimately insulation, optimum regenerator: 2 MJ/kg

100 % normal batch, dry, ultimately insulated: 3 MJ/kg (*2.7 MJ batch preheat)

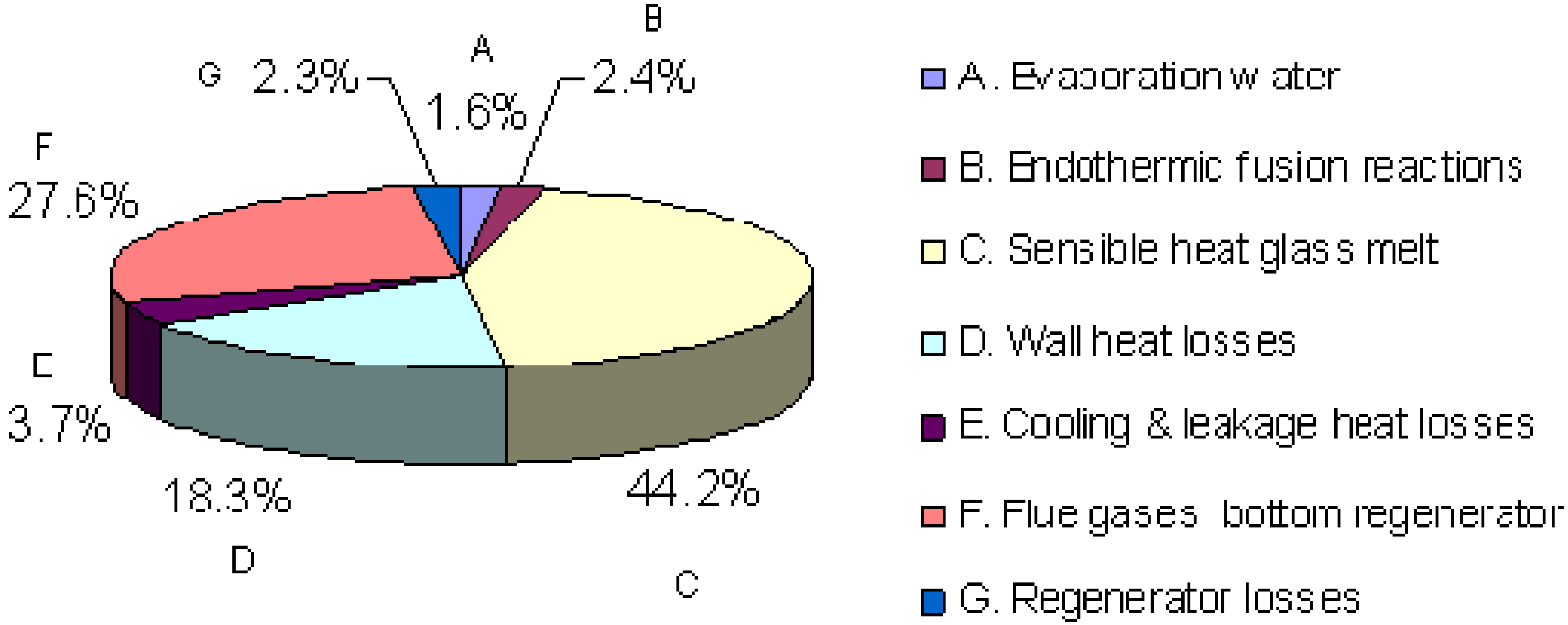
Ranking energy consumption:
Container glass furnaces database 2003 - 2010



Conclusion: bringing all furnaces to the top 10 % (2010) will give on average 21 % energy savings: BEST PRACTISE

End-port fired regenerative container glass furnace

3.62 GJ/ton molten glass - 83 % cullet



Among most optimum container glass furnaces today, without batch preheat

Lowest emissions & energy consumption

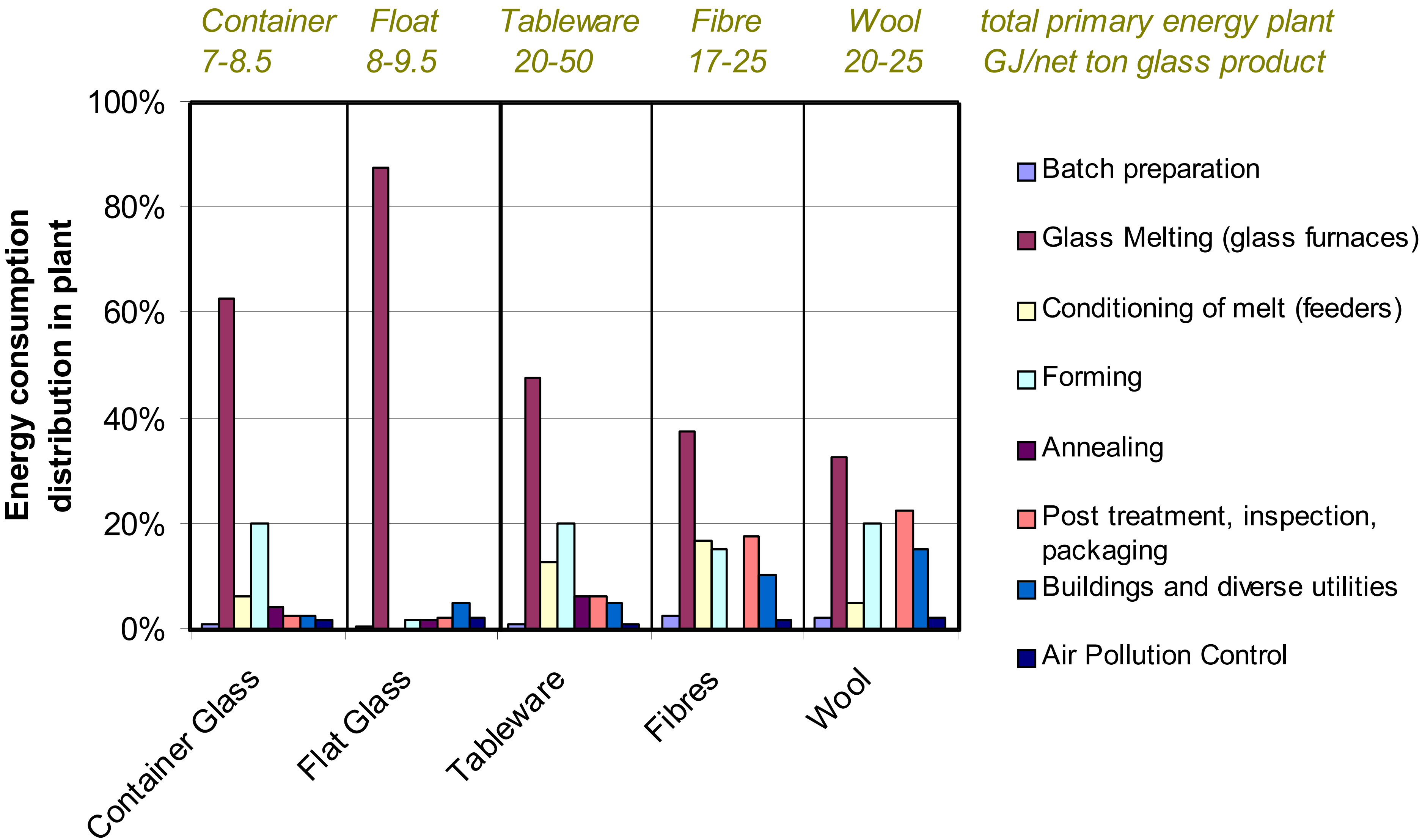
Container glass sector – best results

NOx: 500-700 mg/Nm^3 air-fired (no SCR)
NOx: < 0.35 kg/ton melt (oxygen-fired)

Particulate: 80-90 mg/Nm^3 (upstream filter)

Energy: 3.4 - 3.55 MJ/kg melt (50 % cullet)
3.1 MJ/kg including batch preheat, high cullet level

Typical energy (primary energy equivalent) distribution in different glass sectors (2009)



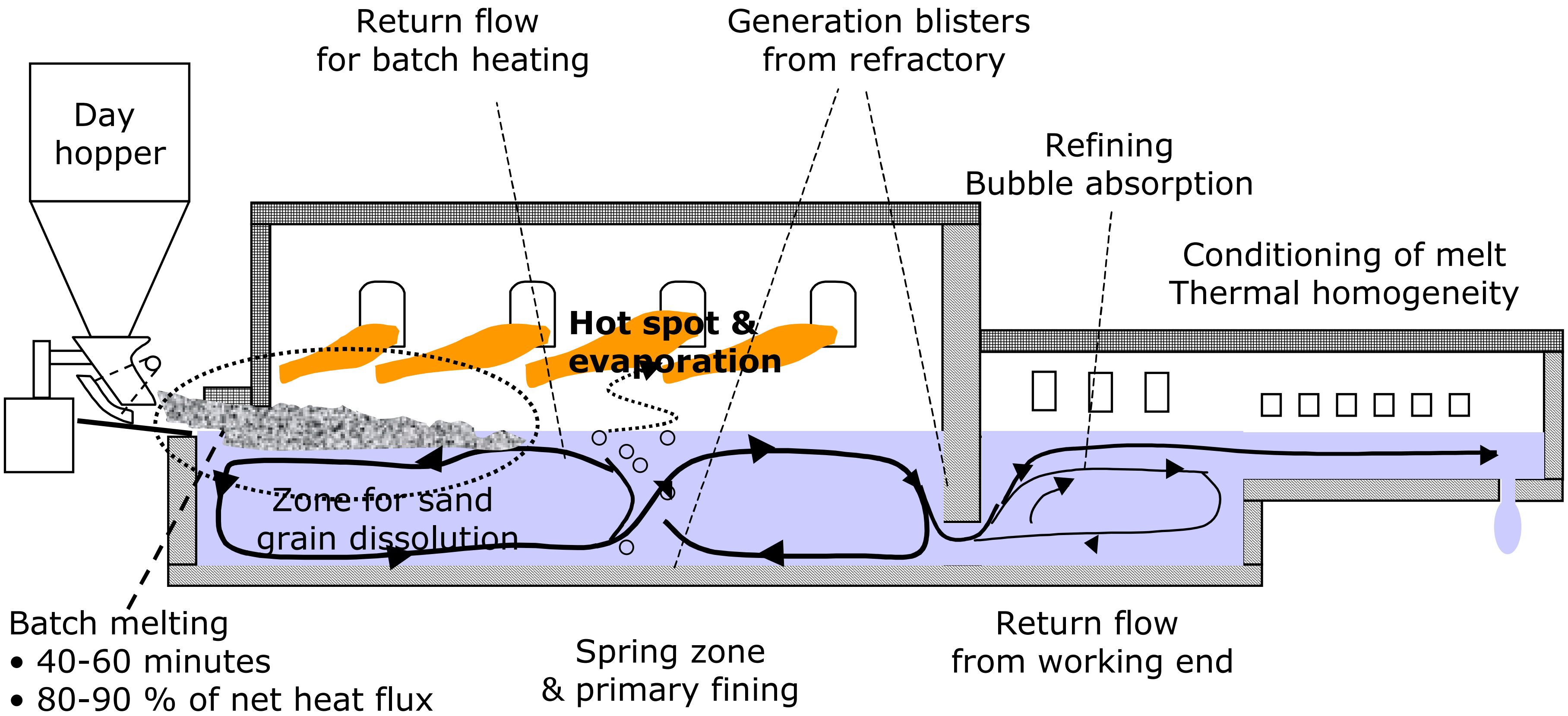
Analysis of industrial glass melting processes today

Glass melt quality = time x
temperature x
f (mixing) x
g (chemistry)

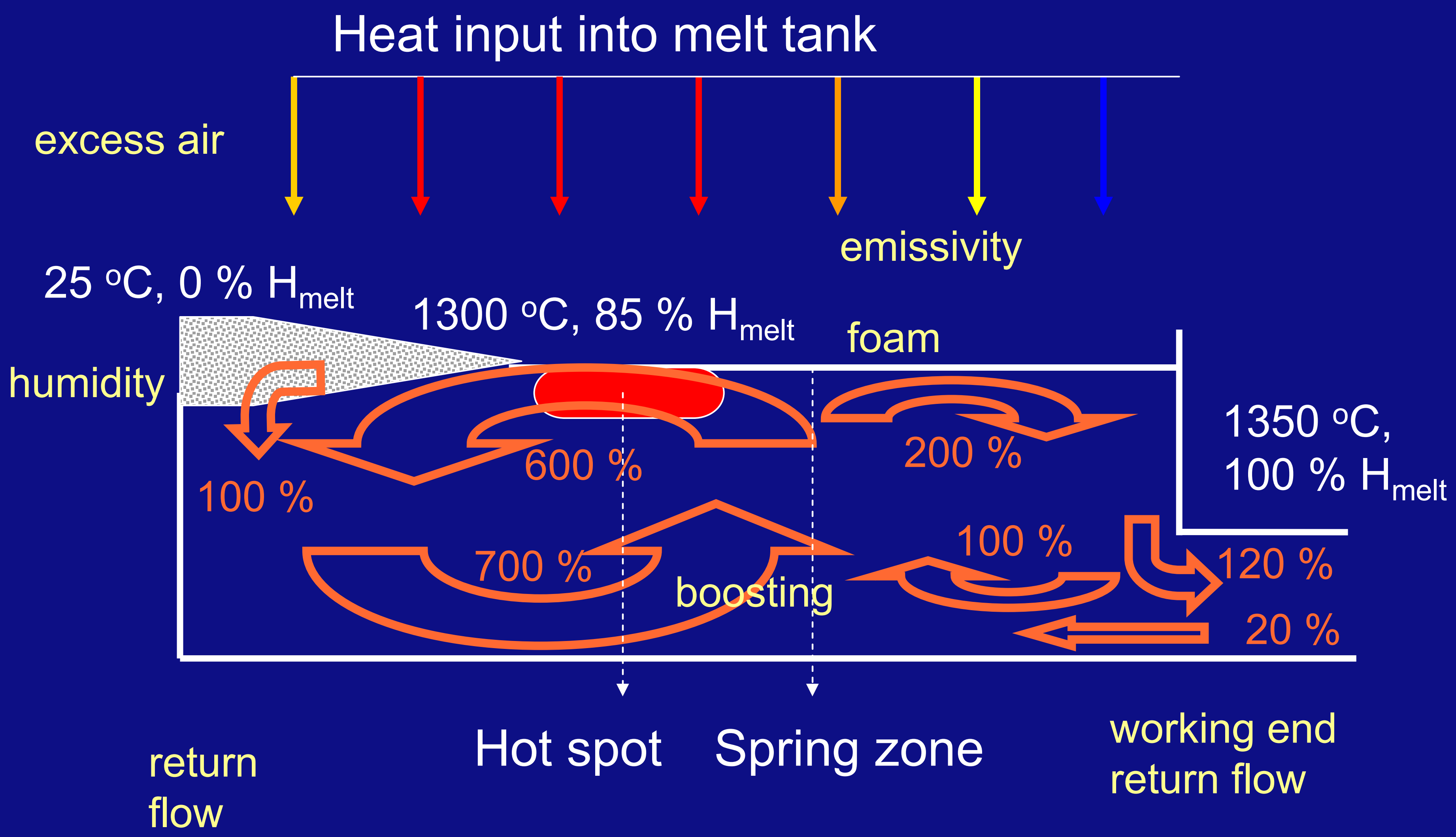
On average melting consumes 65 % of the total energy of glass production

High quality glass melting

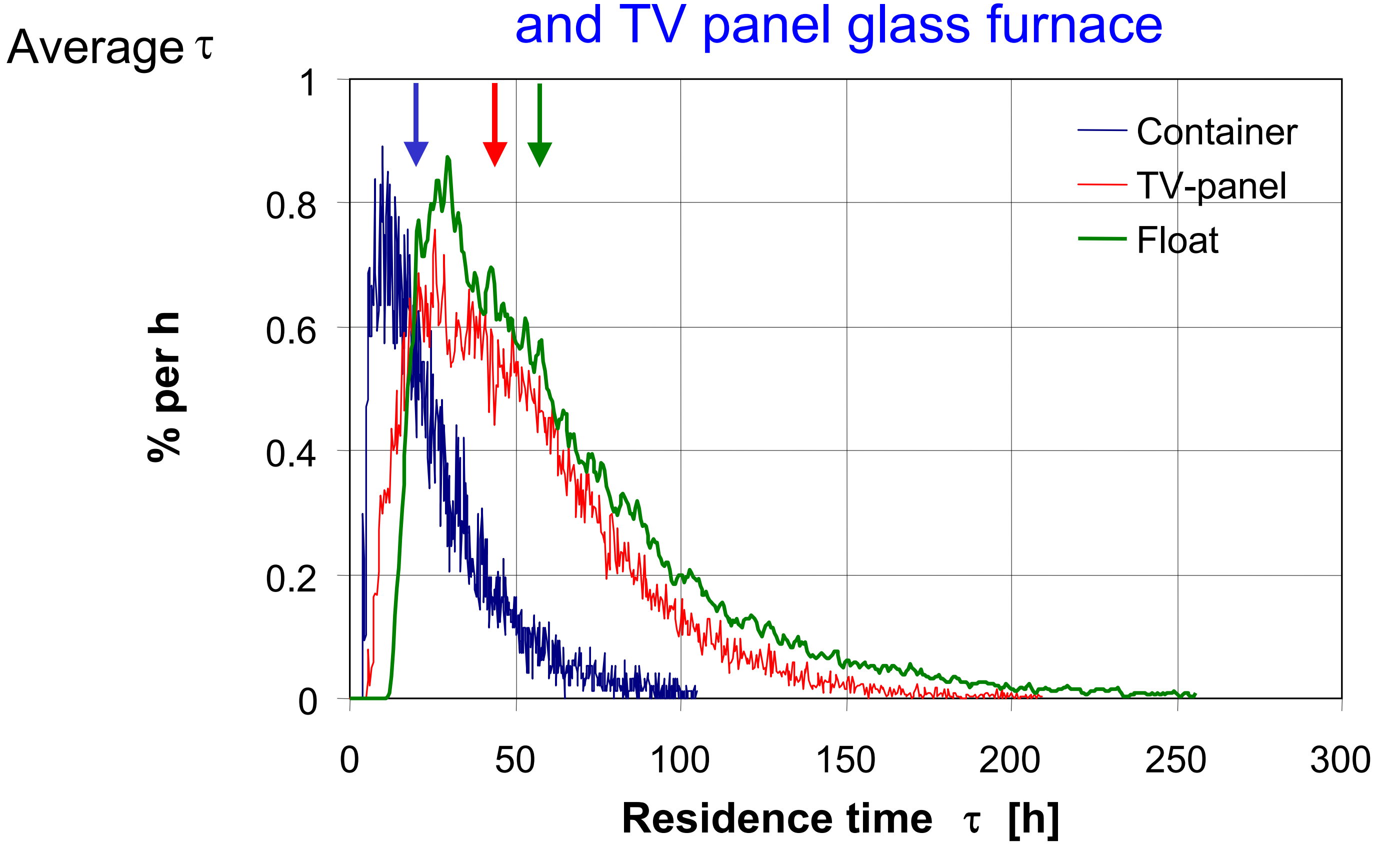
- Control of batch composition
  - Cullet quality: no ceramics/glass ceramics > 2 mm
  - Cullet colors
  - Redox number & reducing power of cullet
    - DWL, purity, seeds
- Complete melting of batch
- Dissolution of sand in melt
- Primary fining: bubble removal
- Secondary fining: bubble re-absorption
- Conditioning: Uniform viscosity prior to forming


Return flow
for batch heating
Generation blisters
from refractory
Day
hopper
Refining
Bubble absorption
Conditioning of melt
Thermal homogeneity
Hot spot &
evaporation
Zone for sand
grain dissolution
Batch melting
• 40-60 minutes
• 80-90 % of net heat flux
Spring zone
& primary fining
Return flow
from working end

