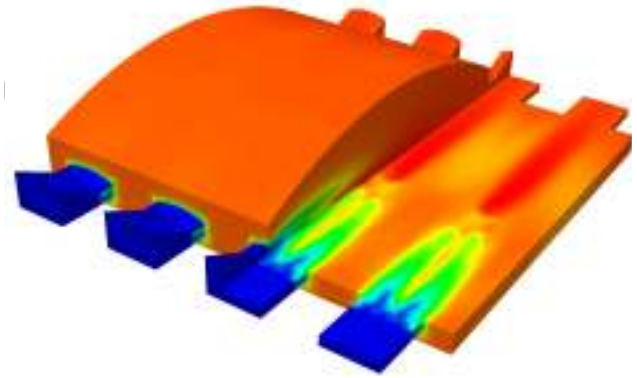
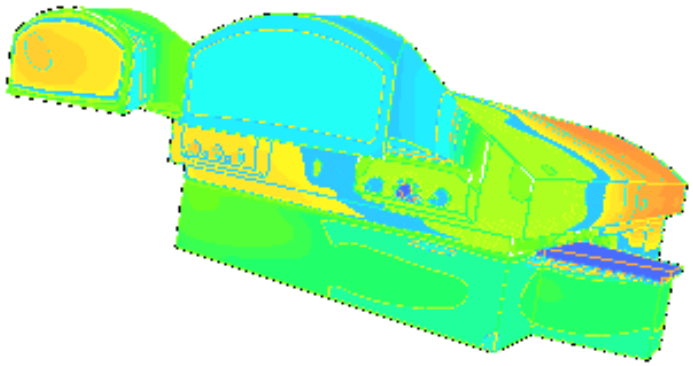
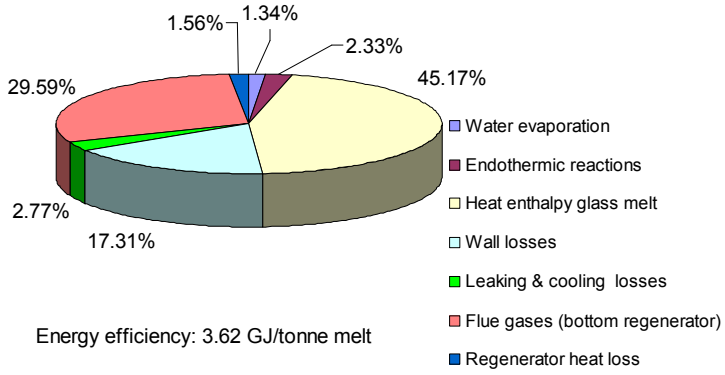






Energy efficiency: 3.62 GJ/tonne melt

TNO Glass Group 2011

Expertise

- Glass Melting Technology
- Process Simulations (experimental, thermodynamic, CFD) for process design & process operation
- Model Based Process Control of Glass Furnaces
- Sensor Development for High Temperature Processes
- Energy Efficiency & Emissions of Glass Production

TNO

Independent Research Organization

- Applied Scientific Research
- ±4500 Professionals
- Based in the Netherlands
- Co-operation with many EU universities

Main fields:

- Health Care & Life Sciences
- Maritime
- Buildings
- Earth Sciences
- Materials Science
- Energy & Environment
- Military R&D
- Industrial Innovation

Mission TNO Glass Group

- **Support glass industries & their suppliers, by**
  - Innovative solutions for energy efficient, environmental sound and high quality glass production
  - Applying fundamental R&D results in practice
  - Developing and teach glass technology training courses
  - Enhancing transfer of know-how
  - Use Multi-disciplinary approaches
  - Develop network to communicate
    - Glass industry – suppliers – academia – R&D institutes - government
  - Develop tools for improving glass productions
    - Simulation models
    - Measuring methods
    - Sensors
    - Process Control

Vision TNO Glass Group

Glass industries have access to economical feasible technologies to produce high quality glasses with

- High energy efficient processes
  (15 - 25 % energy reduction from 2005 to 2020-2030)
- Solution of environmental problems
- Closed raw materials chains (recycling)
- Optimum controlled production processes
- Highly educated & trained personnel

Target Groups/Customers

- **Glass Industries**
  - Float glass
  - Container glass
  - Fibre Glass
  - Special Glass
  - Tableware/domestic
- **Raw Material & Equipment Suppliers**
  - Raw materials: sand, soda, borax, …..
  - Refractory materials
  - Industrial gases
  - Furnaces
  - Air Pollution Control equipment
- **Solar industries**
- **Governmental Institutions**
  - National (USA, Netherlands, Germany, UK,…)
  - EU organizations