Critical Analysis of Conventional Glass Melt Process

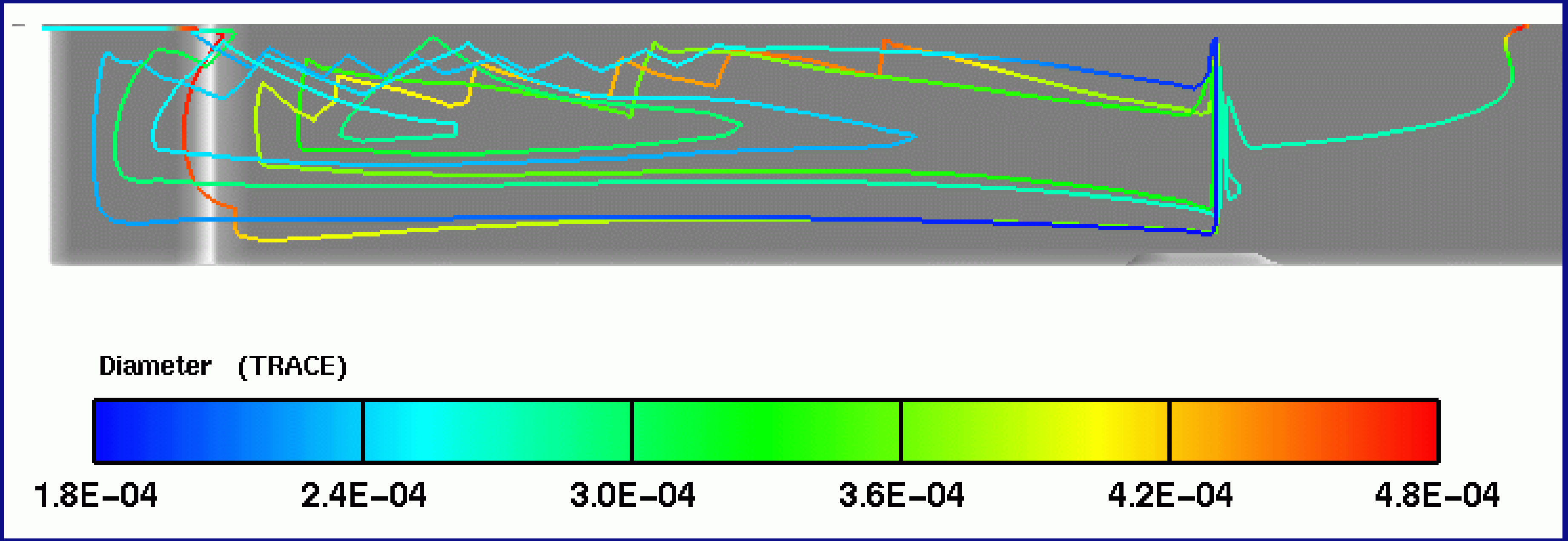


Residence time distribution float, container and TV panel glass furnace



min. residence time/average residence time = 0.15-0.20

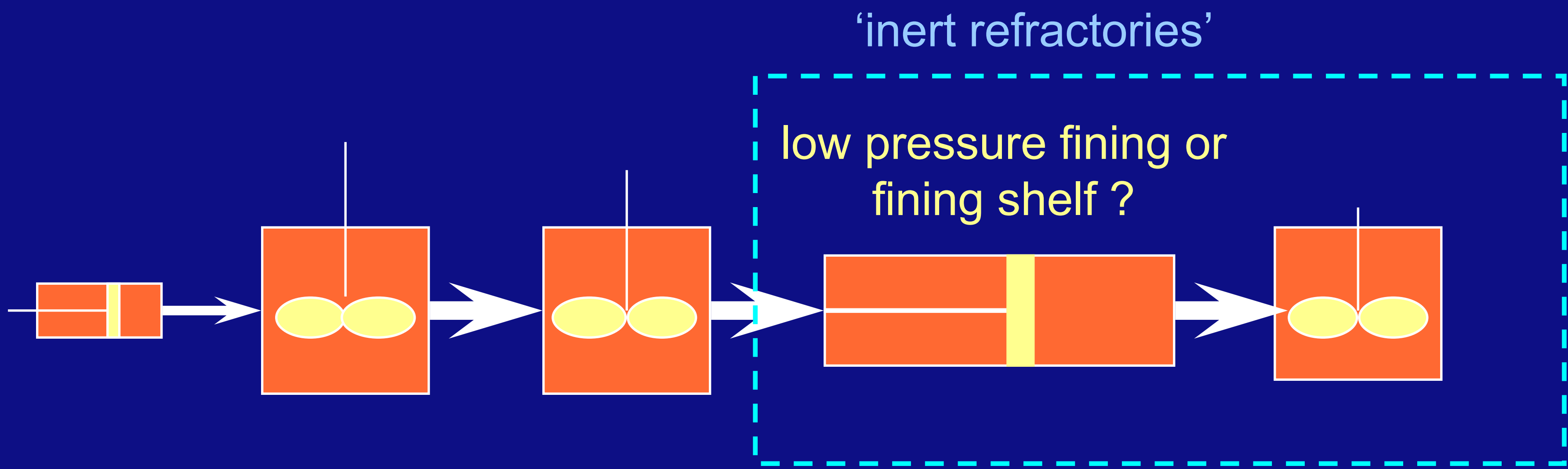
Many different trajectories (paths) in tank



Improved design features

- Optimize **"Space Utilization"**
  - Avoid strong recirculation flows from fining zone into melting-in zone
- Separation of melting-in and sand dissolution section from fining area, enhance convective flows only in melting zone **but not** in primary fining zone!

Example ‘ideal situation for glass melting’



20-1200 ^{o}C
batch
blanket

1300-1350 ^{o}C
melting

heating
1550 ^{o}C

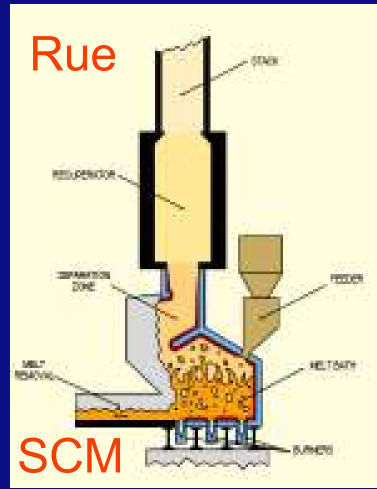
1500-1600 ^{o}C
fining

1350-1100 ^{o}C
refining &
conditioning

0.75 hour	0.75 hours	1 hours	1- 2 hours	1.5 -2 hours

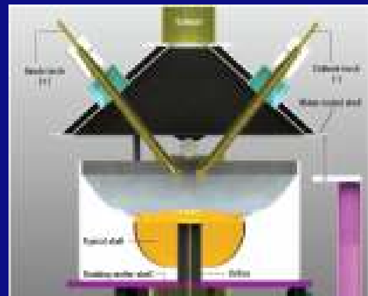
Selection of refractory per zone

Advanced fining & melting



Submerged combustion: short residence time & high heat flux (SCM)

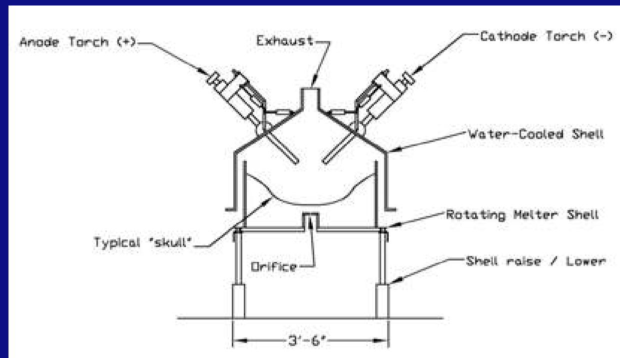
Thin film melter: refractory issues



Plasma melting: very high temperatures plasma,

- short torch lifetime high energy costs
- suitable for special glass types (low alkali)

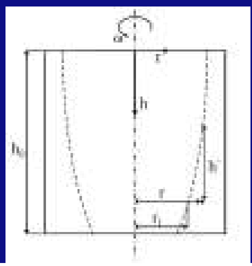
Gonterman



Fining shelf: short distance for ascension

Low pressure fining: fining shaft at pressures < 0.3 bar

Centrifugal fining: short bubble removal time in fast rotating vessel



Klouzek, Prague

Batch (blanket) melting

- Residence time in batch blankets: 0.5 - 1 hour
- Floating of batch isles on top of melt
- > 80 % of energy to be transferred to melt is absorbed by batch blanket (within 0.5 -1 hour)
- Most heat is supplied by re-circulating glass melt from hot spot zone

$$J_{SiO2}(melt) = 0.332 \cdot v^{1/2} \cdot x^{-1/2} \cdot \rho^{1/6} \cdot \eta^{-1/6} \cdot D_{SiO2}^{2/3} \cdot (C^*_{m,SiO2} - C_{m,SiO2})$$

$$C_{b,SiO2} \cdot dX_b/dt = C^*_{m,SiO2} \cdot dX_b/dt + J_{SiO2}(melt)$$

Melting of batch layer thickness X:

$$dX/dt = 0.332 \cdot v^{1/2} \cdot x^{-1/2} \cdot \rho^{1/6} \cdot \eta^{-1/6} \cdot D_{SiO2}^{2/3} \cdot (C^*_{m,SiO2} - C_{m,SiO2}) / (C_{bSiO2} - C^*_{m,SiO2})$$

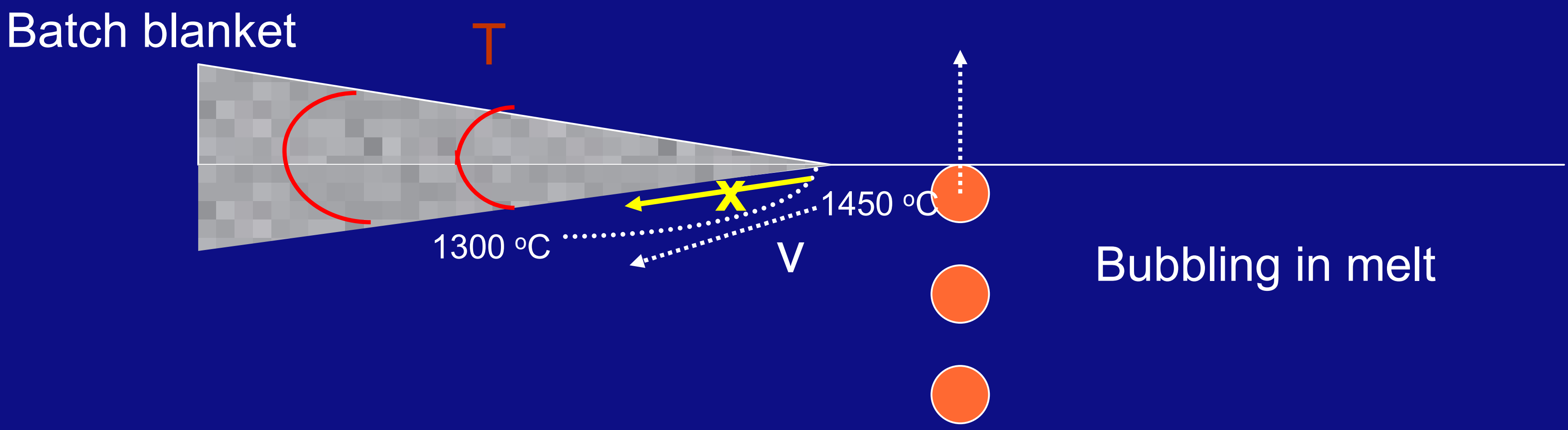
$C_{m,SiO2}$ = concentration SiO_2 in melt (bulk) kg/m^3

$C^*_{m,SiO2}$ = saturation concentration SiO_2 in melt kg/m^3

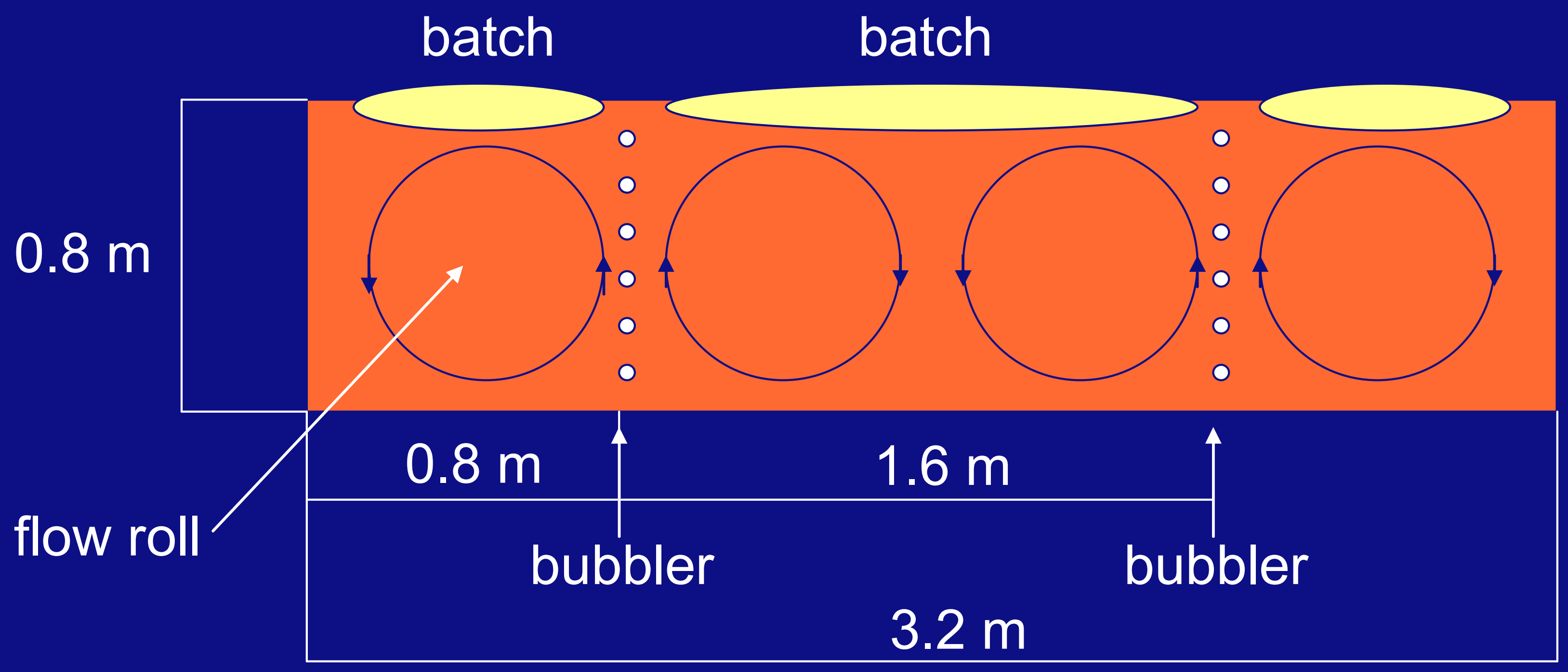
$C_{b,SiO2}$ = concentration SiO_2 in batch kg/m^3

v = glass melt velocity underneath batch m/s

x = distance from batch tip m

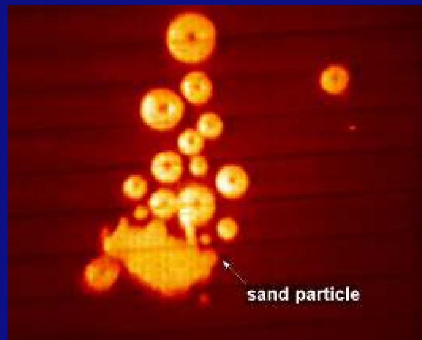


Rapid Melter
Concept 2



Sand dissolution

- Typical temperature window 1100-1350 ^{o}C
- Strong convection improves sand grain dissolution
- Separation between sand grain dissolution zone and fining zone is essential
- Avoid temperatures > 1350 ^{o}C to minimize overlap between fining and sand grain dissolution.

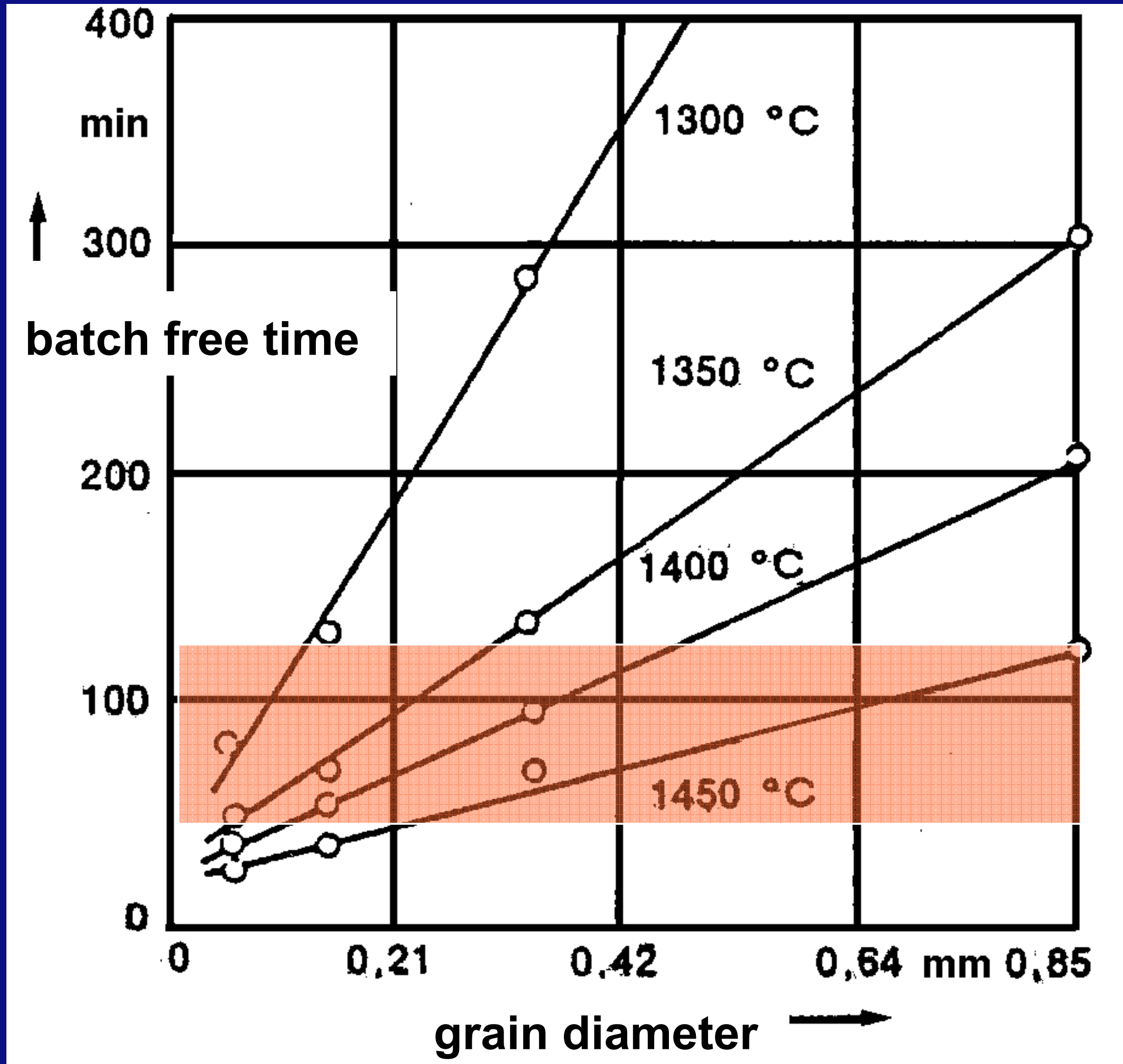


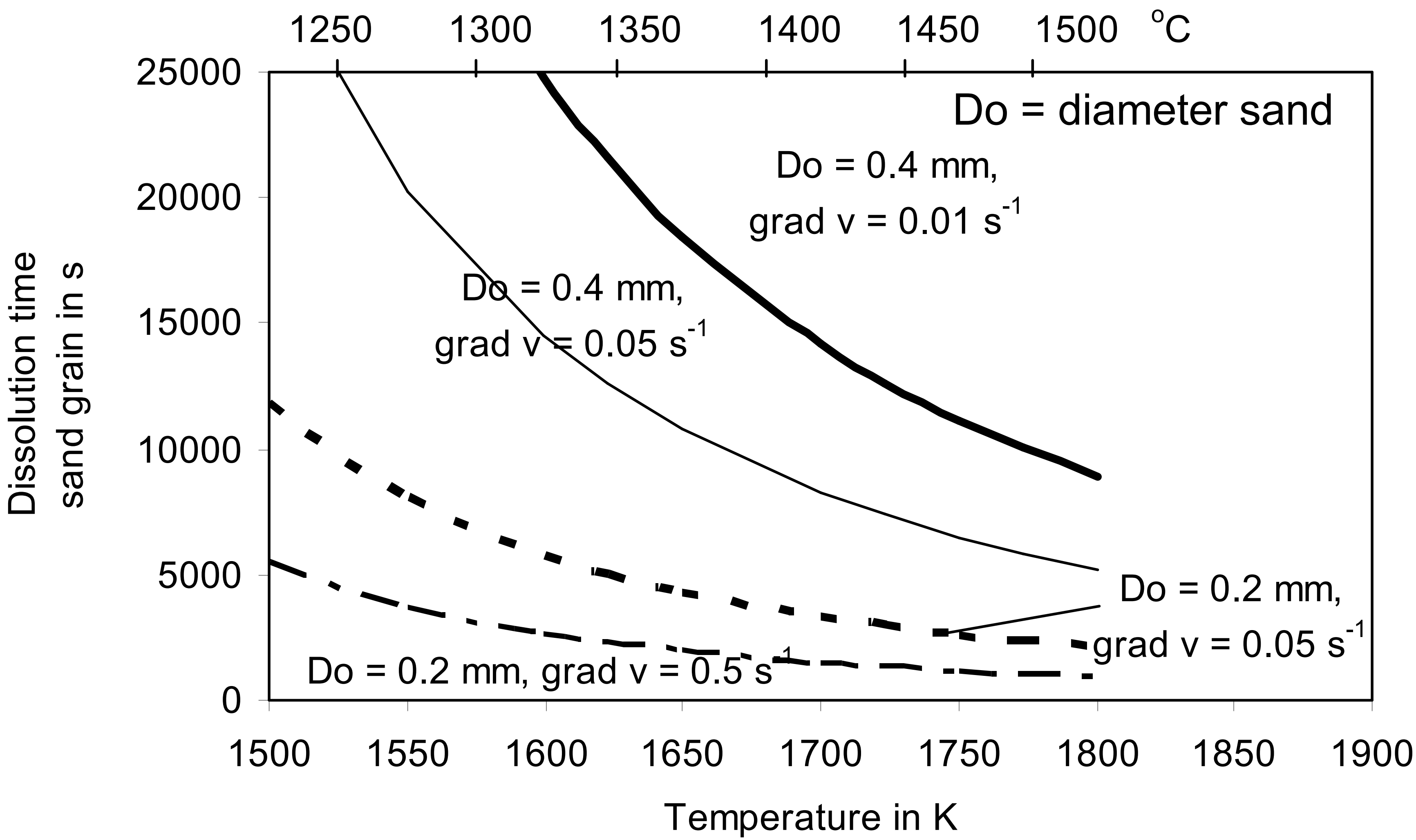
Glass Service

- Analysis of minimum residence time required
  - Batch free time experiments

    Depending on:
    - Glass composition (Na_2O, CaO, MgO content)
    - Sand grain sizes (size distribution)
    - Convective flows
    - Temperature

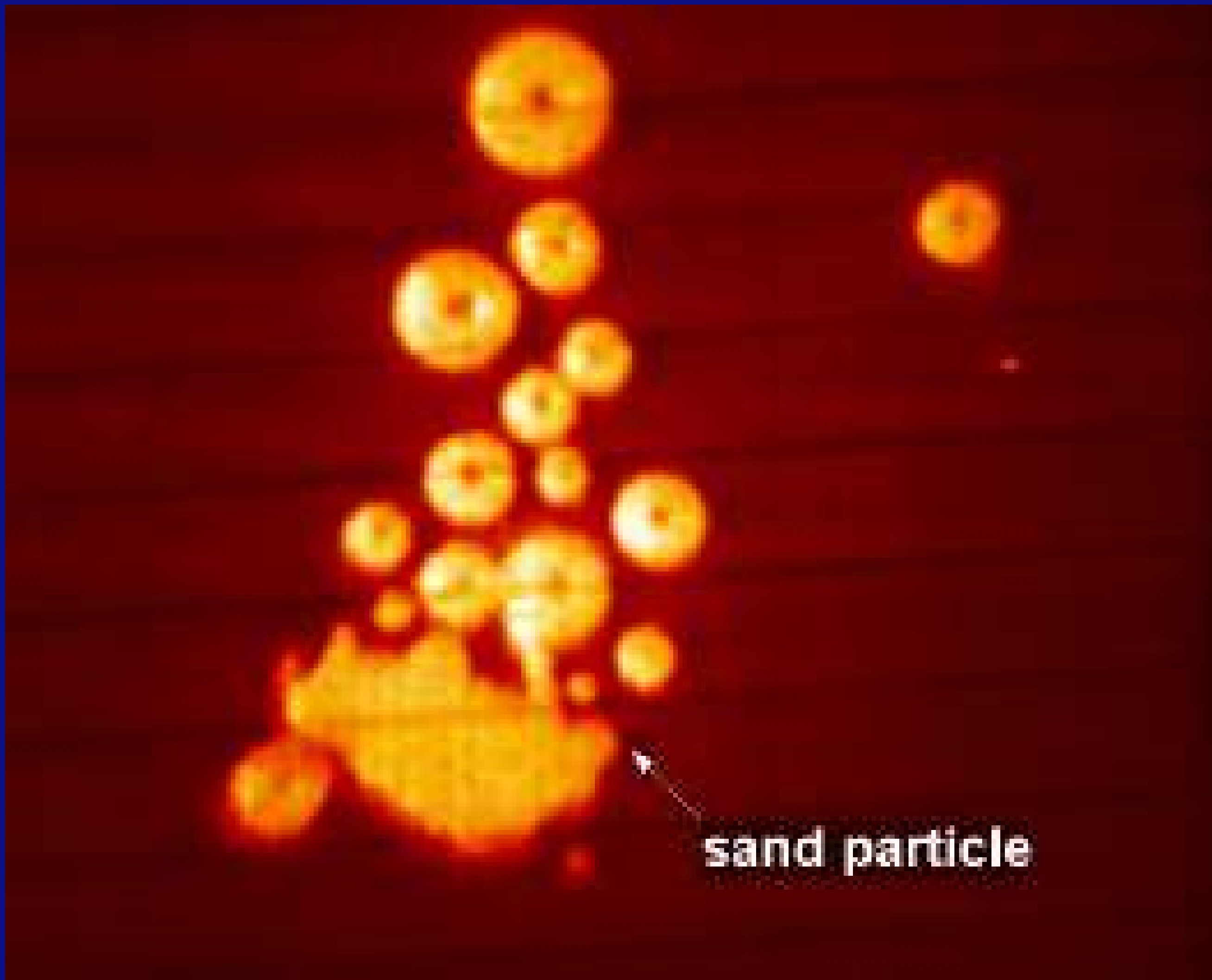
Effect of temperature and grain size on "batch free time" in soda-lime-silica glass melting



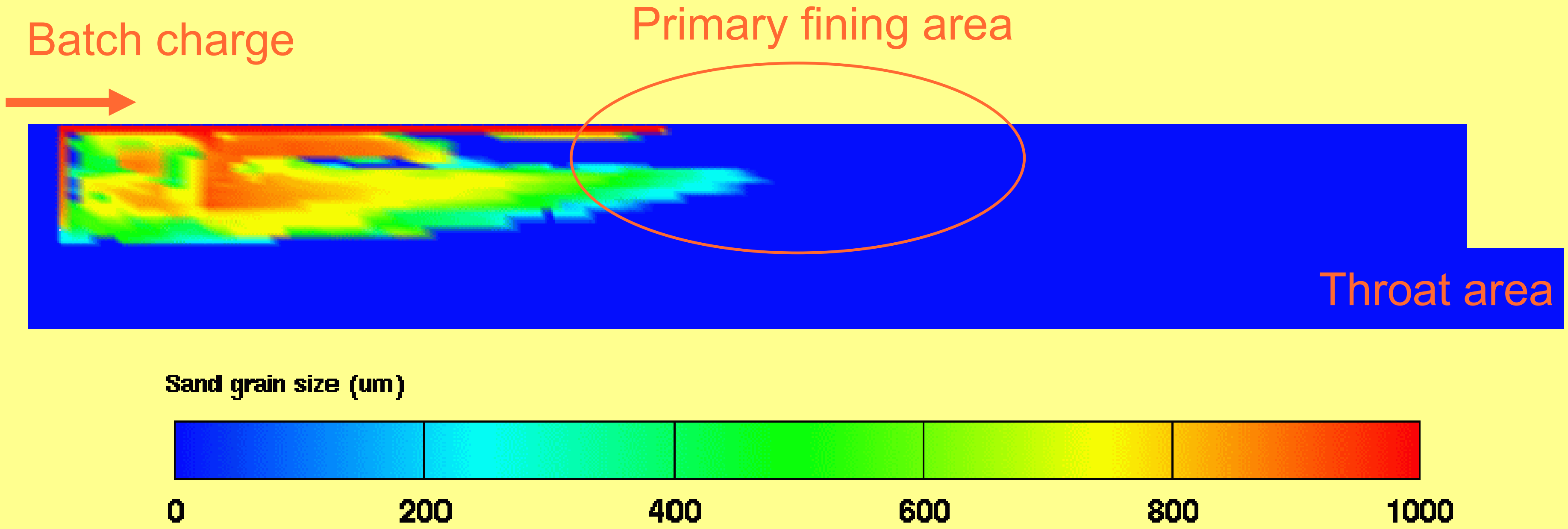


Dissolution time of sand grains in container glass melt as function of temperature for different convection intensities

Sand grains in molten glass and bubble formation



Sand grain dissolution in melting tank

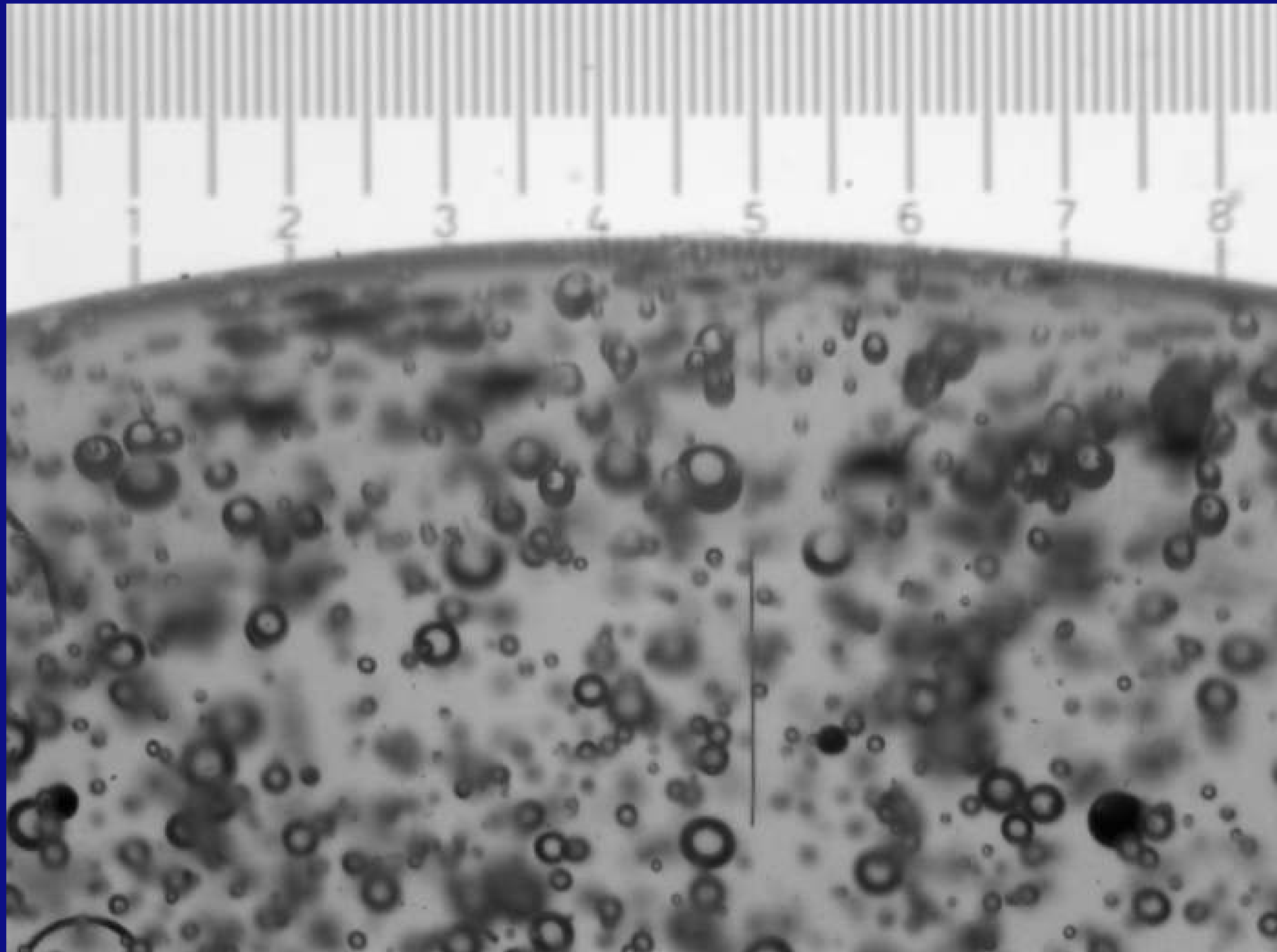


FINING

Just after batch melting:

50000 - 200000 seeds (D = 50-400 microns) per kg glass!!

0 to 8 mm



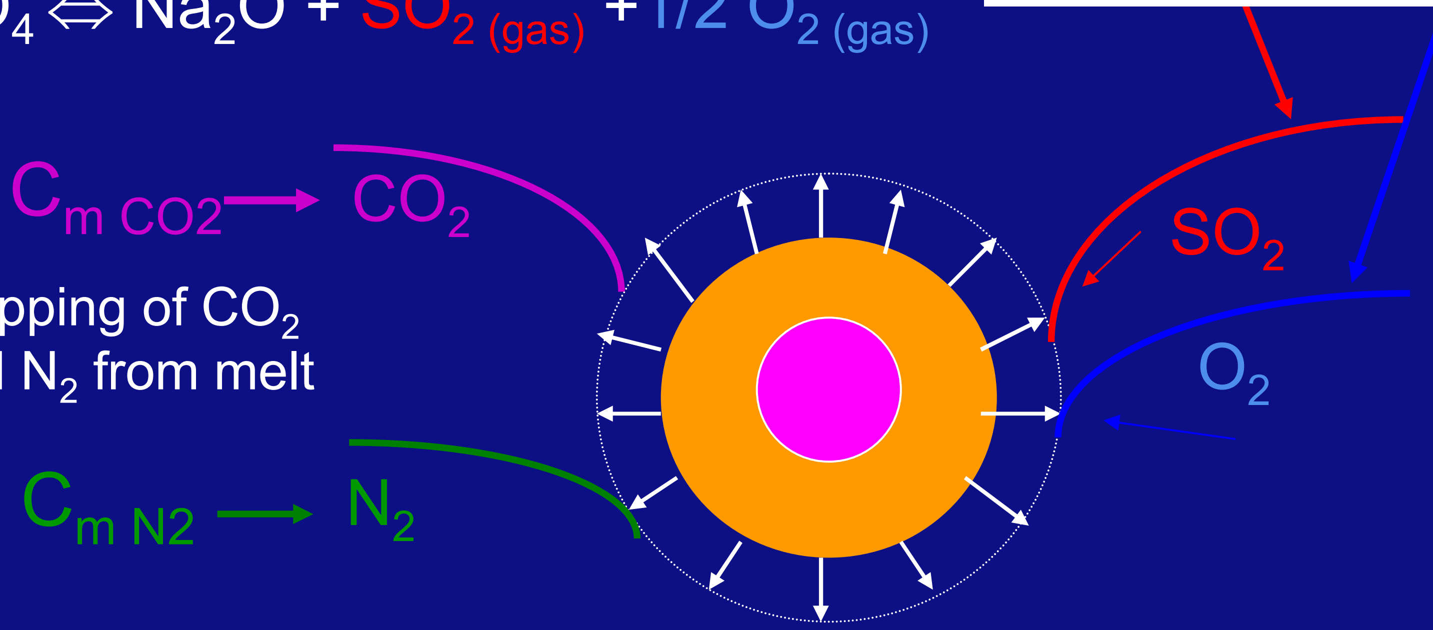
Fining (primary)

- Fining agents added to the batch to enhance bubble growth & to increase the rising velocity of these bubbles
- Often used fining agent: Sodium sulphate

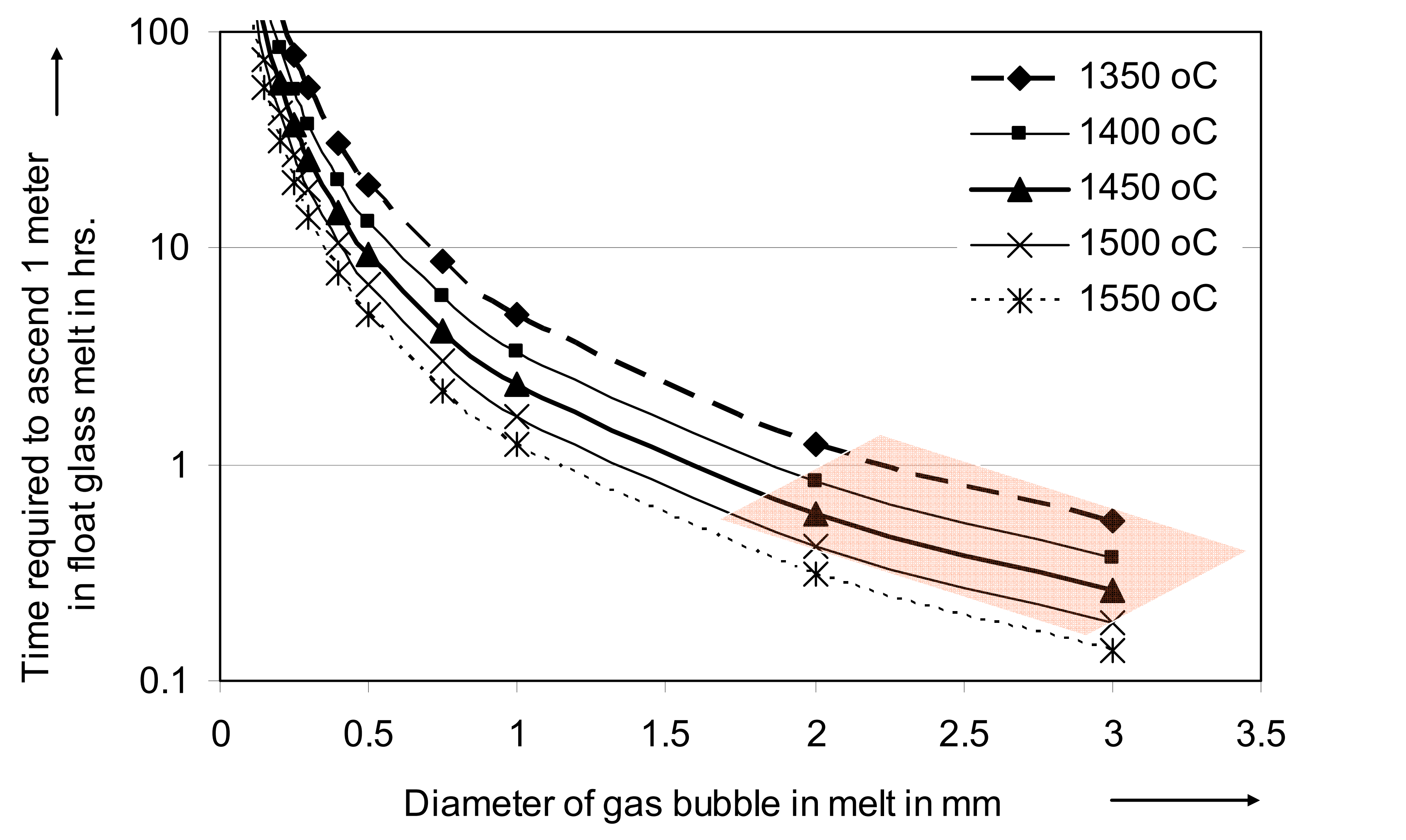
Fining reaction: $T > T_{\text{Fining onset}}$

$$K' = \frac{pSO_2 \cdot \sqrt{pO_2}}{[SO_3]}$$

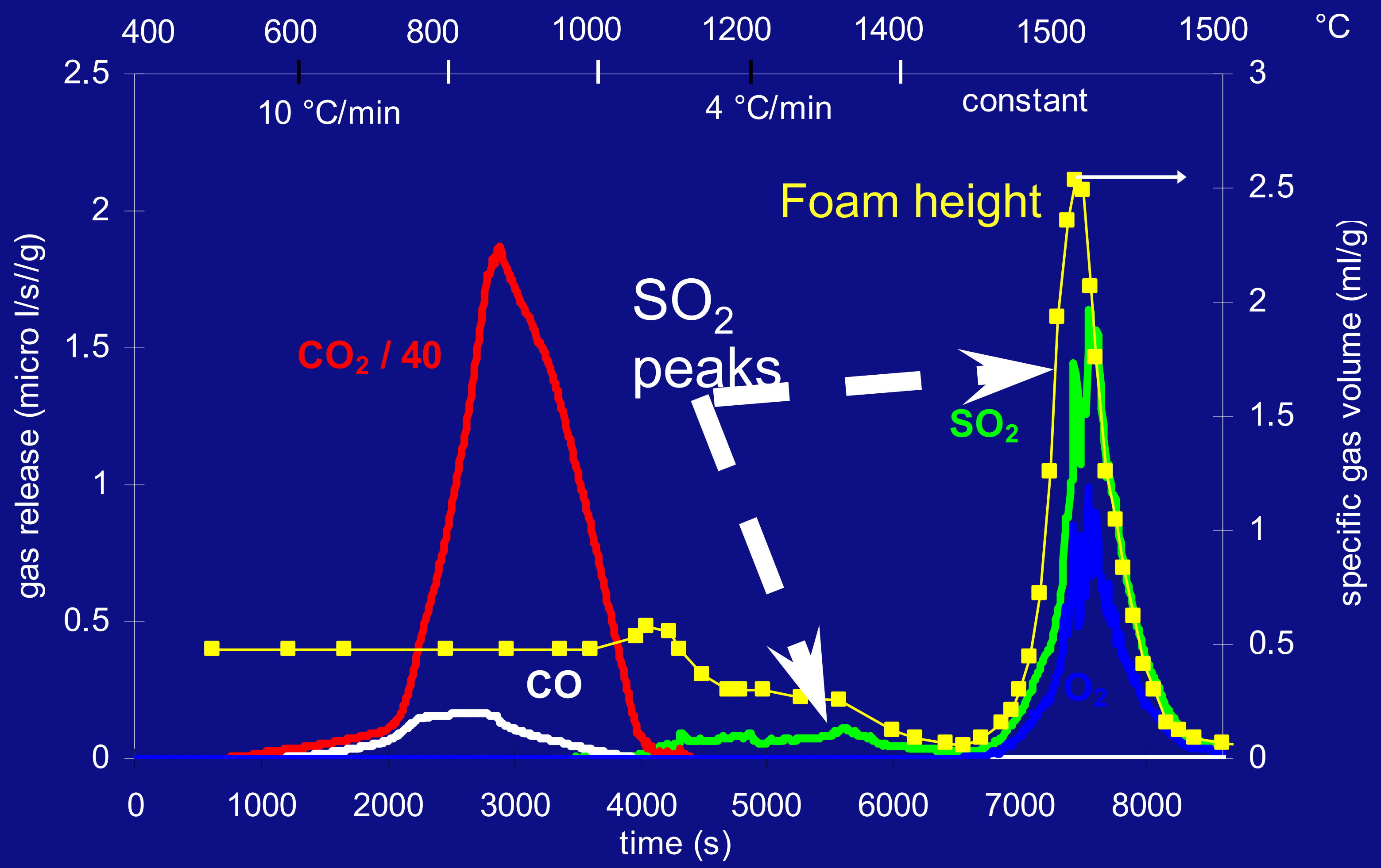
$Na_2SO_4 \Leftrightarrow Na_2O + SO_{2\,(gas)} + 1/2\ O_{2\,(gas)}$