Glass melting

Solar

Modeling of processes

Process Control

Process innovation in glass industry

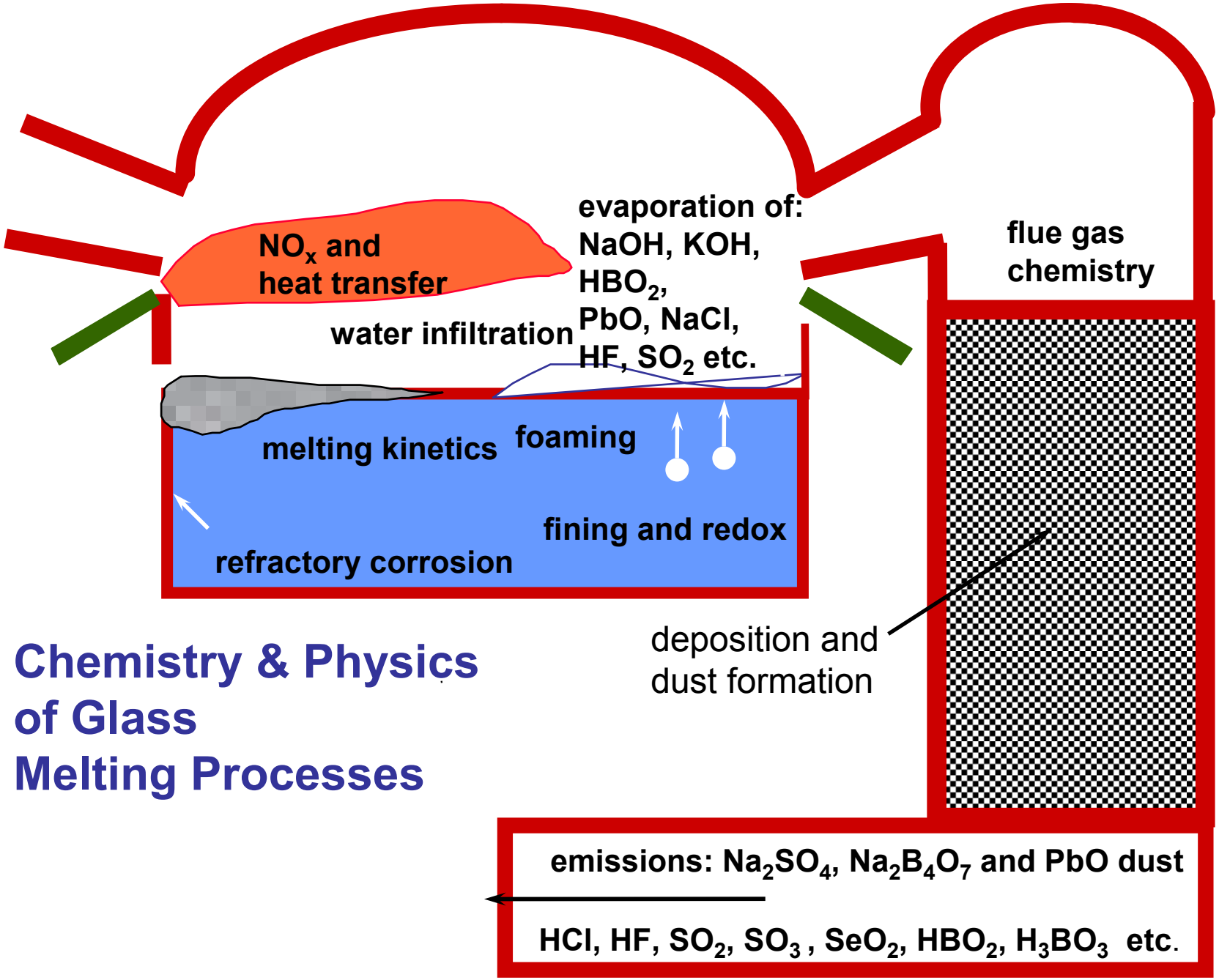
Drivers in process innovation:

- Greenhouse gas reduction / EU-ETS
- Energy efficiency targets
- Emissions (i.e. NOx, SOx, dust, …)
- Costs and yield optimization
- Toxic components (i.e. lead, ...)
- Competence (i.e. training, ...)
- Recycling
- Quality
- Flexibility of production
- Furnace lifetime

Differentiation on segment (flat, container, ..) & region (Europe, ..)

Basic Approach(es)

1. Understand the basics of glass production processes
   - Chemistry & Thermodynamics
   - Heat & Mass Transfer
   - Interaction between different phases (glass melt – atmosphere – refractory)
2. Simulate process steps by dedicated experiments (Design experimental set-ups)
   - Laboratory equipment for simulations
   - Measuring glass melt properties
3. Describe process steps or phenomena by simulation models
4. Use simulation models to find optimum process design & process settings
5. Use experiments or industrial measurements to validate predictive process models
6. Use models to investigate process dynamics & develop control strategies



Chemistry & Physics of Glass Melting Processes

Glass melt technology

Energy reduction:

- energy benchmarking, energy balance models, batch preheating technology, glass tank design, oxy-fuel combustion, combustion technology, melting fluxes

Emission abatement:

- NOx reduction: burner optimization, LowNOx furnace designs, NOx sensor & control
- CO_2 emission reduction: energy efficiency improvement, de-carbonated batch
- SOx emission reduction: minimization sulfate fining addition, alternative fining

Reduction of other volatiles:

- Reduction Na, F, B, Se via optimized furnace settings and new batch additives
- Emission predictive models
- New environmentally sound glass compositions

Recycling:

- Closing the product lifecycle: high % cullet recycling, control defects,
- Recycling of internal waste streams: recycling of filter dust
- Sorting of cullet and removal of pollutants from cullet

Glass quality (new glass compositions)

- Optimization of fining and homogenization

Main glass technology areas

Raw materials:

- alternative sodium raw materials, pelletizing, batch preheating

Refractory corrosion:

- superstructure model refractory attack
- melt-refractory attack

Process modelling:

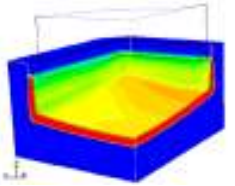
glass tank simulation model: furnace design (integrated models for the melter, batch, combustion space, boosting, feeder models)

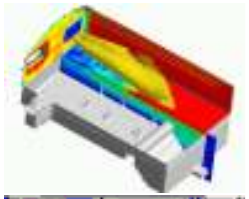
Process diagnosis & analysis:

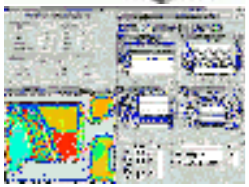
- glass process analyser (GPA)
- soft-sensing via simulation models
- glass defects database
- process sensors: CO-NOx sensor, in-situ redox sensor batch
- energy saving potentials