Dilution of N_2 & CO_2 in bubble by fining gases



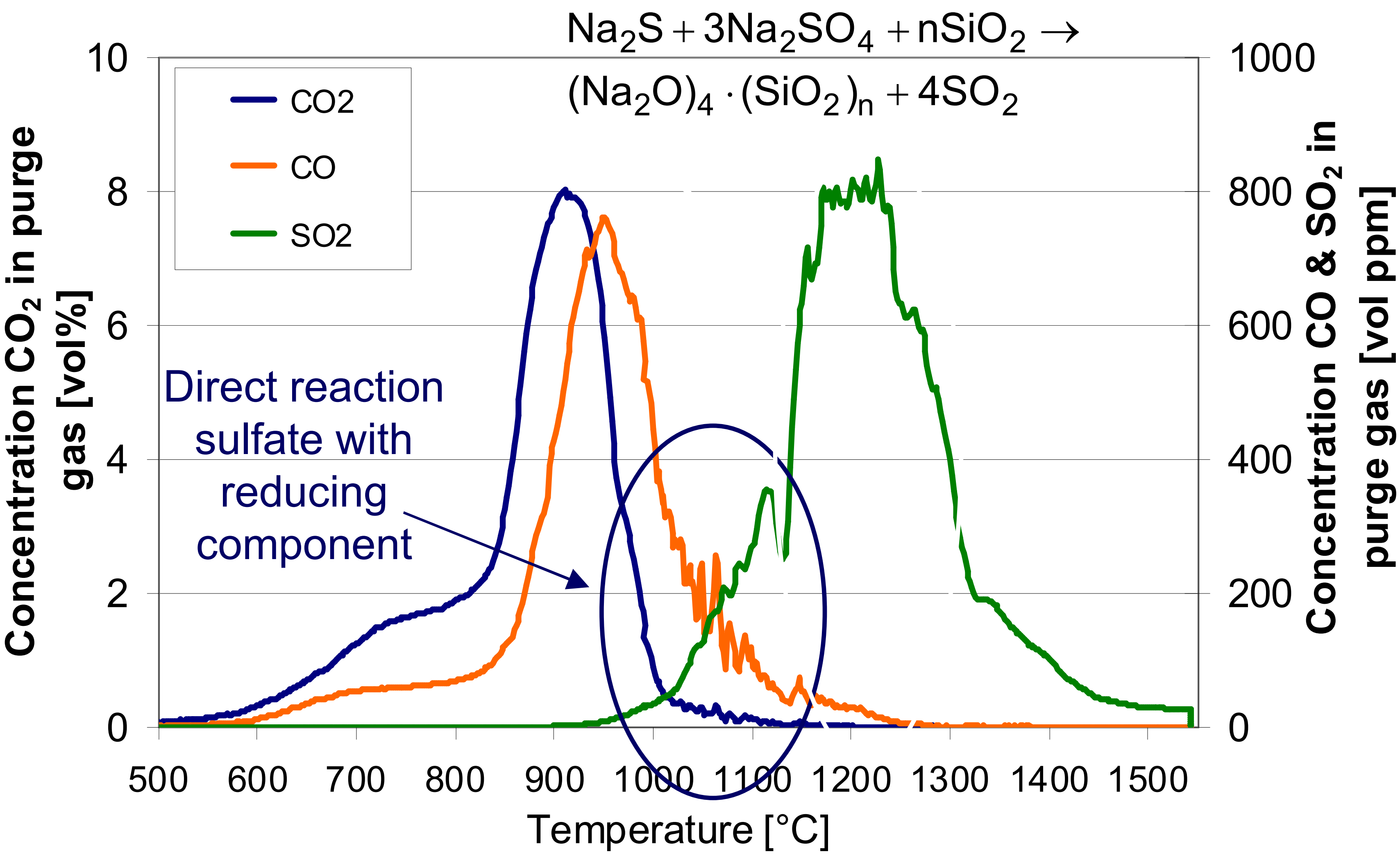
Time required to ascend 1 meter in float glass melt in hrs.
100
10
1
0.1
1350 oC
1400 oC
1450 oC
1500 oC
1550 oC
0
0.5
1
1.5
2
2.5
3
3.5
Diameter of gas bubble in melt in mm



Foaming and gas release from normal sulphate containing batch **without reducing** agents in N_2 atmosphere: flint glass

Fining at high T!

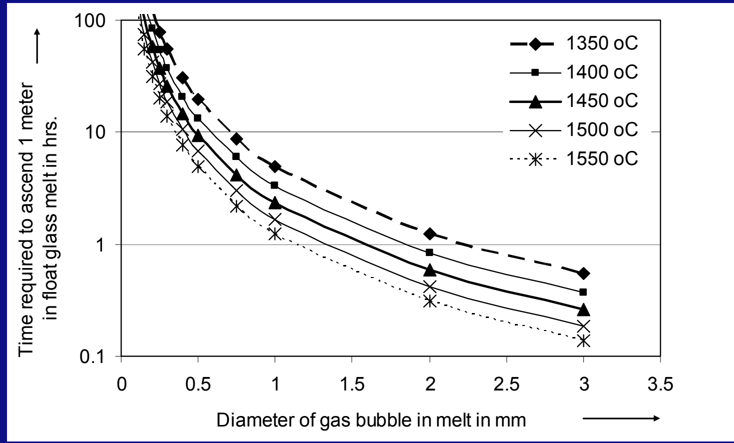
Slightly reduced batch – fining at lower T !!



No oxygen evolution observed

Sulfur content = 0.5 mass%SO_3
Added carbon content = 0.05 mass%

Primary fining

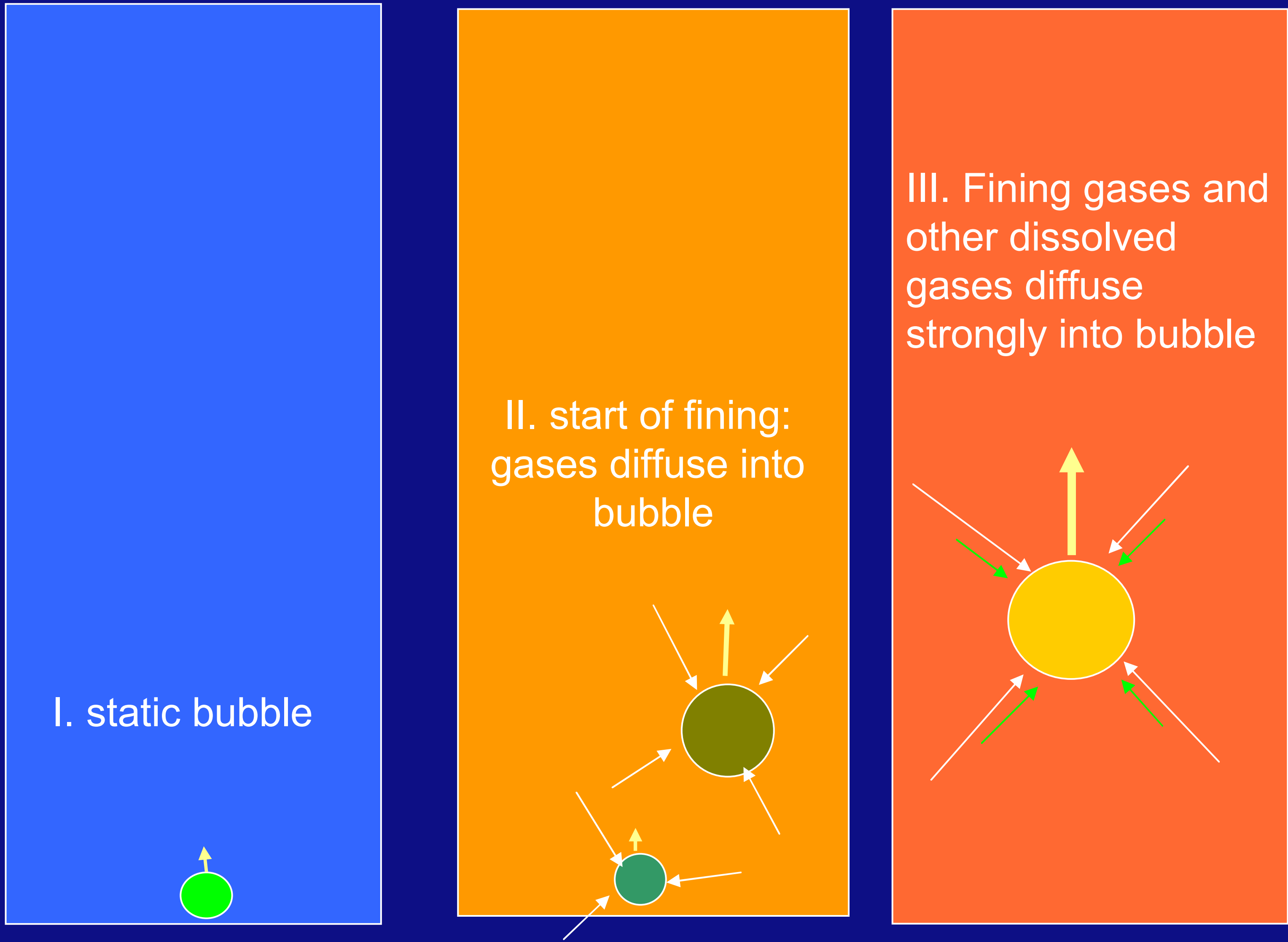


- Bubble Growth
  - Above fining onset temperature
  - Bubbles should grow to D >>0.5 mm
- Removal of dissolved gases from melt (stripping)

- Fining onset temperature depends:
  - sulfate content batch
  - reducing agents in batch
  - water vapor (oxygen firing versus air-firing)

Fining onset temperature

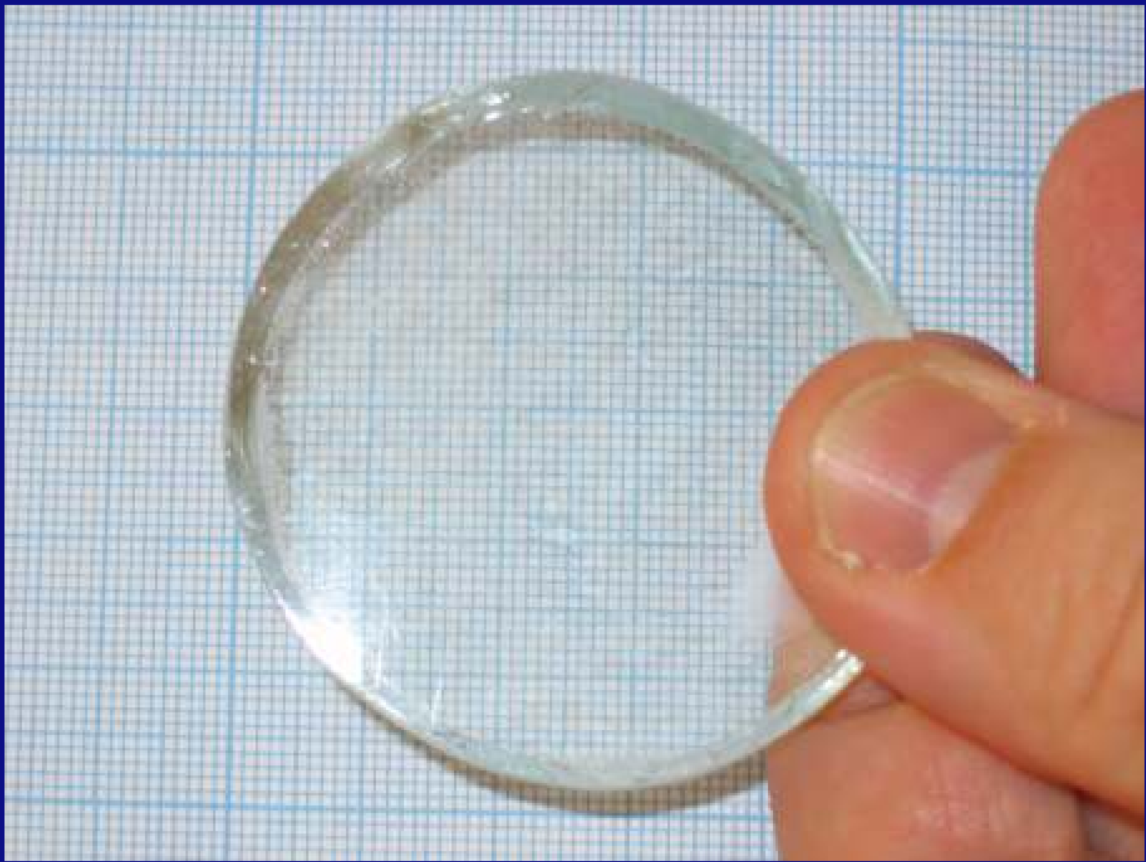
- EGA tests
- Bubble observation in glass melt
- Determination of gas evolution from melt & sudden increased bubble growth

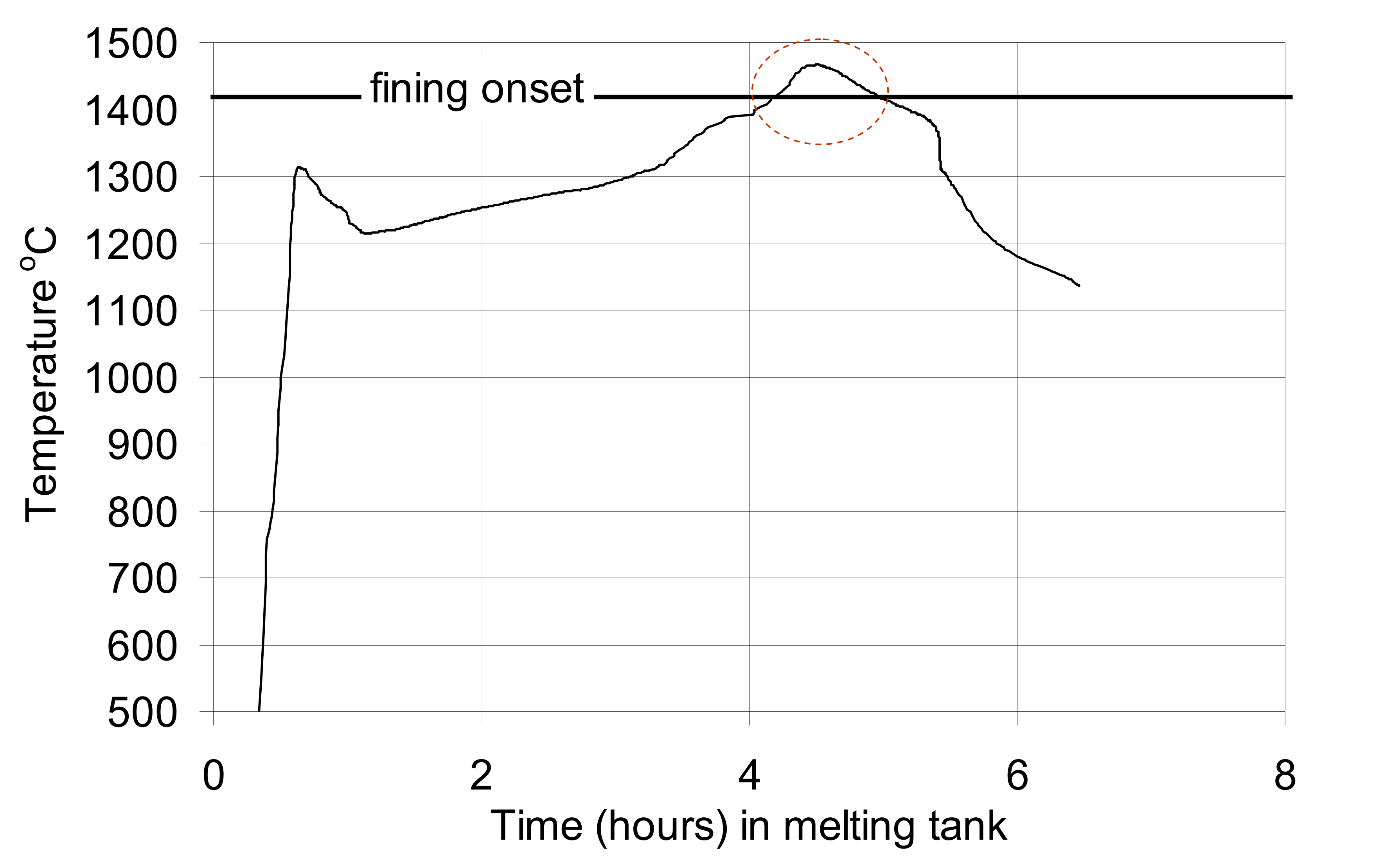


Reaction in melt: release of fining gases

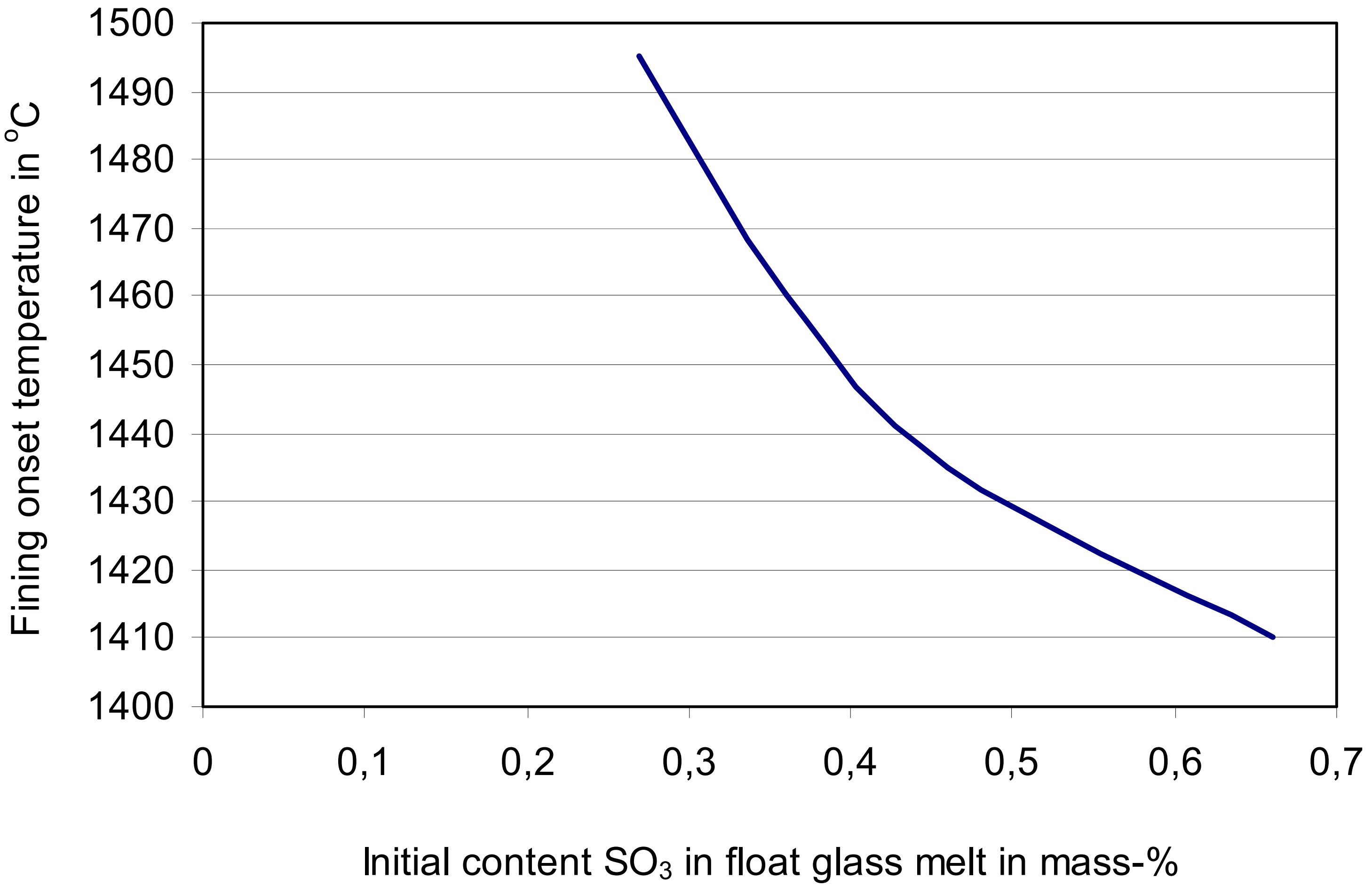
$P_{gases\ melt} > p_t$ (p_t is pressure in bubble)

3 hours molten float glass batch in laboratory at 1450 ^{o}C





Temperature – time course of ‘most critical’ trajectory
In float glass melting tank



1500
1490
1480
1470
1460
1450
1440
1430
1420
1410
1400
Fining onset temperature in °C
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
Initial content SO3 in float glass melt in mass-%

Secondary fining

Second step: Secondary fining/Refining

- Dissolution of (small) remaining bubbles
  - Only effective if bubble contains gases (CO_2, O_2, SO_2+O_2) that dissolve in cooling melts
  - Glass melt **should be lean** in dissolved gases

Proposal – for SLS glass with high melting quality

- High convective melting-in zone (residence time 60 minutes)
  - High heat transfer rate to batch
  - Temperatures < 1300-1350 ^oC to avoid early sulfate decomposition
- Shallow fining zone (H < 0.5 m) with extra heating (1400-1525 ^oC, > 1 hour depending on H and $T-T_{onset}$)
  - sufficient time > fining onset temperature for all melt trajectories
- Slow cooling of melt between 1400-1250 ^oC (secondary fining)

Energy & NOx

CFD modeling of melt & combustion

Classical Design → Energy Efficiency & primary NOx emission reduction are main targets

Characteristics

- End-port fired
- Spacy regenerators $\eta = 70\ \%$
- Spacy combustion chamber
- Specific pull: 3 - 4 tons/$m^2 \cdot$day
- Batch preheating
- Insulated bottom & crown (< 2 kW/m^2)
- Sidewalls average loss < 4 kW/m^2

Disadvantage:

- Wide residence time distribution
- Relatively high structural losses

Important TOOL: **GLASS FURNACE MODELING:** Results of **CFD simulation models**

- Temperatures at all possible positions
  - Combustion space
  - Glass melt
  - Refractory
- Glass melt and Combustion gas velocities
- Trajectories (particle tracing) in tank
  - Thousands of different paths from charging end to throat or spout
- Redox and dissolved gases
  - Redox state of melt at each position (pO_2 or Fe^{2+}/Fe^{3+})
- Residence time distribution
  - Minimum residence time is of importance for melting process
- Glass melt quality indices per trajectory
  - Trajectory with minimum melting or fining index is decisive for glass

Application of CFD models

- For furnace design (lowest energy, highest glass quality)
  - Optimum depth of tank
  - Position bubblers or dam or burners
  - Size and design of throat
  - Design combustion chamber (LOwNOx, less evaporation)
- For optimum process settings
  - Optimum fuel-boosting ratio
  - Temperature profile (energy distribution) & Bubbling rate
  - Creation of distinct spring zone to avoid short cut
- Time-transient (time dependent) for colour or pull change
  - Optimize colour change process: reduce transition time
- Time-transient for process control (r-MPC)
  - Sensors give model continuous new information: model tracking
  - Model continuously gives recommendation for input parameter changes to follow optimum process path (low energy, high glass quality, constant T)

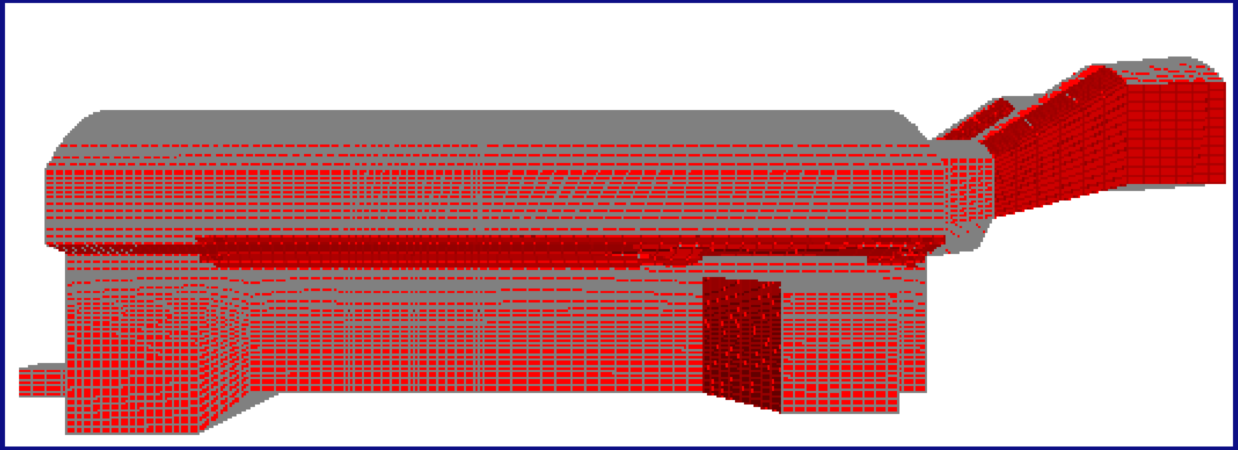
CFD Models

- Start with basic concept
  - Type of furnace
  - Combustion chamber & burner port features
  - Boosting, bubbling, weirs, deep refiner
  - Type of doghouse construction

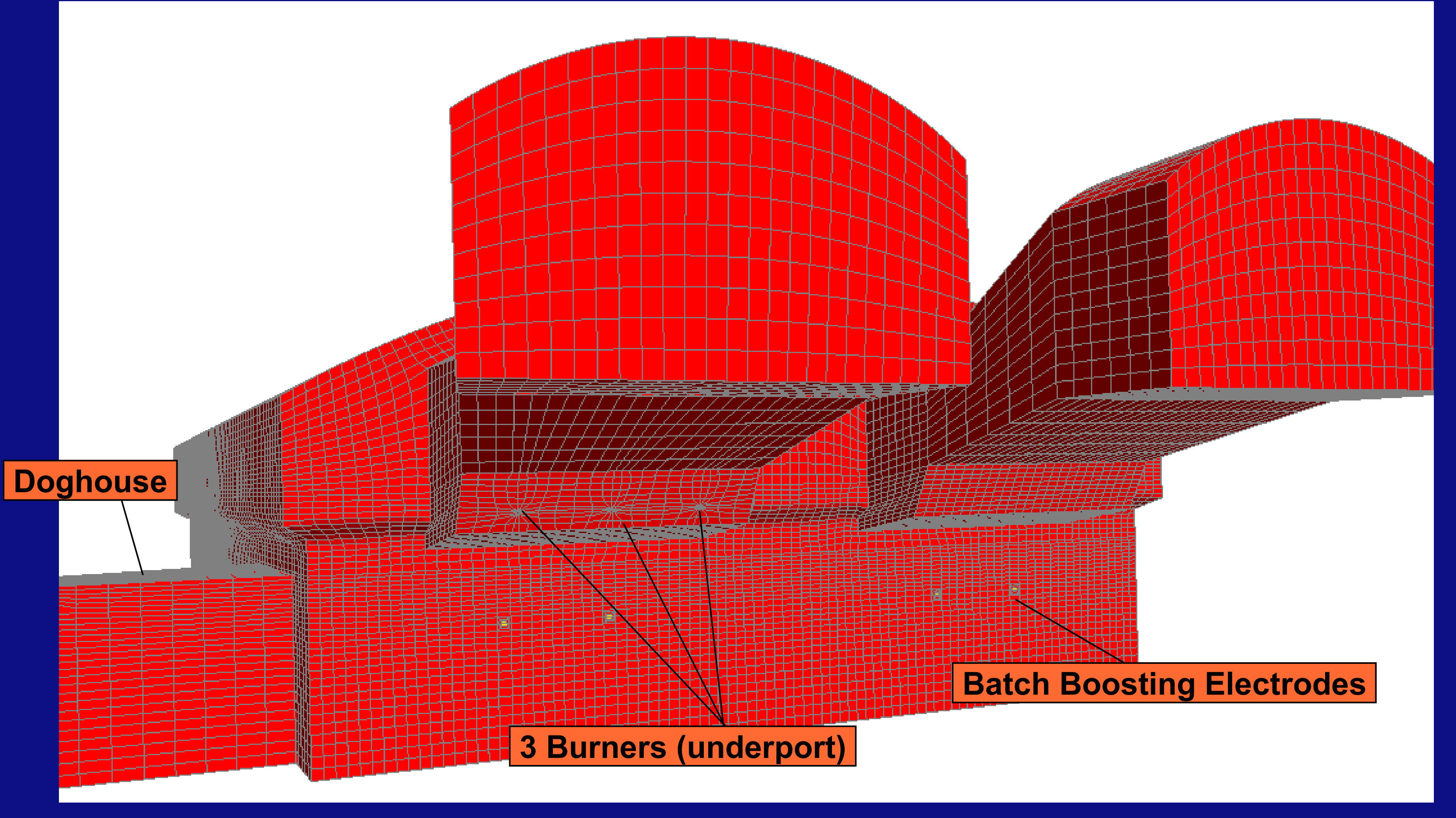
- Optimize design by CFD and determine glass quality and energy efficiency by CFD model
  parameters:
  - Effect of glass tank depth
  - Throat design
  - Positions bubblers & electrodes
  - Heating profile
  - Length – width ratio
  - Dimensions weir/dam or fining shelf
  - Number and positions of burners
  - Burner port angle and burner port dimensions

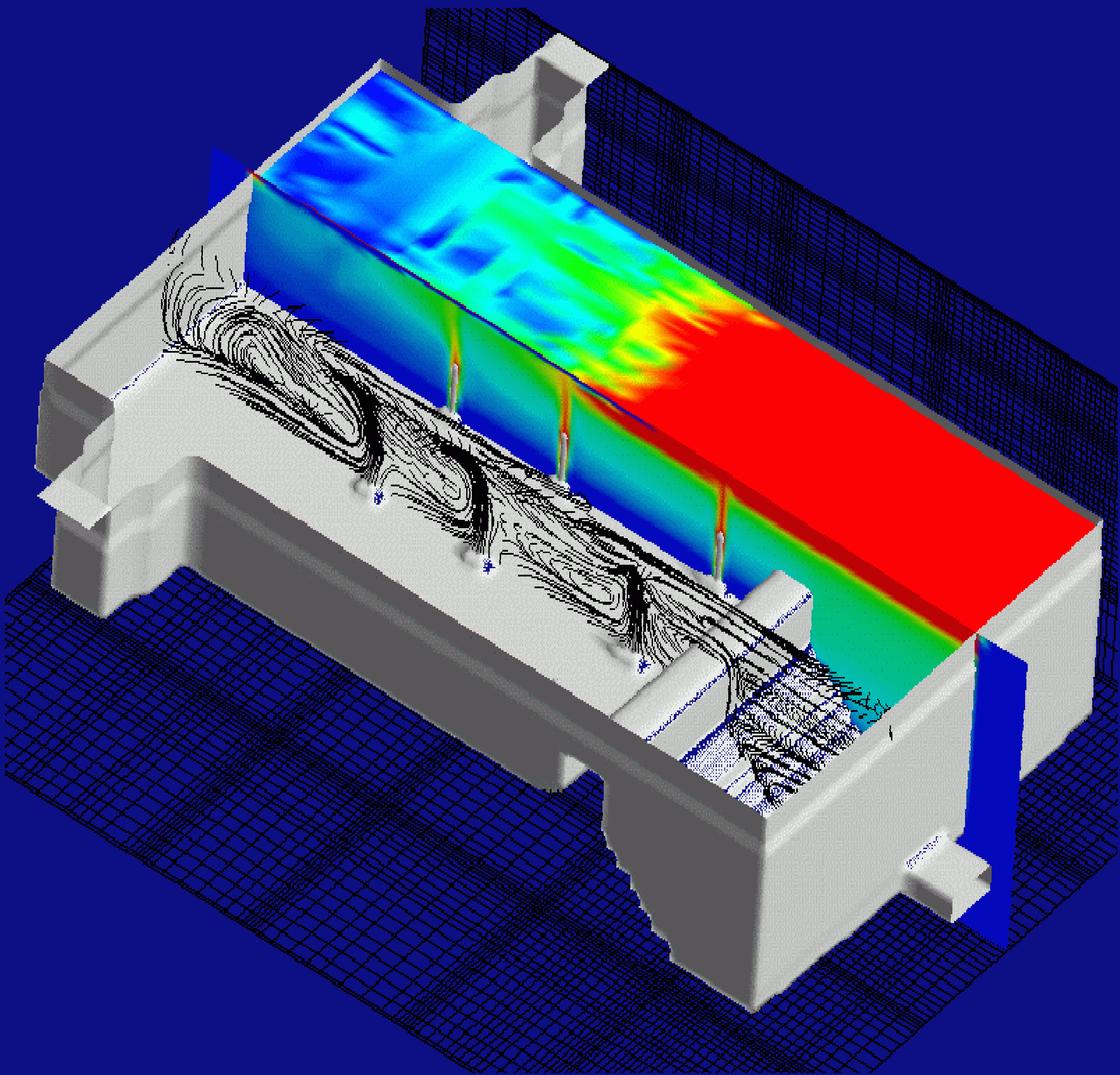
Design, Operation & CFD Models

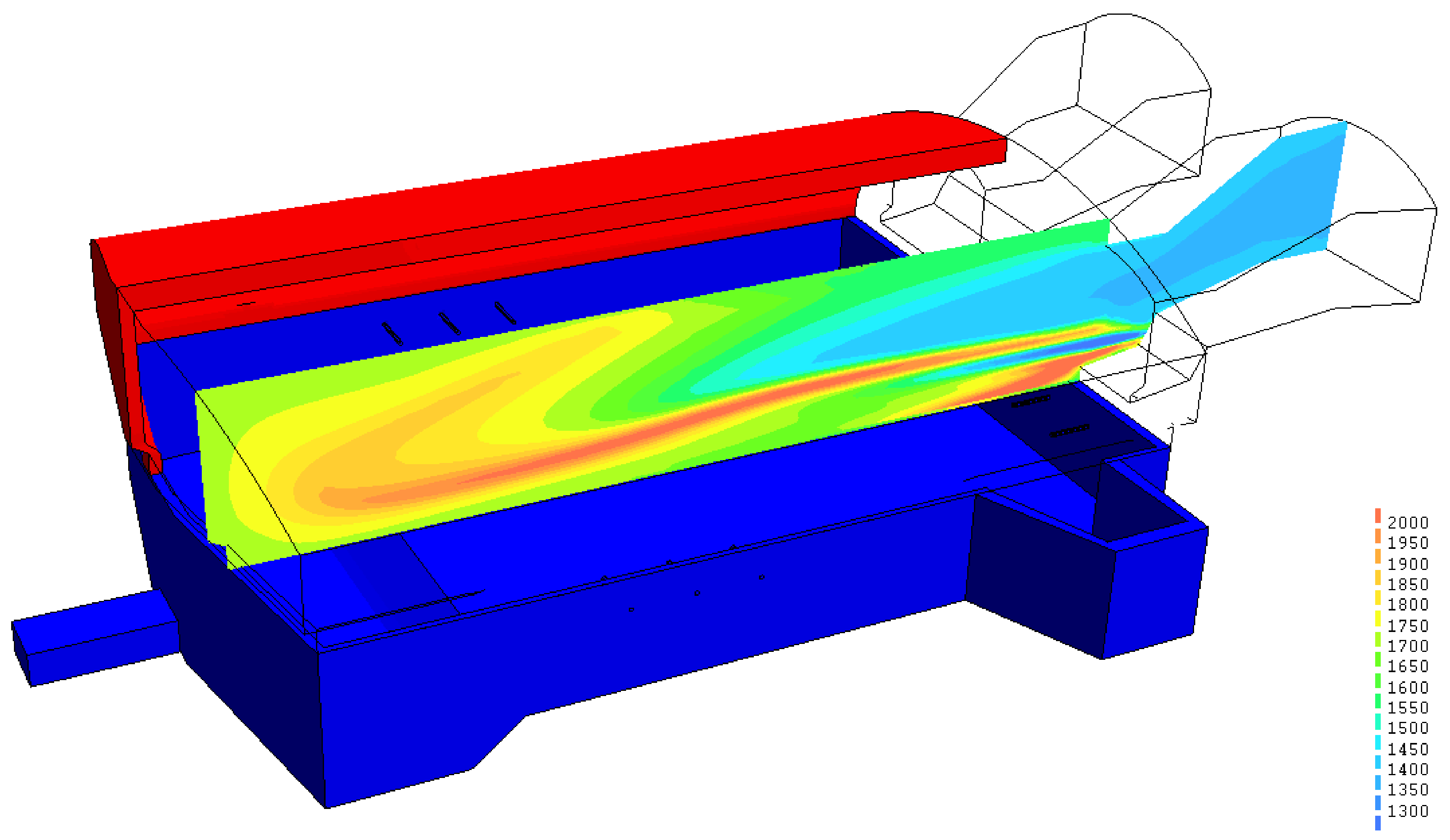
- Optimize glass melt flow pattern
- Optimize heat transfer and heat transfer distribution
- Avoid short cut flows along melter bottom
- Design combustion chambers & burner ports
  - Slow mixing of fuel (gas) and air (or oxygen)
  - Create soot flames (improved heat transfer and low NOx)
  - Avoid post-combustion in ports/regenerators
  - Avoid excessive wall temperatures in superstructure



Geometry & Grid



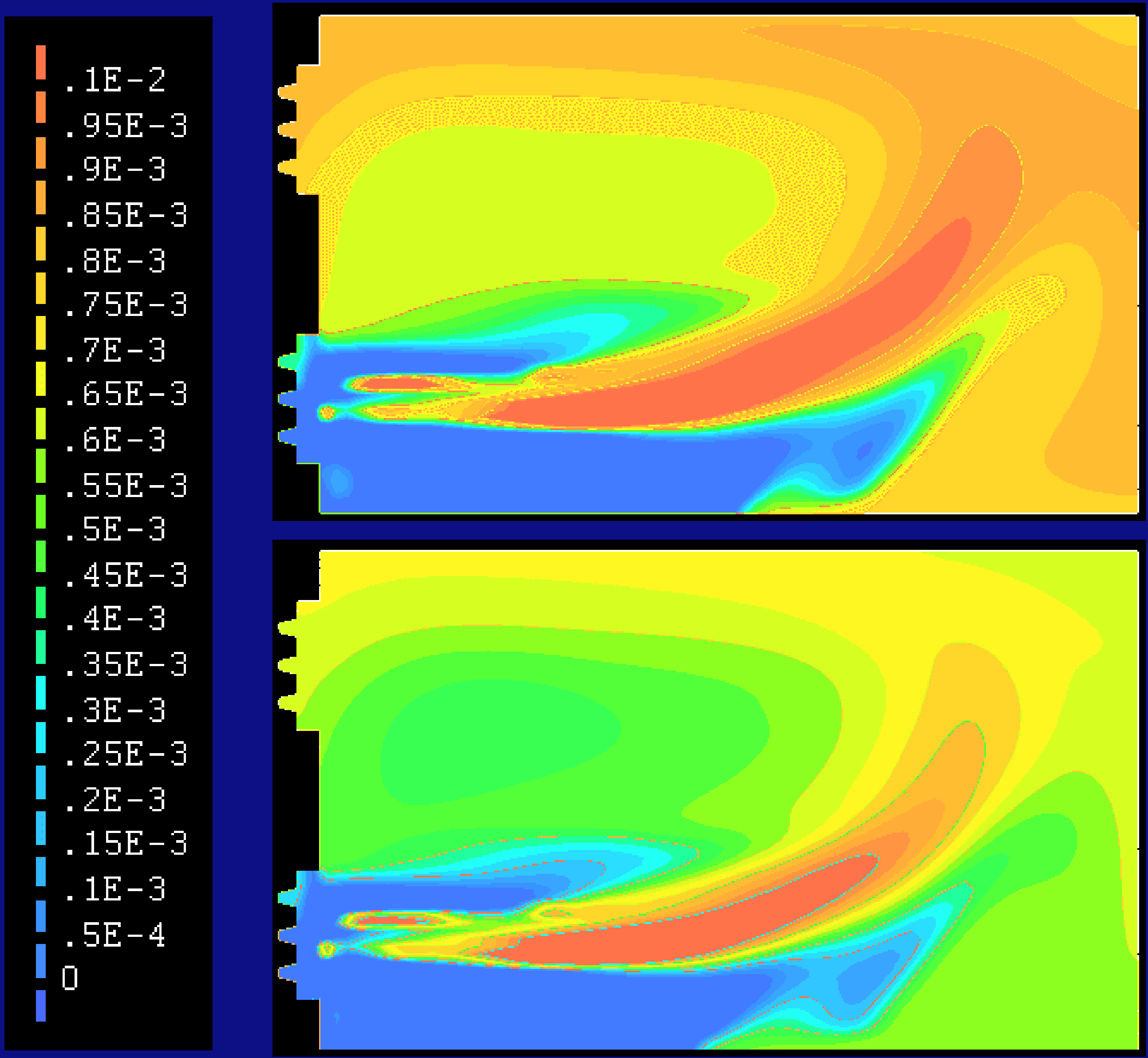




Temperatures in combustion chamber (scaling in ^{o}C)