Process control:

- model based predictive control based on GPS and GPA



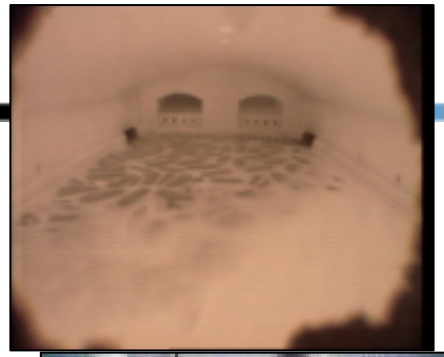


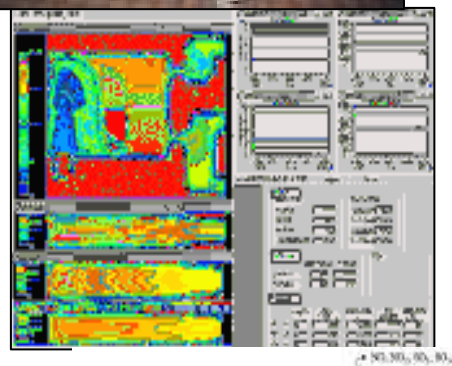


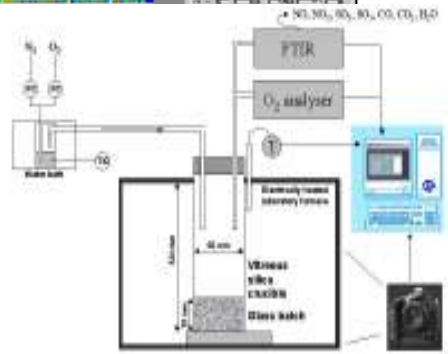
Glass Melting activities

- **Field support**
  - Energy benchmarking
  - Emission measurements
  - Mass balance measurements
  - Model validation measurements
  - Furnace audits
  - Improvement projects, defect reduction
- **Laboratory measurements**
  - Characterization of foaming behavior and evaporation
  - Estimation of dissolved gases
  - Evolved Gas Analysis during Melting & Fining
  - Fining & Batch melting
  - Redox analysis
  - Evaporation & Carry-over experiments
  - Measurements: surface tension, density and thermal expansion
  - Refractory exposure tests

Facilities







- Experimental set-up to simulate processes
- Experimental equipment for glass melt properties
- Mobile laboratory for field-measurements
- Computational Fluid Dynamic Models Glass Furnaces
- Process Control Software
- Glass Technology Textbook (800 pages, 2011)

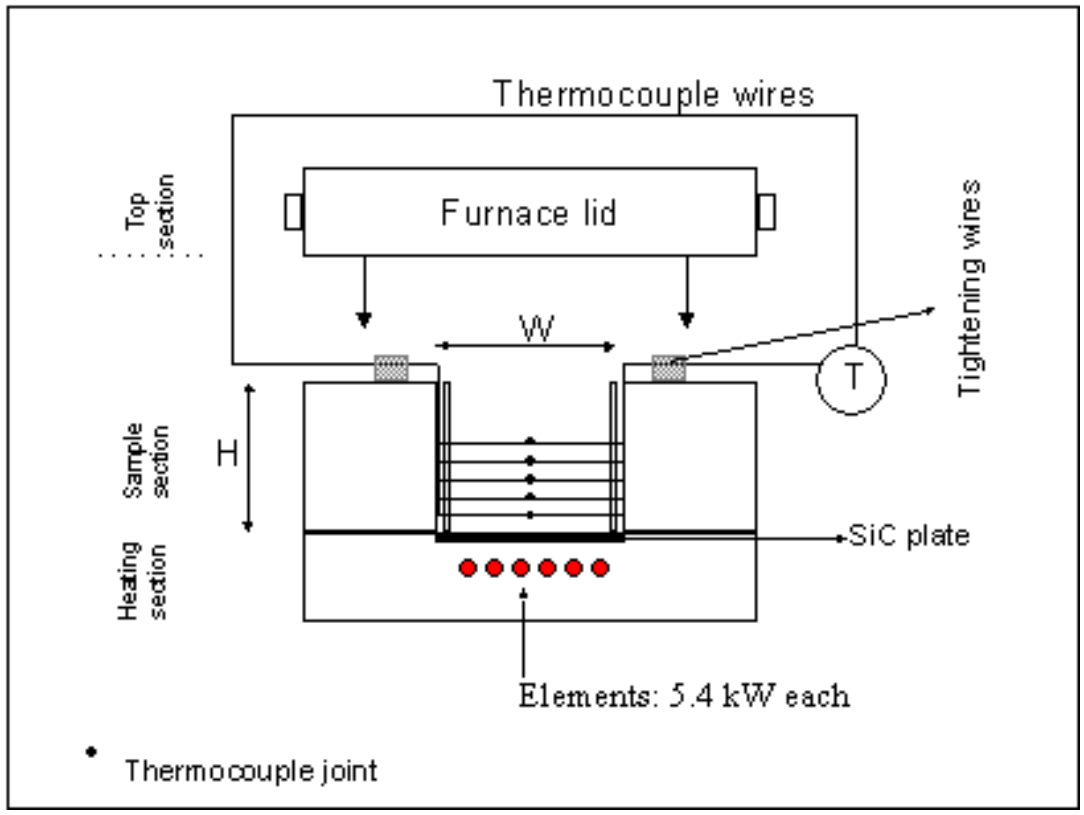
TNO dedicated **Lab-experiments** to investigate process steps for industrial glass melting:

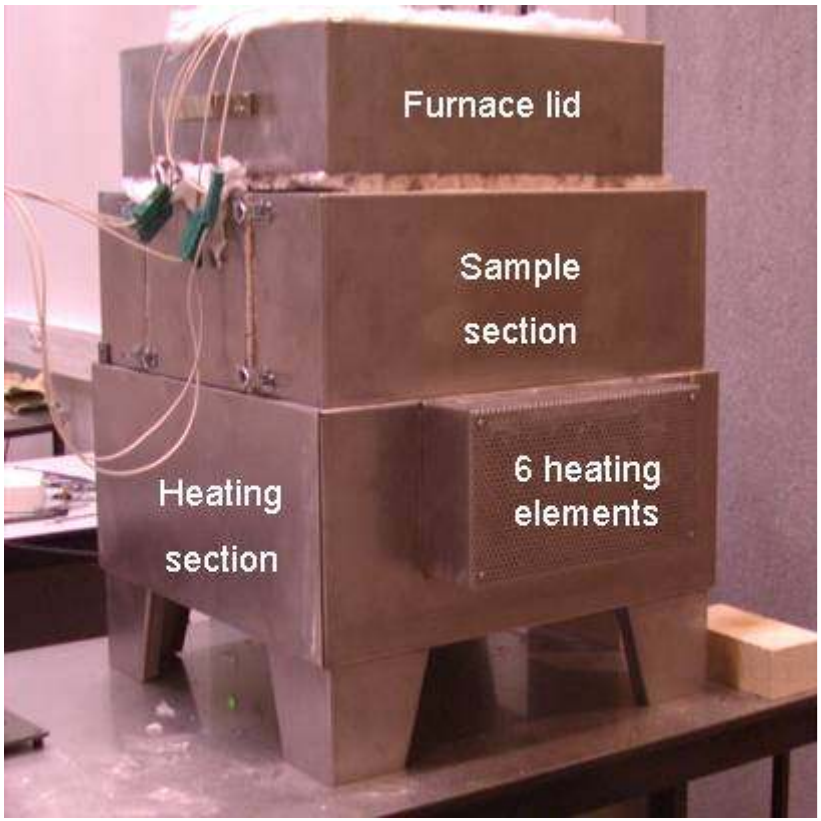
Examples

1. Bubble observation (fining/refining) in glass melts
2. Foaming behavior of batches
3. Evolved gas analysis during melting-in and fining
   - to study reactions during batch melting & batch chemistry
4. Characterization of batch blankets
5. Transpiration glass melt evaporation tests
6. Corrosion tests for refractory materials
7. Batch melting studies