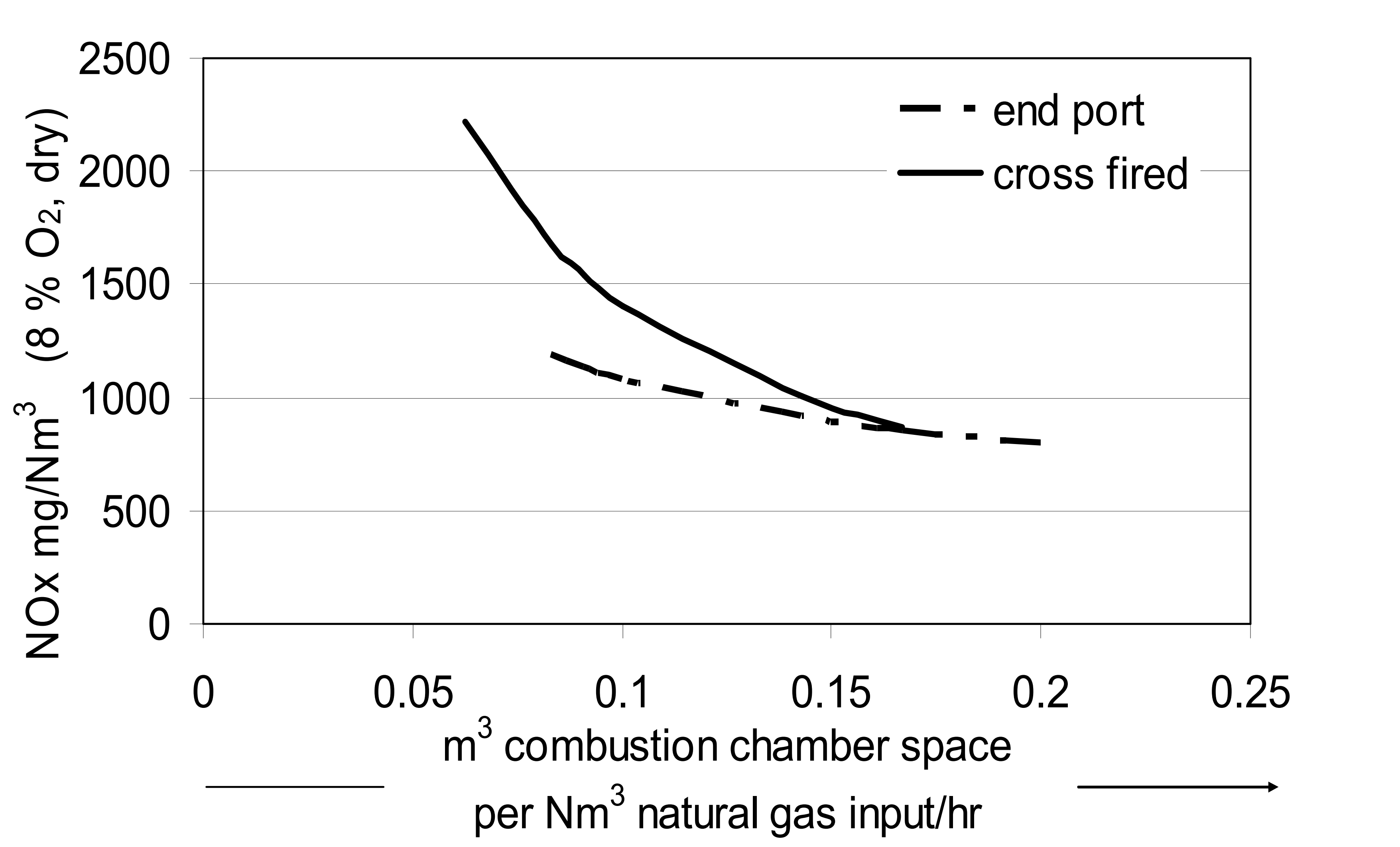
NOx

End-port fired furnace horizontal cross section at level of burners



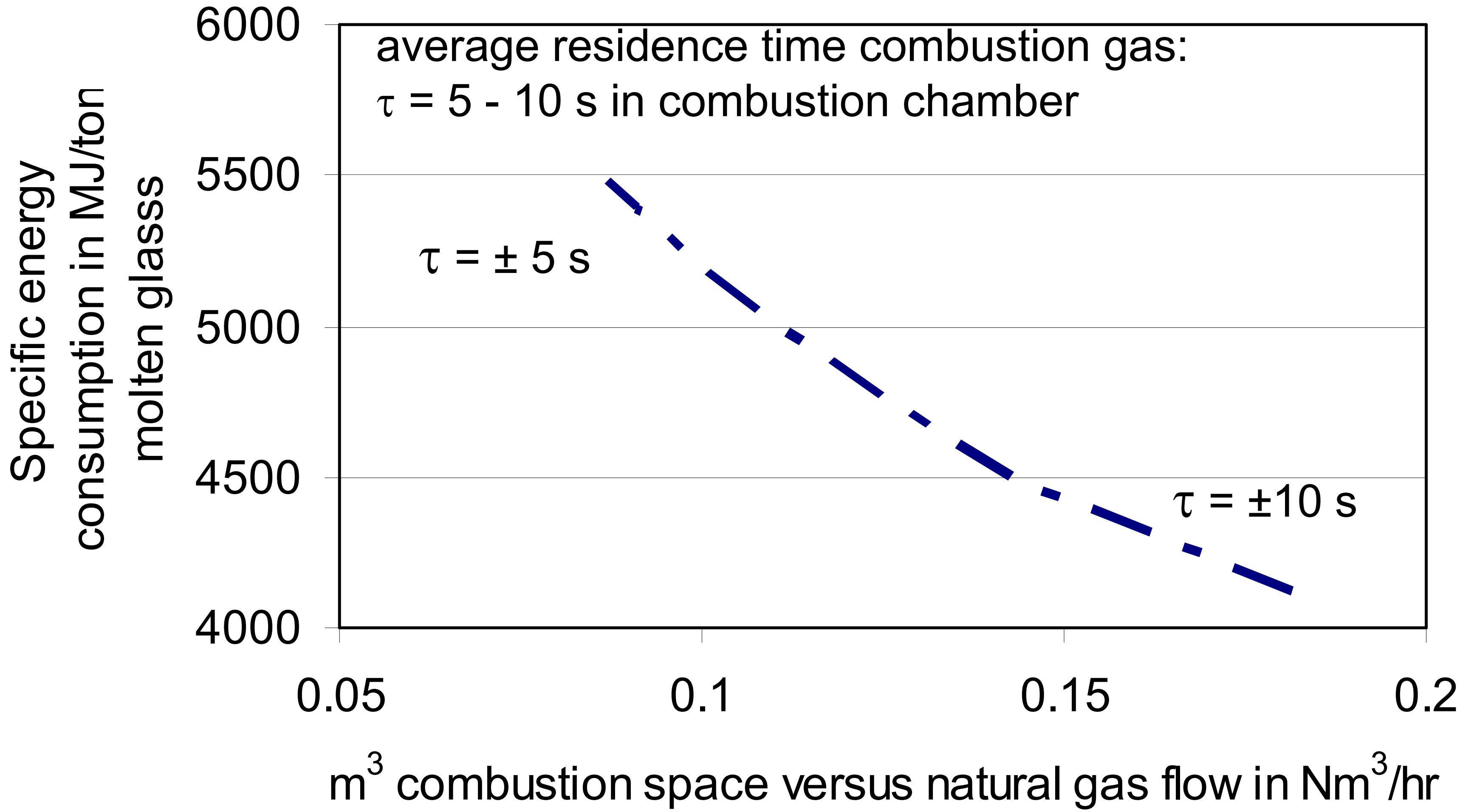
Base case

4 inch higher crown

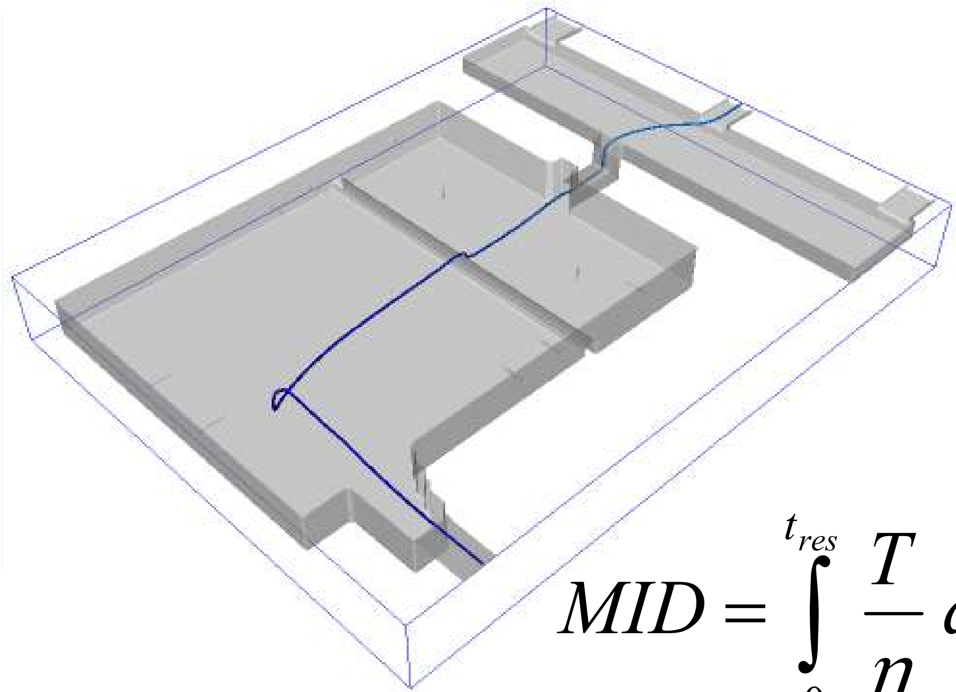


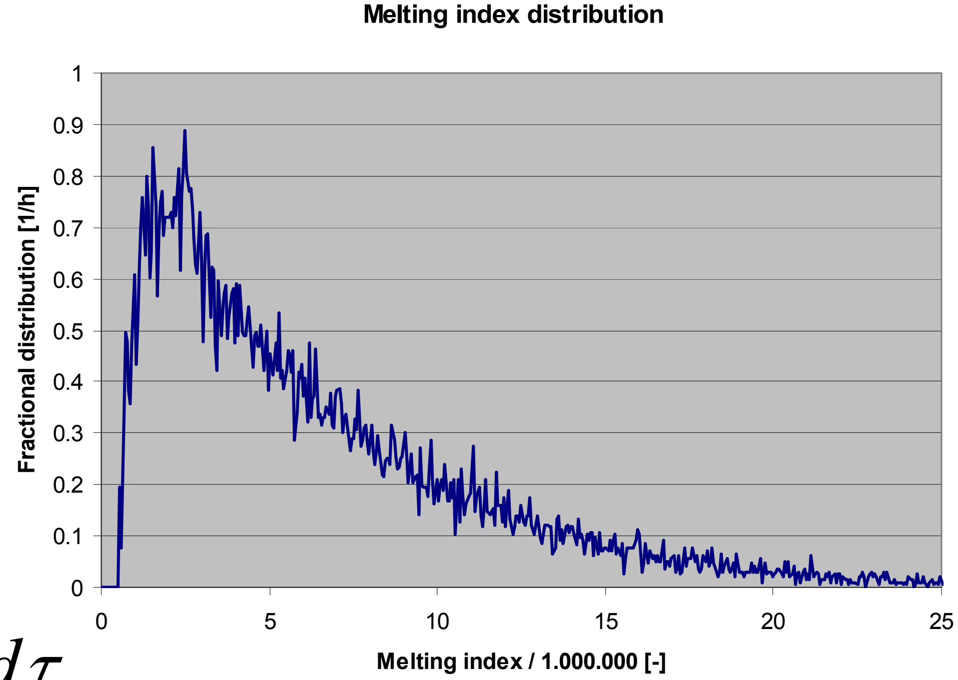
NOx emission levels depending on relative size of combustion chamber

Found (rough) correlation between specific energy consumption container glass furnace and relative combustion space volume

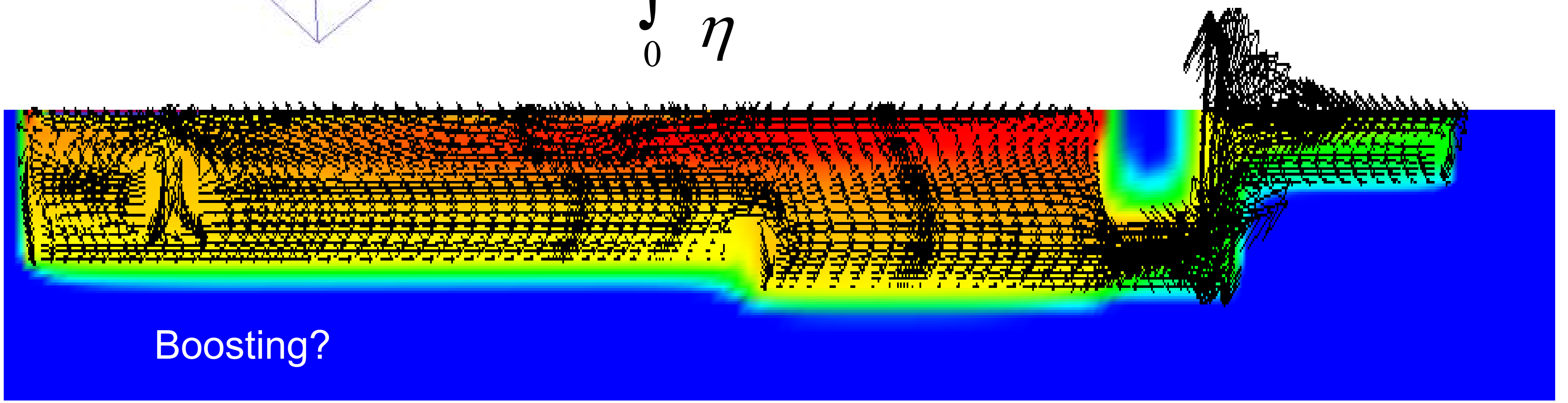


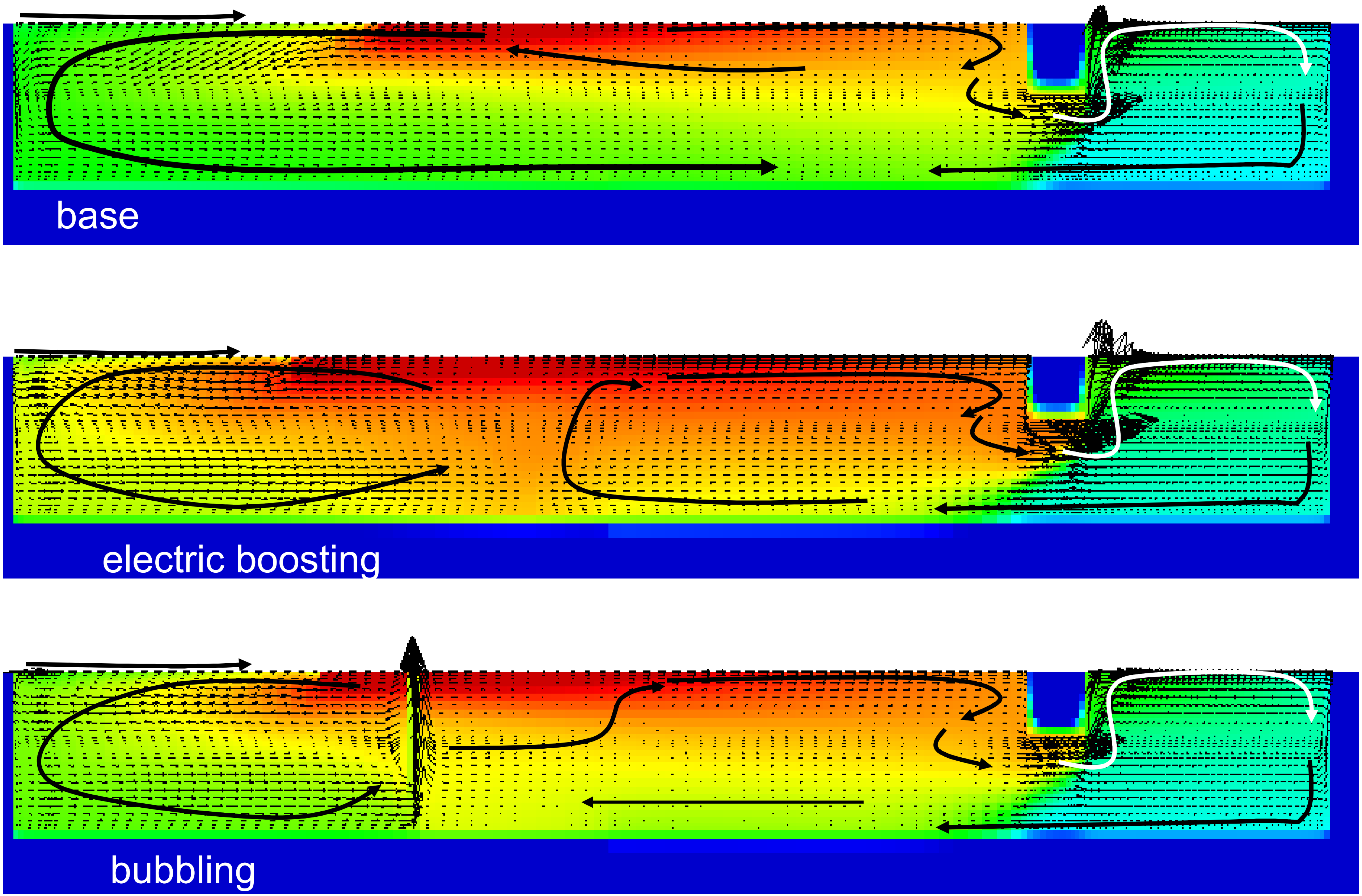
Particle path for minimum melting index



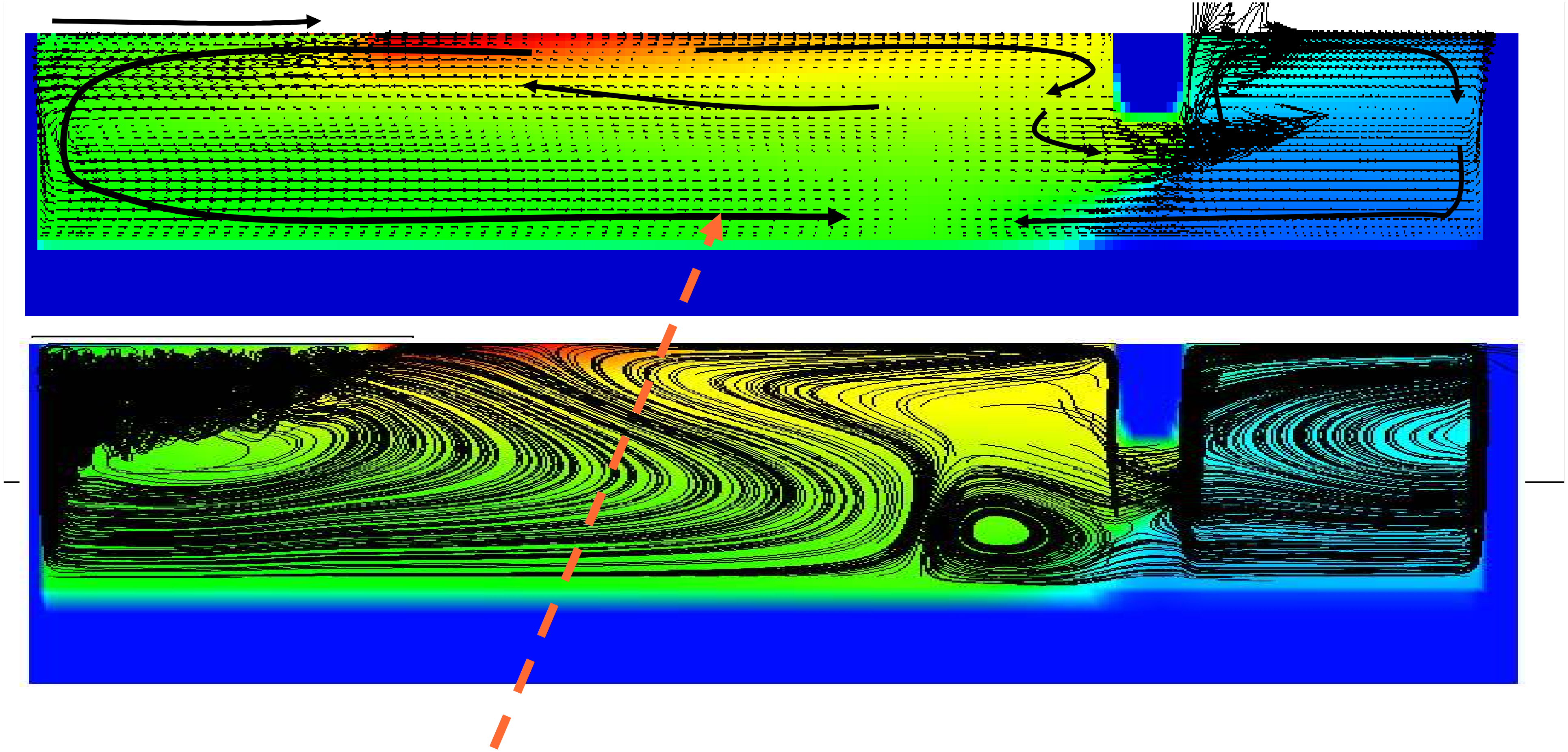


$$MID = \int_0^{t_{res}} \frac{T}{\eta} \, d\tau$$




base
electric boosting
bubbling

Characteristic flow and temperatures:



Tendency for short cut flow!

Efficient glass melting

- High glass quality (requirement depends on glass type)
  - Homogeneity
  - No bubbles
  - No inclusions
  - Color
  - High space utilization (limit recirculation)

- Furnace lifetime
- Low energy consumption
- Low emissions
- Flexibility, short transition times

Design & Operation for Conventional Glass Furnaces

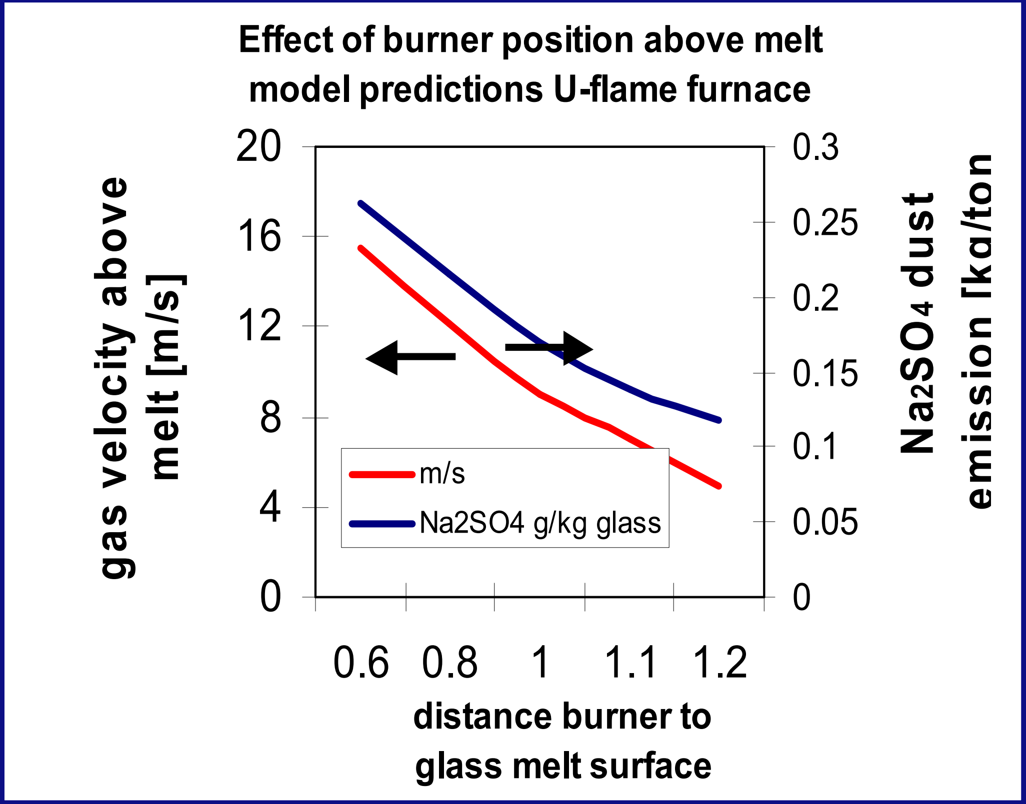
Recommended design considerations
conventional glass furnaces

- **Carry-over:**
  - Use extended doghouse with open radiation to incoming batch
  - Avoid gas velocities just above non-sintered loose batch > 6 m/s
  - Avoid very fine raw materials
  - Especially for end-port fired furnaces & batch preheating: special doghouse constructions are necessary

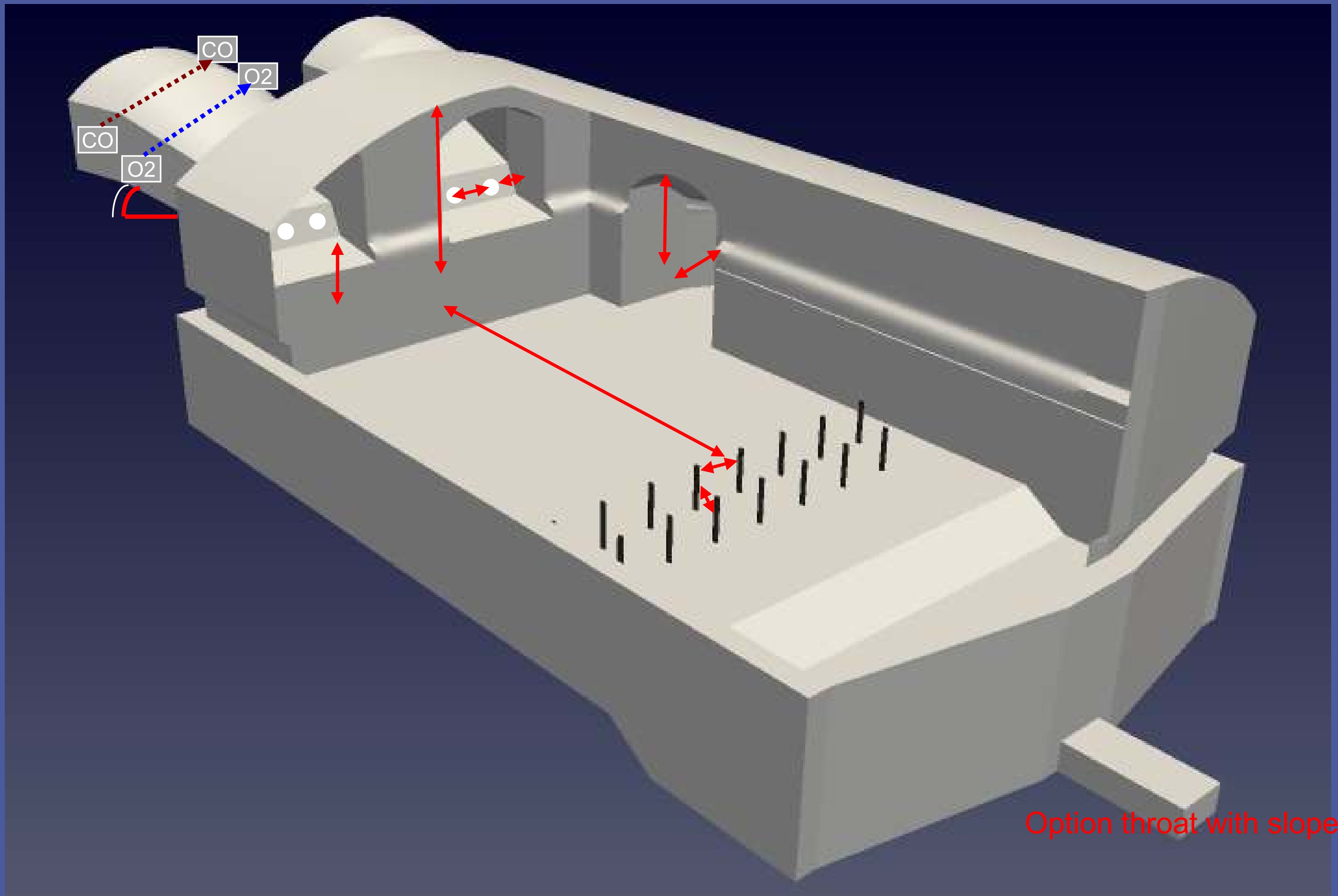
Particulate (dust) emissions

Dust emissions will increase:

- Reducing flames may increase evaporation and dust emission > 50 %
- 2 x higher gas velocity gives 70 % more dust
- 50 °C higher surface T melt: gives 50 % more particulate emission
- Water vapour increases evaporation rate of Na, K, Boron



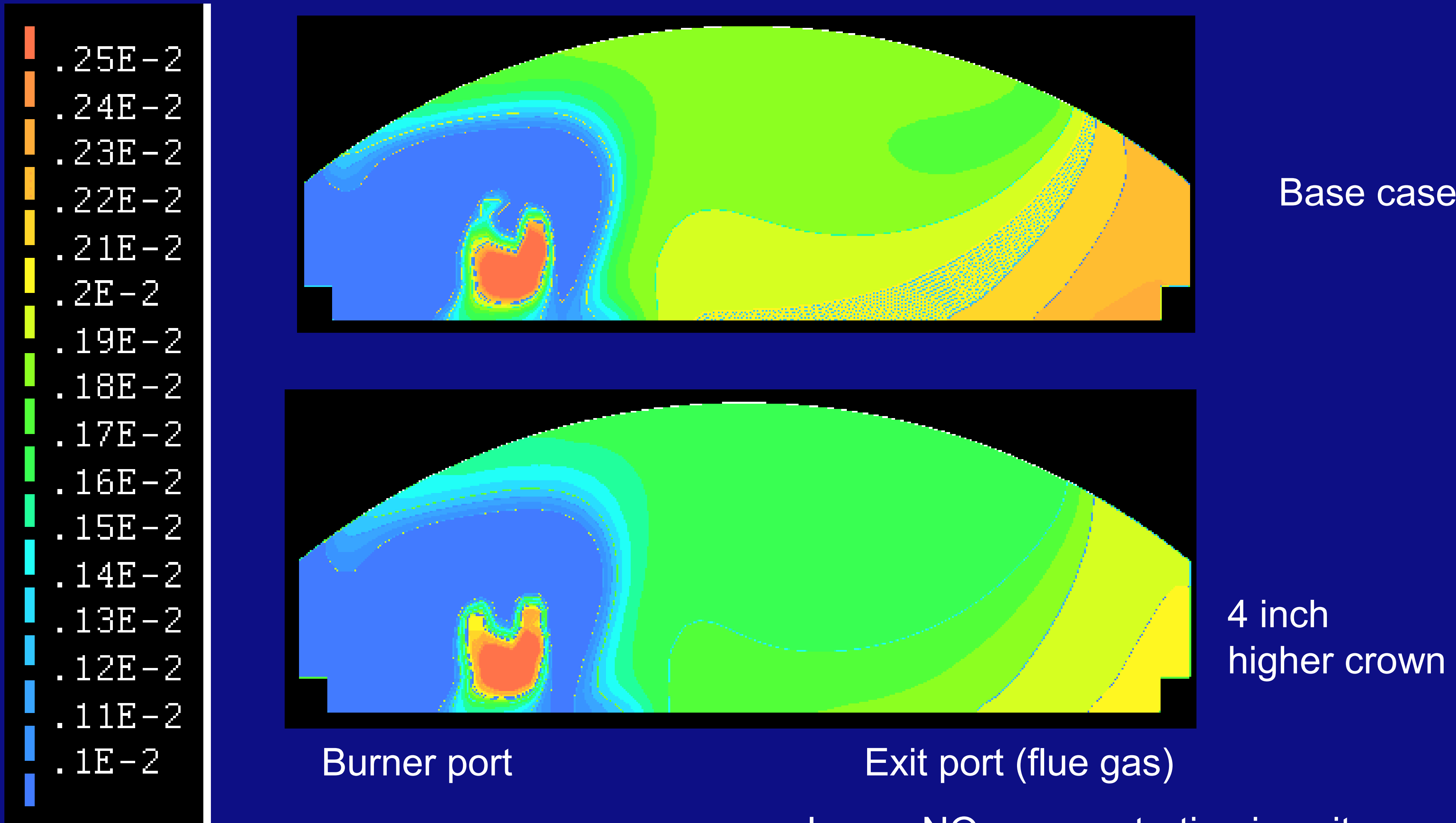
Important dimensions !



NOx

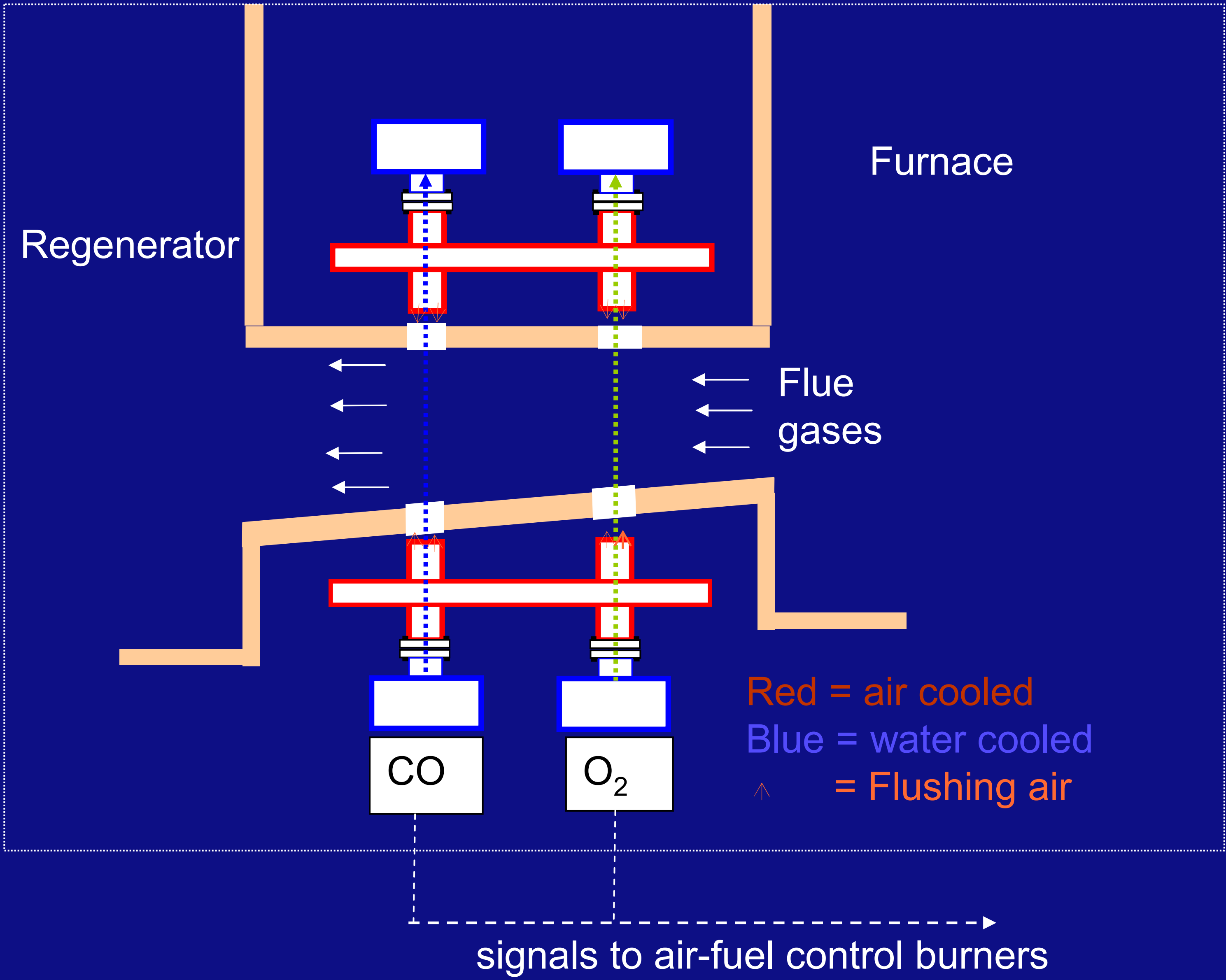
End-port fired furnace vertical cross section at 25 % from furnace length from port

NOx scaling in mole fraction



Lower NOx-concentration in exit

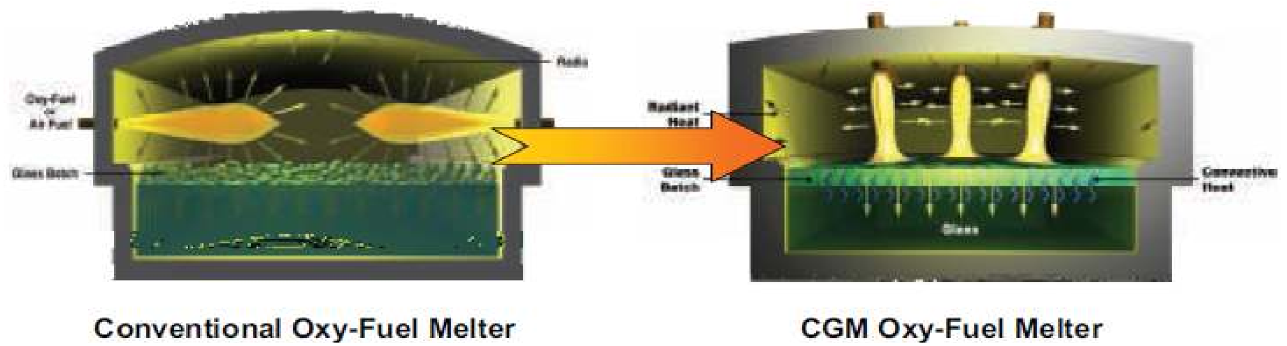
Installation of CO and O_2 sensors (laser absorption) in hot exhaust gas of glass furnace



Recommended design considerations conventional glass furnaces

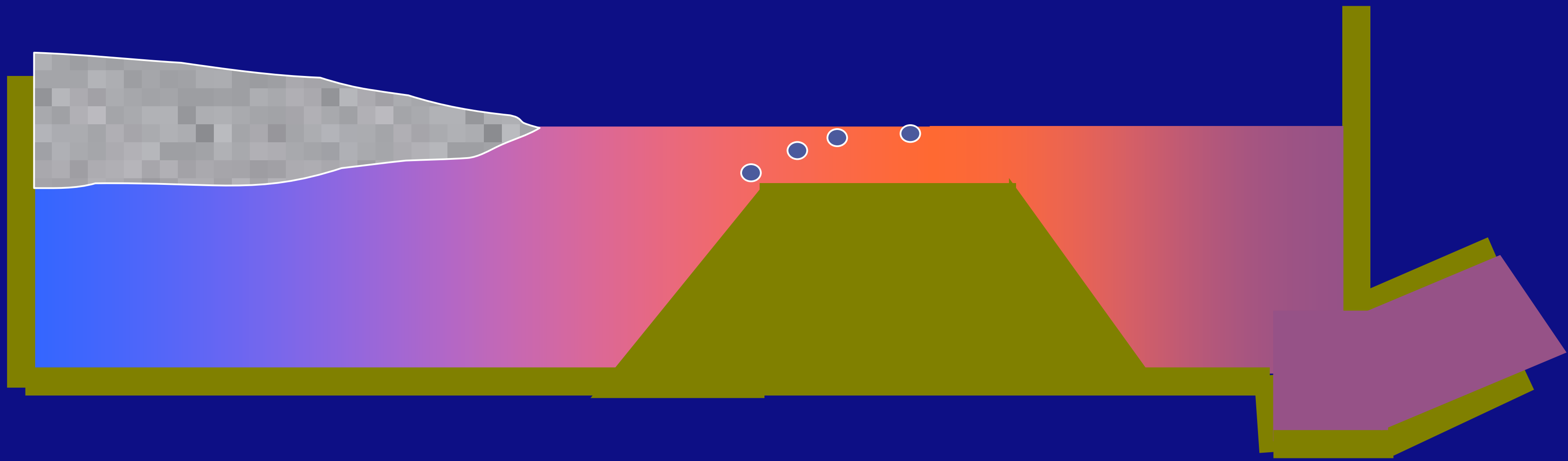
- **Glass melting tank**
  - Use CFD models to optimize Length-Width-Depth of tank
  - Depth of melt depending on glass color
  - Use CFD models to optimize position of bubbling zone, weir and barrier or batch boosting
  - Use modern barrier boost designs in case of boosting
  - Keep well distributed batch over full width of melting tank
  - Improve heating flux to melting batch
  - Consider fining shelf

BOC

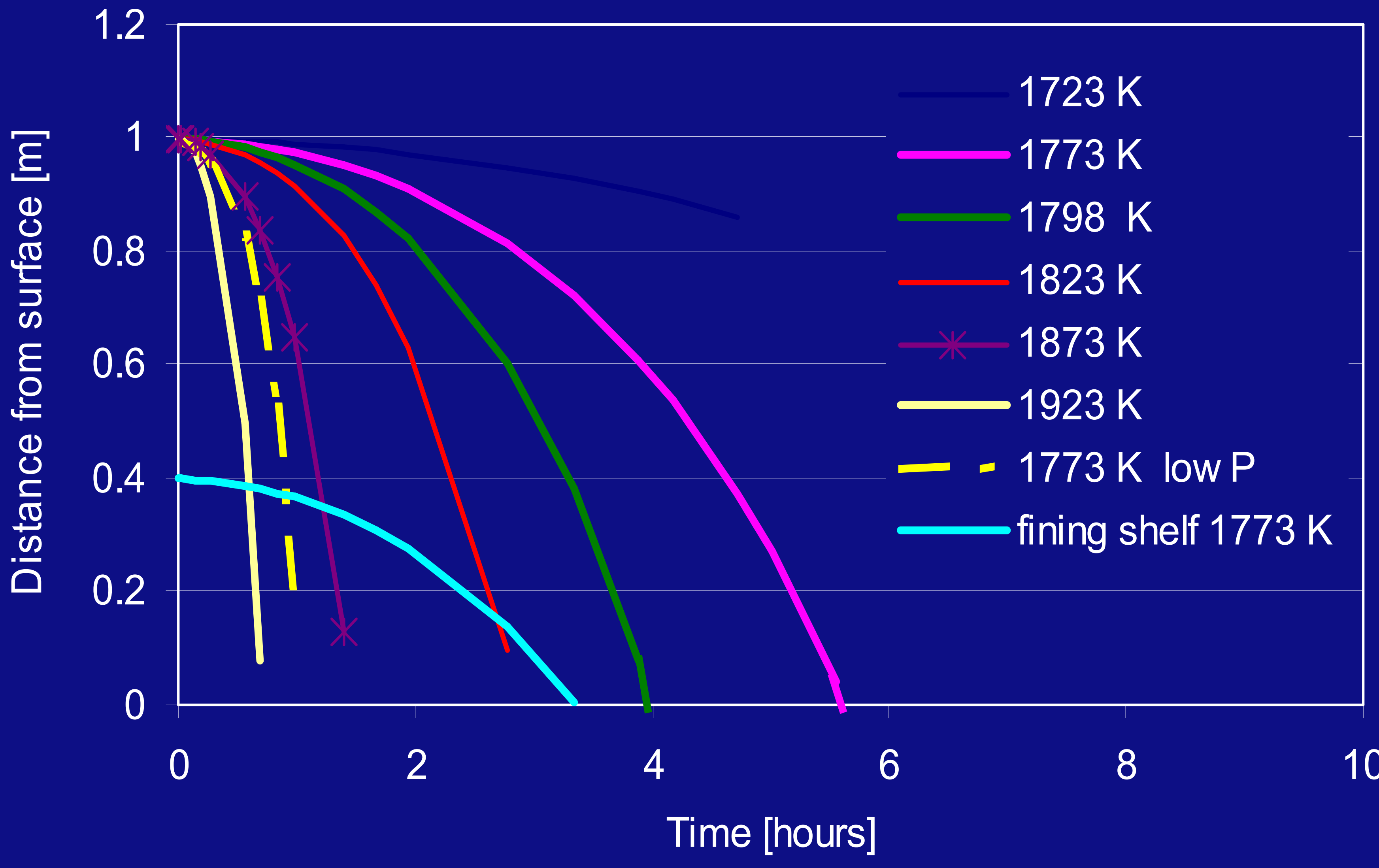


Application of “top” burners CGM for high pulled furnaces

Principle fining shelf



Distance from surface during sulfate fining in flint glass melt: seed starts at 1 meter depth