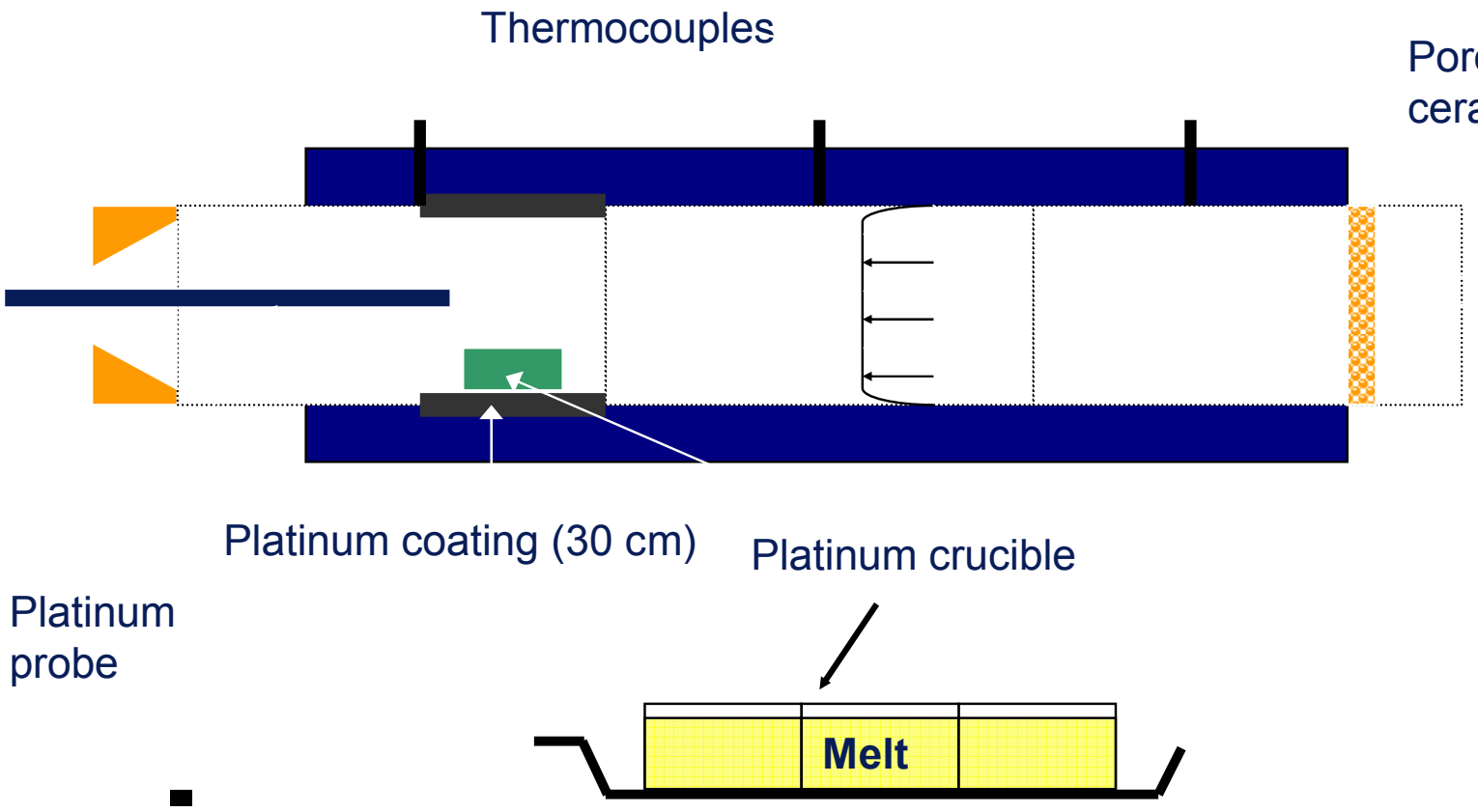
Characterization of batch

Experimental set-up for determination of **thermal heat conductivity of batch blanket**





Transpiration evaporation test methods

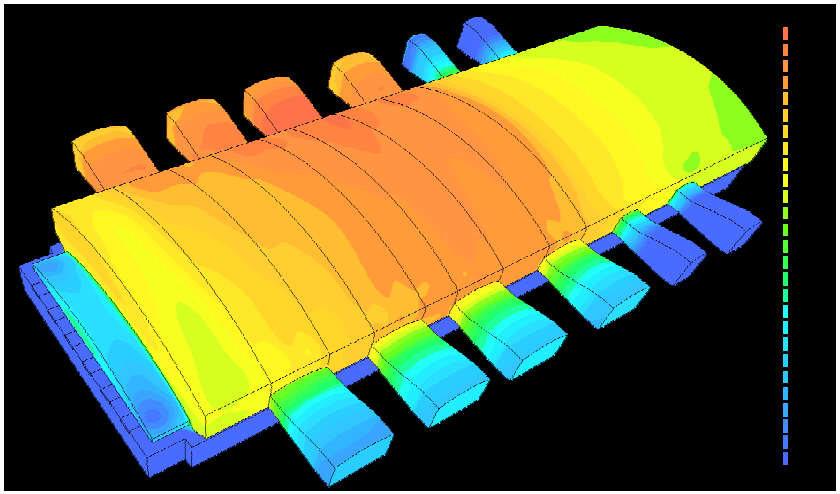


Simulation models

- Computational Fluid Dynamics
  - Glass melting
  - Glass furnaces
  - Combustion
- Thermodynamic Models
  - Sulfate fining
  - Refractory corrosion
  - Evaporation studies

Important data:

- Glass melt properties
- **Properties of Gases in Melts**
- Radiation in melt
- Redox reactions
- Sulfate chemistry
- **Batch blanket properties**



GTM-X

TNO innovation for life

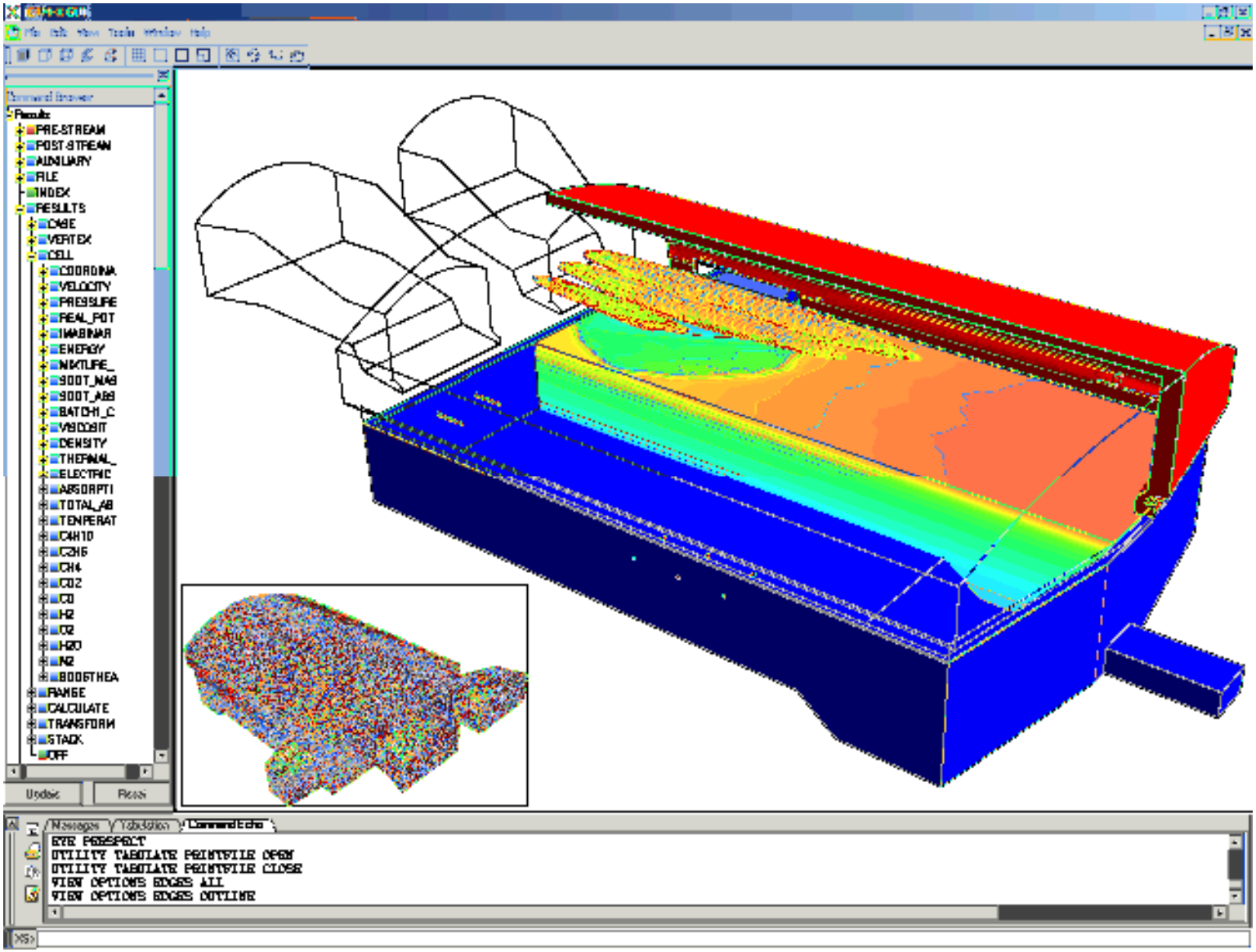
Glass
- Batch models
  - 2.5D, 3D, 2-phase
- Radiation models:
  - Rosseland
  - (spectral) DOM
- Electrical boosting
- Bubbling
- Foam model
- Crown model
- Stirring
- Energy sources
- Particle trace
- Redox
- Glass colour change
- Non-linear mixing
- Volatilization
- 3D & 1D walls
- Glass surface height
- Thermal homogeneity
- Refractory wear
- Glass quality indices