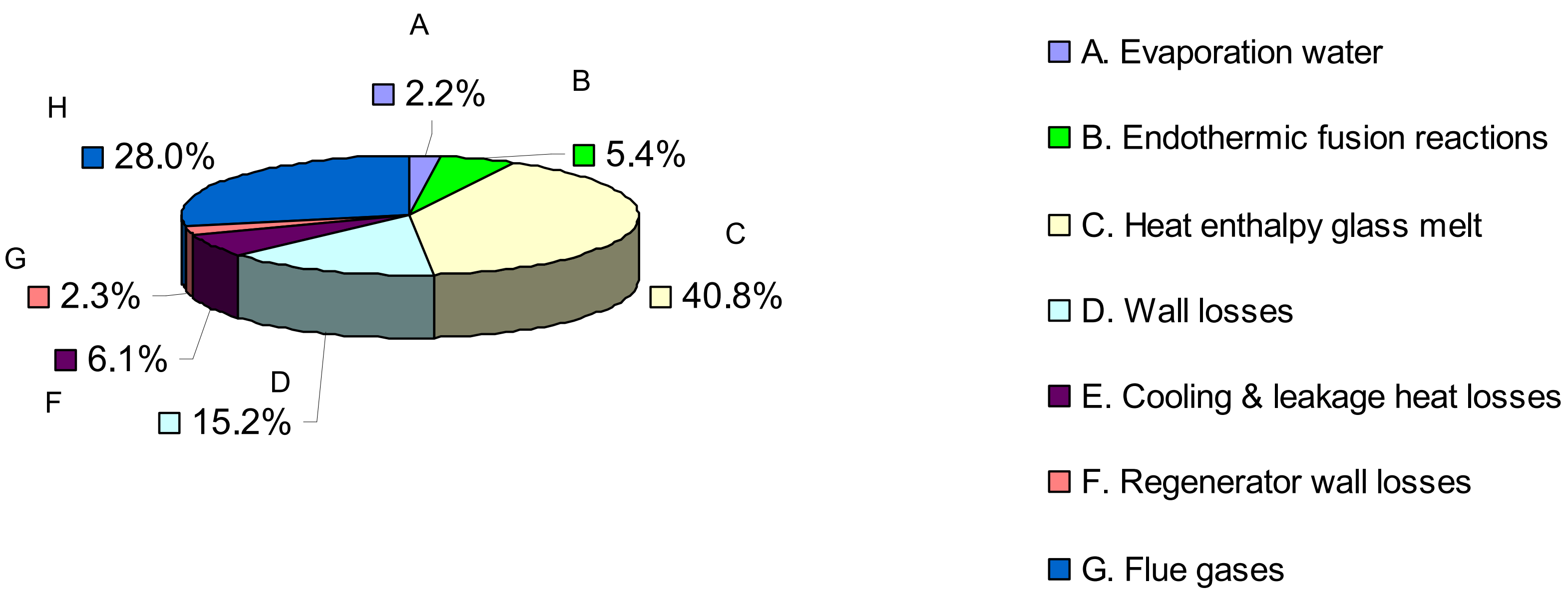


Fining shelf: 40 % reduced fining time or 35 ^{o}C lower fining T

Recommended design considerations **conventional** glass furnaces

- **Glass melting tank**
  - Optimize flow patterns in melt
    - Avoid glass melt bottom flow towards throat
    - Avoid too short residence times
    - Avoid static (dead water) zones → cat scratches
    - Optimize “space utilization”
    - Use CFD modeling to optimize:
      - Flow patterns
      - Heat transfer
      - Position Spring zone & Hot Spot
      - Barrier Boost system
      - Temperatures & Residence times (e.g. above fining onset)
    - Avoid too small weirs!
    - Avoid short distances between bubbles & AZS weirs
    - Optimize throat design (sloped throat) to avoid **upward drilling**
    - Design throat to enable interim repairs
    - Focus on doghouse design & batch charging (keep short blankets)

Energy flows modern end-port fired container glass furnace
40% cullet 320 tons melt/day   4.20 MJ/kg melt



Measures	320 tons glass melt/day	
Estimated savings	MJ/ton	% savings
Base case	4.192	0
Batch humidity 3.5 → 2 %	4.08	2.7
Emissivity flames 0.18 → 0.25	4.13	1.4
20 % better insulation	3.98	5.2
Batch preheating 300 ^{o}C ●	3.43	18
Air excess 10 % → 5 %	4.15	1
Cullet 40 → 75 % ●	3.81	9
Crown 10 % higher	4.22	-0.6
Regenerator 63 → 68 %	3.991	4.8
Throat temperature 1325 → 1300 ^{o}C	4.105	2
No cold air infiltration -500 Nm^3/hr	4.12	1.7

Table Energy Saving Potentials for Modern End-Port Fired Regenerative Container Glass Furnace (moderate boosting 1000 kW) - gas firing

Considerations new (advanced) furnace designs

Statement

- Most glass furnaces produce a ‘range’ of glass qualities (small glass melt packages with different melting history) because of different trajectories from inlet to outlet in the tank

- It is important to improve control of these trajectories or to develop furnaces with distinct trajectories **to avoid**:
  - glass ‘packages’ with low melting temperature history
  - glass ‘packages’ with low residence time in the furnace
  - glass ‘packages’ that remain very long in the furnace

This will cost extra energy and pull

  - glass ‘packages’ that stay in dead water zones
    - glass ‘packages’ that are contaminated

Optimum flow conditions glass melt tank

- High ratio **minimum** versus **average residence time** of glass in tank: ‘good use of tank volume’ (space utilization)

- Design of throat
  - Compromise between glass quality & energy efficiency & throat lifetime
    - straight through throat (high): return flow from refiner
      - ➢ return flow blocks the forward bottom flow from the melter
    - narrow, shallow throat or submerged: hardly (cold) return flow

- All parts of melt should reach fining onset temperature
  - More important than residence time is **fining index**
  - Fining shelf will increase chance of bubble removal without need of excessive glass melt surface temperatures

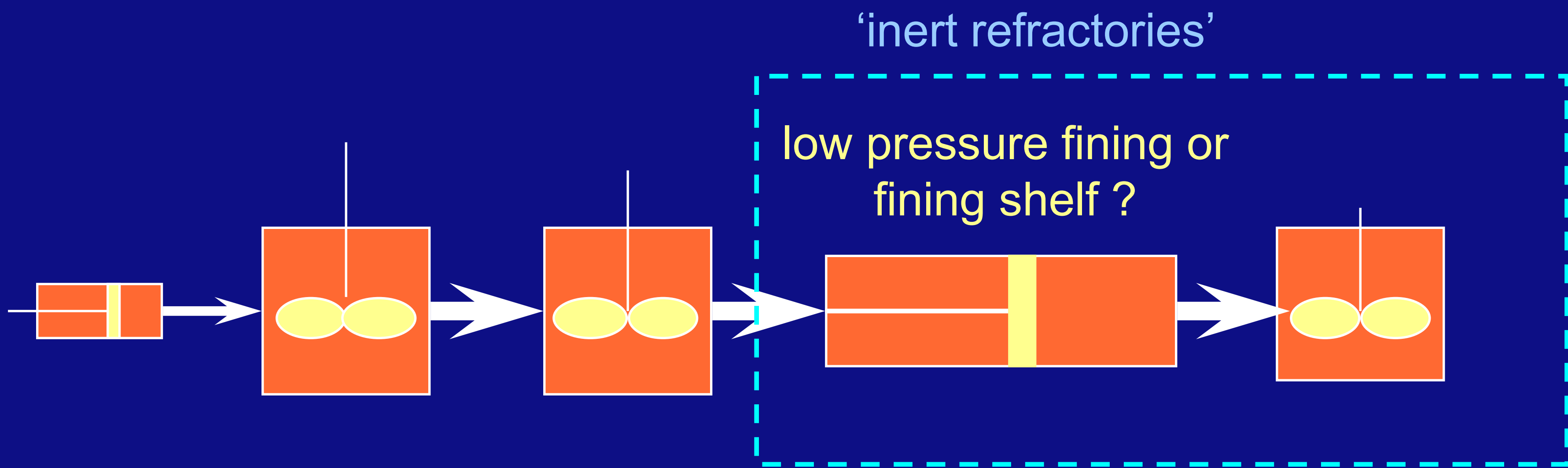
Instead of non-controlled stages of the melting process in one tank

- Segmented melter design
- Dedicated sections for different functionality
- No strong re-circulation patterns (this will increase energy costs & gives variety in glass quality)

Process steps

- Batch melting
- Sand grain dissolution
- Primary fining
- Secondary fining
- Homogenisation

Example ‘ideal situation for glass melting’



20-1200 °C batch blanket	1300-1350 °C melting	heating 1550 °C	1500-1600 °C fining	1350-1100 °C refining & conditioning
0.75 hour	0.75 hours	1 hours	1- 2 hours	1.5 -2 hours

Selection of refractory per zone

Glass melter – **segments** for:

- Batch melting (average residence time 1-1.5 hours):
  - Thin layer (< 0.05 m)
  - or Very strong convection (small batch piles)
  - Compacted batch (intense grain contact and fast heat conduction)
  - 0-800 ^{o}C takes 2x longer than 800-1300 ^{o}C: batch preheating helps!
- Sand grain dissolution (average residence time 1.5 hours)
  - Strong convection: stirring or bubbling
  - 1200 < T < 1350 ^{o}C
  - Narrow sand grain distribution 80-250 microns
- Fining (primary), average residence time 2-2.5 hours
  - Glass level < 0.3-0.4 meter
  - Bottom fining shelf > 1400-1450 ^{o}C
  - Surface melt < 1500 ^{o}C *(to limit evaporation)
  - Residence time about 2 hours (fining zone: 50-75 m^2 for 500 TPD)
  - Preconditioning of melt by helium bubbling (< 1350 ^{o}C)
  - Shallow atmosphere of helium (or <<1 bar) above melt in fining zone
- Refining/ Conditioning (1325-1275 ^{o}C: 1 hour)

Example “segmented furnace & fining shelf”

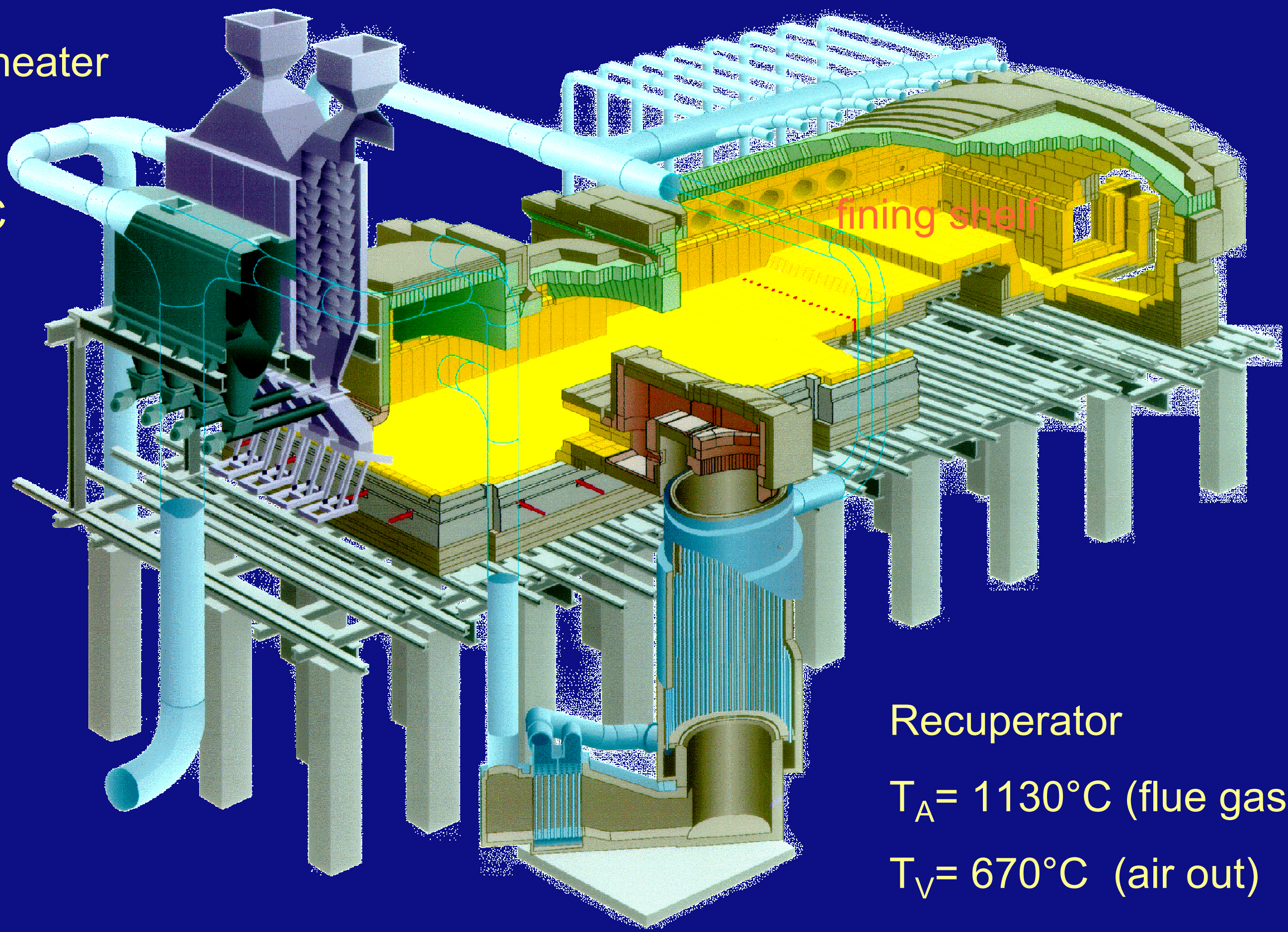
SORG

Cullet pre-heater connected to Recuperative Container Glass Furnace

Cullet preheater

T_E=20°C

T_A= 280°C



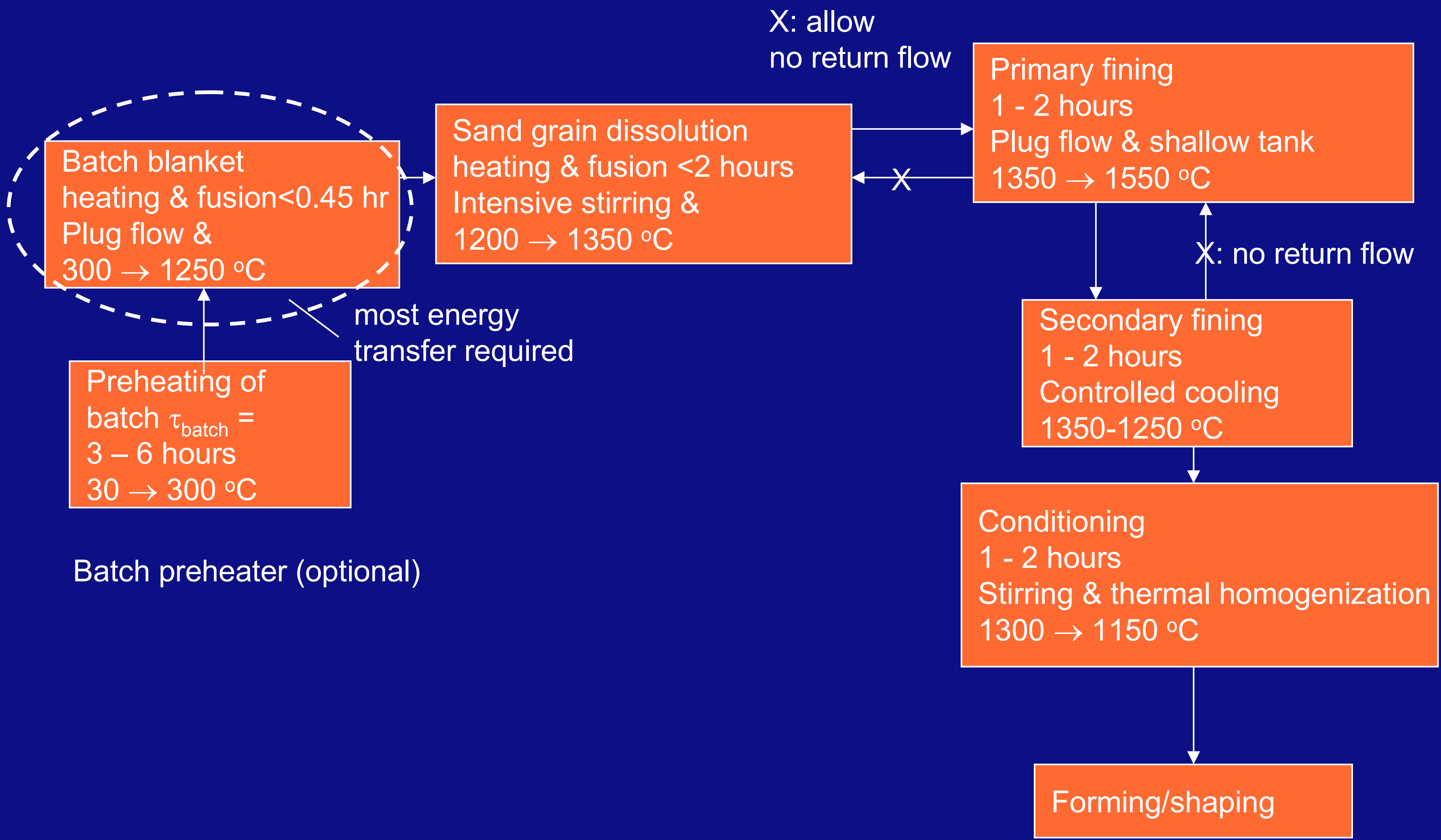
Recuperator

T_A= 1130°C (flue gas in)

T_V= 670°C (air out)

Typical aspects of industrial melting Soda-Lime-Silica Glass

	T interval °C	Time in hours	Conditions
Batch heating	30-1300 °C	1	Thin layer, creation of batch tips
Sand grain dissolution	1100-1350 °C	2	**Strong convection**, aggressive melt, avoid too high temperatures (> 1350 °C)
Primary fining (sulfate)	1350-1550 °C	1.5 to 3	**No recirculation**, high temperatures, redox control and sufficient fining agent
Homogenisation	1200-1550 °C		Stirring, bubbling avoid glass melt with recent refractory or glass surface contact in throat or canal
Secondary fining	1350-1250 °C	0.75 to 2	Slow cooling of melt
Refractory protection	Silica > 1400 °C (air firing) & Silica > 1480 °C (oxygen firing) tank walls: cooling avoid strong convection		No aggressive melts or NaOH vapou
Limit evaporation	> 1400 °C strong evaporation		Avoid: High glass melt surface temperatures, high CO and H_2O contents combustion chamber, high gas velocities above melt
Limit foam formation			Control of redox, avoid excess fining


X: allow
no return flow
Batch blanket
heating & fusion<0.45 hr
Plug flow &
300 → 1250 °C
Sand grain dissolution
heating & fusion <2 hours
Intensive stirring &
1200 → 1350 °C
X
Primary fining
1 - 2 hours
Plug flow & shallow tank
1350 → 1550 °C
X: no return flow
most energy
transfer required
Preheating of
batch τbatch =
3 – 6 hours
30 → 300 °C
Secondary fining
1 - 2 hours
Controlled cooling
1350-1250 °C
Conditioning
1 - 2 hours
Stirring & thermal homogenization
1300 → 1150 °C
Batch preheater (optional)
Forming/shaping

New elements in furnace designs

- Revolution
  - Segmented (compact) melters
  - Physical fining techniques
  - Limited number of trajectories in furnace
  - New heating techniques for batch blanket & fining zone

- Evolution:
  - Fining shelfs (shallow areas in tank)
  - Increased combustion space sizes
  - Model based control & sensors (CO, redox melt/batch)
  - Improved refractory materials, especially downstream spring zone
  - Use of modelling for furnace design (tank, throat, electrodes, bubbling, barriers/fining shelfs, combustion chamber)

Conclusions

- Most glass melting tanks show very wide residence time distribution
  - **Average** versus **minimum RTD**: 0.15-0.2
  - Ratio $RTD_{av}/RTD_{min} \rightarrow 0.4$: Furnace volume reduction (50 %): less capital costs
  - **But batch melting process has to be changed to realize this!!**
- Each process step requires its own conditions
  - Temperature level, chemistry, mixing conditions
  - Design per section & Control of these parameters **per section**
  - ➢ **Segmented melting unit** to be developed by aid of CFD models
- New furnace design with narrow RTD will improve:
  - Energy efficiency $\Rightarrow$ 15-20 % extra energy savings
  - Transition speed during glass change
- Conventional furnaces: Energy efficiency in glass furnaces can be improved by about 20 % on **<u>average</u>** for container glass furnaces

CelSian TNO

Glass & Solar