Main Model
- Navier-Stokes
  - Finite Volume
  - Energy (buoyancy)
- Steady-state & transient
- State-of-the-art solvers
- Multiple Domains
- Grid:
  - body-fitted
  - multi-block
  - multi-level grids
  - structured
  - collocated
  - p-modifiers
- Parallel
- Materials Database

GUI
- Pre-processor (Pre-Stream)
- Post-processor (Post-Stream)

Combustion
- Radiation models:
  - (spectral) DOM
- Combustion models:
  - Flamesheet model
  - f-g PDF model
  - Dissociation correction
  - FLAME
  - Soot formation/oxidation
  - NOx formation
  - CO
  - Oil
  - Oxy-fuel & oxy-boosting
- Turbulence models:
  - k-e
  - RSM
  - Durbin
  - Elliptical Blending
- Volatilization
- Refractory corrosion
- 3D & 1D walls

Design, Optimization, Trouble-shooting

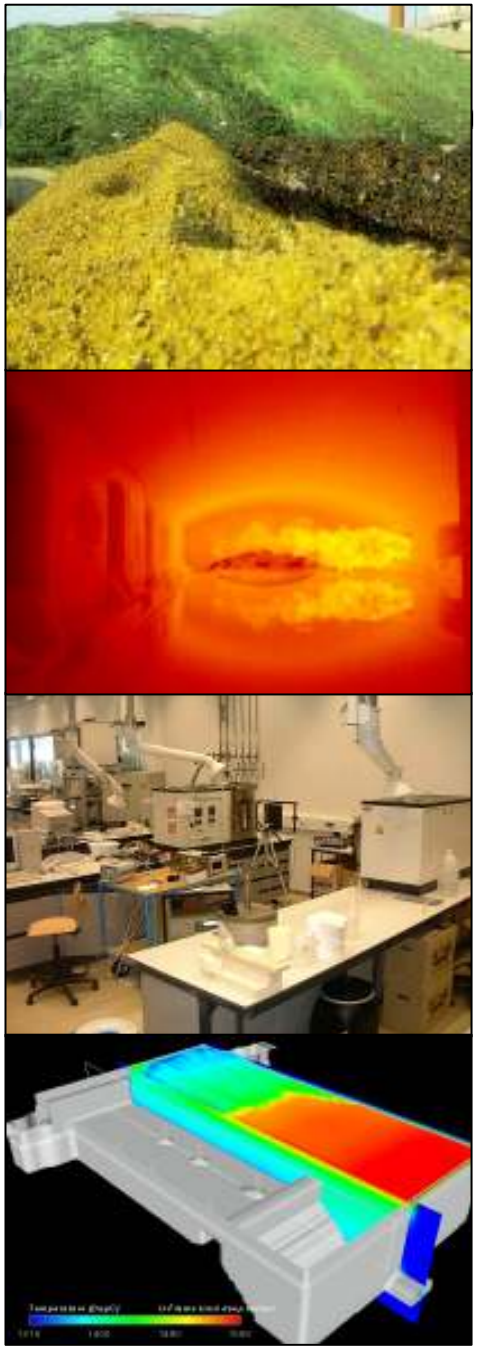

PRE-STREAM
POST-STREAM
AUXILIARY
FILE
INDEX
RESULTS
CASE
VERTEX
CELL
COORDINA
VELOCITY
PRESSURE
REAL_POT
INVARIAR
ENERGY
MIXTURE_
SOOT_MAS
SOOT_ABS
BATCH1_C
VISCOSIT
DENSITY
THERMAL_
ELECTRIC
ABSORPTI
TOTAL_AB
TEMPERAT
C4H10
C2H6
CH4
CO2
CO
H2
O2
H2O
N2
BOOSTHEA
RANGE
CALCULATE
TRANSFORM
STACK
OFF
Messages
Validation
CommandEcho
EYE PERSPECT
UTILITY TABULATE POINTFILE OPEN
UTILITY TABULATE POINTFILE CLOSE
VIEW OPTIONS EDGES ALL
VIEW OPTIONS EDGES OUTLINE

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 distinc 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 (rMPC)
  - Sensors give model continuous new information: model tracking
  - Model → continuously recommendation for input parameter changes to follow optimum process path (low energy, glass quality, constant T)

Industrial projects, products & services

- **Software tools (process simulation) for:**
  - Combustion, melting (glass, silicon), coating
  - Equipment (furnaces, processes, CVD) design
  - Process control
- **Training courses Glass Technology**
- **Energy / Emission reduction programs in industry**
- **R&D for developing new technologies**
  - Energy savings: flue gas heat recovery
  - Low emissions glass production
  - Recycling technologies
  - Glass composition developments
  - New furnace designs
- **Process measurements**
  - Industrial measurements at production plants
  - Laboratory research on melting & fining
  - Optical characterization & Measurement techniques (sensors)



Gaps in knowledge glass melting technology

- Quantitative information on glass melt / refractory interaction
  – effect of non-uniform refractory materials (e.g. AZS) on lifetime, corrosion
- Mechanism and model of foam formation & foam decay
- Control of glass melt flow patterns in tank
- Total heat transfer to batch blanket
- Physical fining for large scale glass melting
- Characterisation of glass (melt) homogeneity
- Information/properties
  - Gases in glass (solubility, reaction equilibria, diffusion)
  - Redox reaction phenomena
  - Relations glass defects versus causes, for bubbles and some cords
- Melting and forming SLS glasses < 12 % $Na_2O+K_2O+Li_2O$
- Selenium retention, ways to increase retention
- Limits of LowNOx combustion (CO, NOx, oxygen excess, flame size)
- Sulphate chemistry in batch & melt
  - Role of sulphites?
  - Fining of amber glass?
  - Effect of cokes / sulphate on efficiency of fining & colour of glass

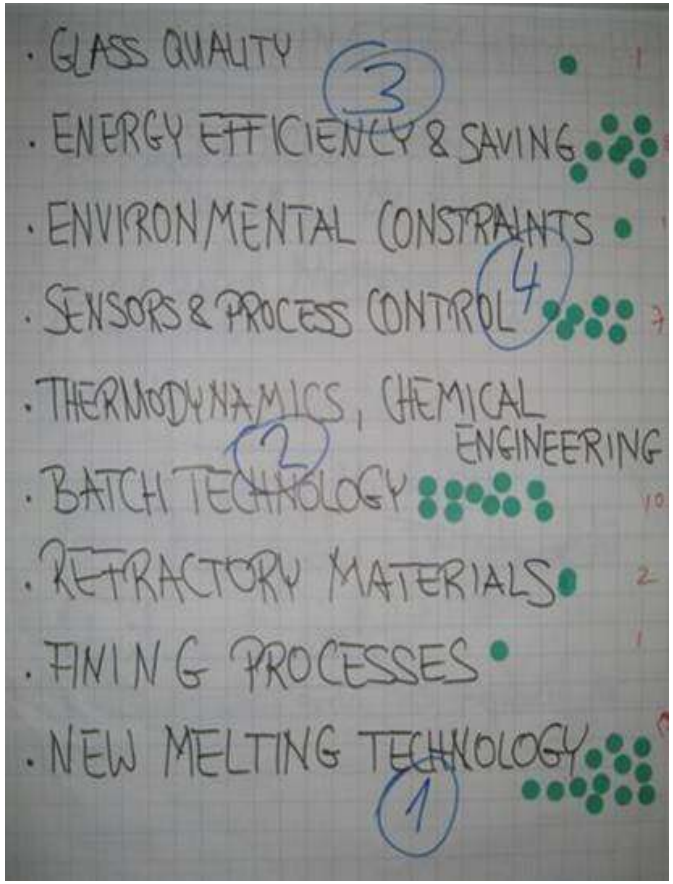
Technology Development Glass Melting

3-4 Years:
- Advanced process control in glass furnaces
- Availability validated thermodynamic models for glass
- Full training course on technology of glass production

8 Years:
- New methods for waste heat (flue gas heat) recovery
- New chemical sensors for glass melts
- Next generation glass melter (faster, energy efficient)
- Improved data on solubility and diffusivity of gases in glass (melts)
- Pre-treatment of batch (raw materials) using flue gas heat contents: increased melting rates and lower energy demand for melting of these batches
- Full model based control systems for furnaces

10-15 Years:
- Sustainable energy / biomass fuelled glass furnaces
- Further improvement next gen glass melter (RAPID Melter)
- New fining methods, industrially applicable
- Replacement of energy-intensive raw materials

ICG-Brig 2008: Prioritizing of thematic clusters



1. **New Melting Technologies (12)**
2. **Tailored Batch Technology (10)**
3. **Energy Efficiency and Waste Heat Recovery (8)**
4. **Advanced Sensors and Process Control (7)**
5. Higher Temperature Refractory Materials
6. Advanced Fining Processes
7. Primary measures for emission reduction
8. Glass Quality

Course on Thermodynamics & Chemical Engineering for Glass Technologists

Past TNO Glass Group PhD studies

- Deposits & Condensation of Flue Gases in Glass Furnaces
- Crystallization behavior of a fluorozirconate glass
- Glass Defects originating from Glass Melt/Fused Cast AZS Refractory Interaction
- Redox behavior and fining of molten glass
- Foaming of Glass Melts
- Optical waveguide amplifiers based on Er-doped phosphate glasses
- Towards more efficient Praseodymium Doped Fibre Amplifiers for the O-band
- Germanium Gallium Sulfide Glasses for Pr-doped Fiber Amplifiers at 1.3 μm
- Radiative Heat Transfer in Glass: The Algebraic Raw Trace Method
- Thermal & chemical behavior of glass forming batches
- Diffusion in Multi-component Silicate Glass Melts
- Reduction of process simulation models (a proper orthogonal decomposition approach)
- Control of Glass Melting Processes based on Reduced CFD Models
- Foam glass production from vitrified municipal waste fly ashes
- Optical method for temperature profile measurements in glass melts
- Modeling of evaporation processes in glass melting furnaces

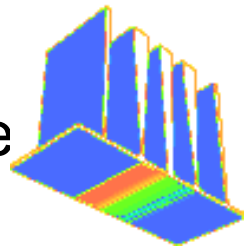
Fundamental research topics

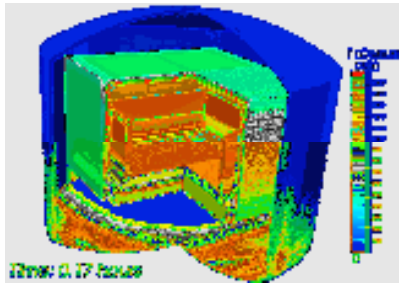
(co-operation with universities)

- Detailed models for evaporation from glass melts
- Glass homogeneity and effect of stirring on it
- Behavior of bubbles and dissolved gases in a glass melt
- Interaction between refractory and glass melt
- New fining methods (He, vacuum, ultrasonic)
- Chemistry & thermodynamics of sulphur species in glass melt & batch
- Gas Solubility and Diffusion in Glass Melts
- Combustion and NOx modeling
- Advanced process control
- High temperature sensors
- New methods for batch melting
- Modified glass compositions and tailored batch

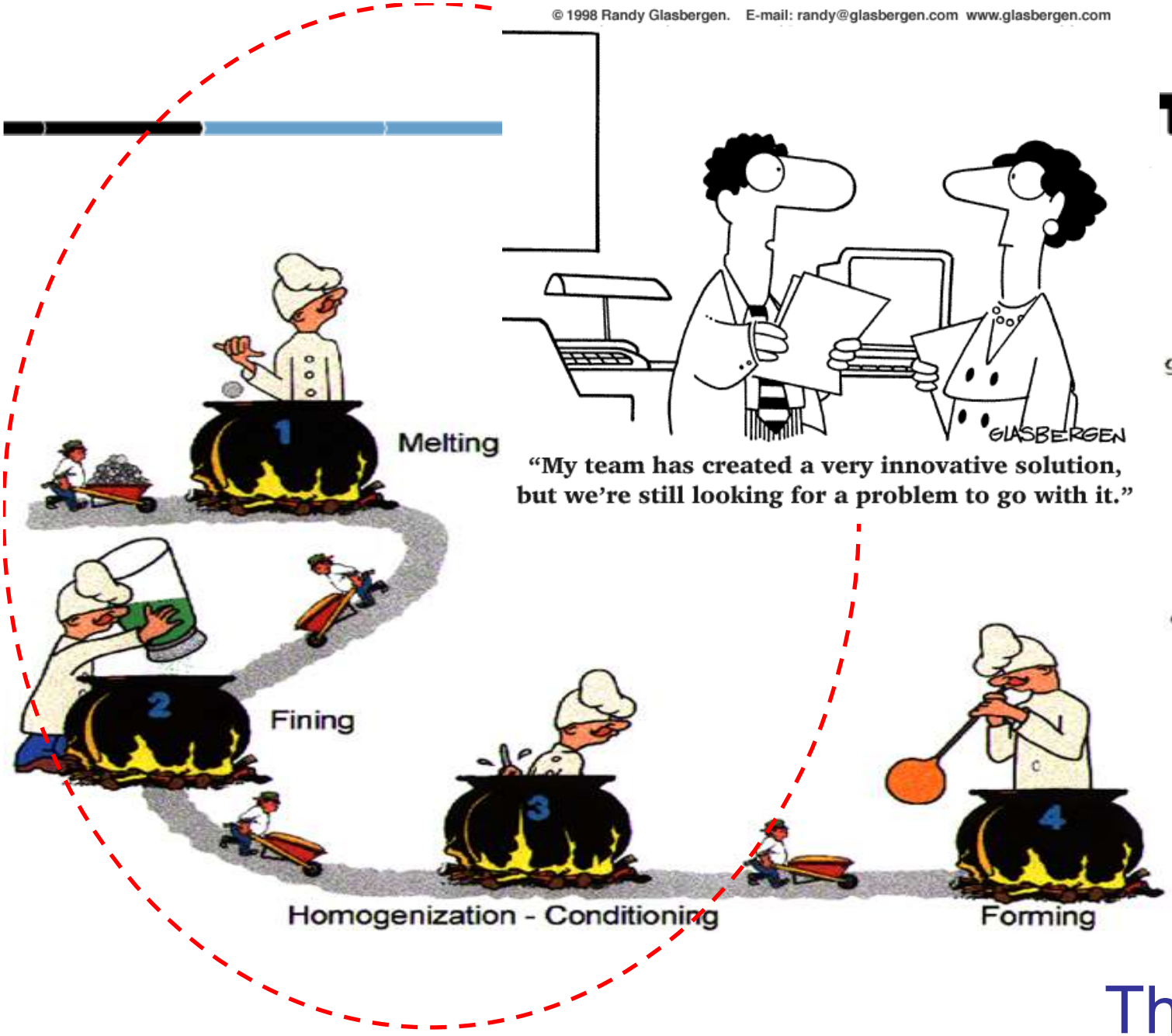
New activities for Solar

- **Objectives**
  - Efficiency improvement PV-cell / modules
  - Cost reduction: Development of profitable and scalable processes, including silicon & glass production
  - Increased device lifetime: Reliability & Performance stability





- **Expertise:**
  - GTM-X Modelling of silicon melting & purification
  - GTM-X modelling of coating processes for PV modules
  - Glass production technology for glass substrates
  - Thermodynamics of silicon purification & melting



"My team has created a very innovative solution, but we're still looking for a problem to go with it."

TNO innovation for life

Step melting giving excellent glass

Thank you!