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**Viscoelastic modelling of stresses
in glass samples at the seal edge**
a frit process parameter study

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Title: Viscoelastic modelling of stresses in glass samples at the seal edge
a frit process parameter study

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*see comment

Customer: Dr. J. P. van den Brink and Dr. ir. W. Potze

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Abstract: The envelope of a CRT consists of three glass parts. Since glass is a brittle material these parts are sensitive to the stress level produced during processing and in use. Maximum stresses occur during safety impact tests.

In order to improve the reliability of the frit process and later processes it is important to know the cause and magnitude of the stresses during and after the frit process.

A viscoelastic simulation of the frit process of two blocks of glass has been carried out to obtain insight in the stress generation in screen and cone glass. The influence on the stresses of various processing parameters is studied.

- Conclusions:**
- Stresses occurring in the glass during the frit process are not only caused by difference in thermal expansion coefficient but mainly by structural rearrangement at higher temperatures.
 - A relatively simple elastic model of glass is not sufficient to simulate the real frit process.
 - Fritting with both higher and lower maximum oven temperature settings will decrease the absolute value of the residual stresses in the screen glass.

- Thermal history of the glass significantly influences the stress evolution during the frit process. Reason for this effect is the degree of compaction of the initial glass products; a rapid cooled ‘fresh’ glass will be subject to high compaction during subsequent thermal processes such as the frit process.
- The difference in frit crystallization dynamics near the maximum temperature of the frit process is negligible.
- Crystallization of the frit at lower temperatures causes the absolute values of the stresses to increase.
- The calculated residual stress is strongly dependent on the choice of the initial parameter initial fictive temperature and the frit process parameters oven temperature settings and frit crystallization dynamics. Therefore a careful validation of the boundary conditions and assumptions has to be made for reliable modelling.

Comment:

This work has been carried out as an orientational research project in the frame of a student practical training at the Nat. Lab. It has correlations with running projects at Disp. Comp. PPD ‘High surface compression’ and ‘Prestressed seal edge’

Contents

1	Introduction	1
2	Problem definition	3
2.1	Thermo elastic theory	4
2.2	Thermo viscoelastic theory	5
3	Numerical method	11
3.1	Discretization of the geometry	11
3.2	Boundary conditions	11
3.3	Material parameters	12
3.4	Nominal process parameters	12
4	Results	15
4.1	Origin of thermal stresses	15
4.2	Variation of oven temperature	21
4.3	Variation of initial fictive temperature	27
4.4	Variation in frit crystallization	32
5	Conclusions and recommendations	37
5.1	Conclusions	37
5.2	Recommendations	37
	References	39
A	Figures of fictive temperature	41
A.1	Influence of oven temperature	41
A.2	Influence of initial fictive temperature	43
B	Distribution of stresses	45
C	Discretization error	47

Distribution

1 Introduction

In figure 1 the envelope of a cathode ray tube (CRT) is sketched. The envelope of a CRT consists of three glass parts: the screen, the cone and the neck. Since glass is a brittle material, these parts are sensitive to the stress level during processing and in use. Specially the maximum stresses which occur during safety impact tests.

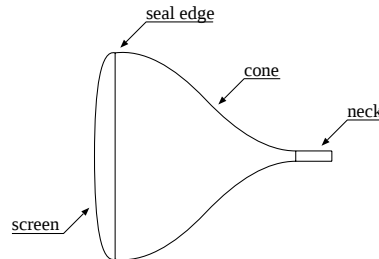


Figure 1: Sketch of a Cathode Ray Tube(CRT)

One of the processes in producing CRT's is the assembly of the screen and the cone. This is done by putting a ceramic paste (frit) on the seal edge of the cone and adding the screen onto the cone. The ceramic material is then hardened in an oven. This process is called fritting. The hardening of the frit occurs at temperatures in the glass transition region.

Objectives Residual stresses causing propagation of preexisting micro flaws are a major factor contributing to product failure both during manufacturing and during product usage. In order to improve the reliability of the frit process and of the later processes it is important to know the cause and magnitude of the stresses during and after the frit process.

In this report viscoelastic stresses generated during the frit process are investigated with a simulation model. Structural relaxation in the two glasses is included in the mathematical model. The main objectives are:

1. to obtain insight in the stress generation in screen and cone glass in the vicinity of the seal edge during the frit process;
2. to determine the influence of various processing parameters on the stress generation in the glass parts.

Outline In chapter 2 the problem is defined and the elastic and viscoelastic theory is explained. In chapter 3 the numerical solution is described and the results are presented in chapter 4. Finally the conclusions and recommendations are presented in chapter 5.

2 Problem definition

A CRT is a complicated 3 dimensional geometry. For reasons of simplicity the basic problem of fritting two blocks of glass is studied. In this way insight in the fritting process can ‘more easily’ be obtained and important process parameters, that affect the stresses in the glass can ‘easily’ be determined.

One of the blocks represents the screen and the other the cone. The two glasses used have different material properties. The appropriate properties will be assigned to those blocks. The frit is not modelled as a geometry, however the influence of the frit to transfer stresses is modelled in the simulation.

The analysis will be carried out with a finite element method (FEM). The finite element code used in this report is MARC [1].

In order to reduce calculation time, only a quarter of the blocks is analysed. This is possible because there are two planes of symmetry ($x = 0, z = 0$) in this simple geometry as shown in figure 2.

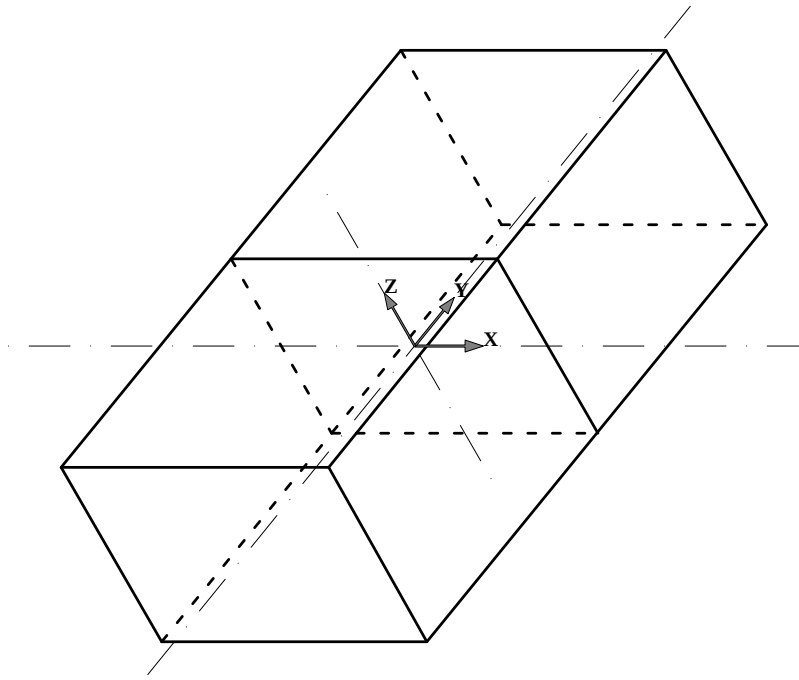


Figure 2: Two blocks of glass

During the frit process, the screen and cone of the CRT are heated in an oven with a maximum temperature which is a few degrees higher than the frit crystallization temperature. The frit crystallization temperature is approximately 430°C. The time-temperature curve of a frit oven is given in figure 3.

In the present calculations, the blocks of glass have a uniform temperature, which equals that in the frit oven. Glass is a viscoelastic material and structural relaxation of the glass is taken into account. This is discussed in the next subsections.

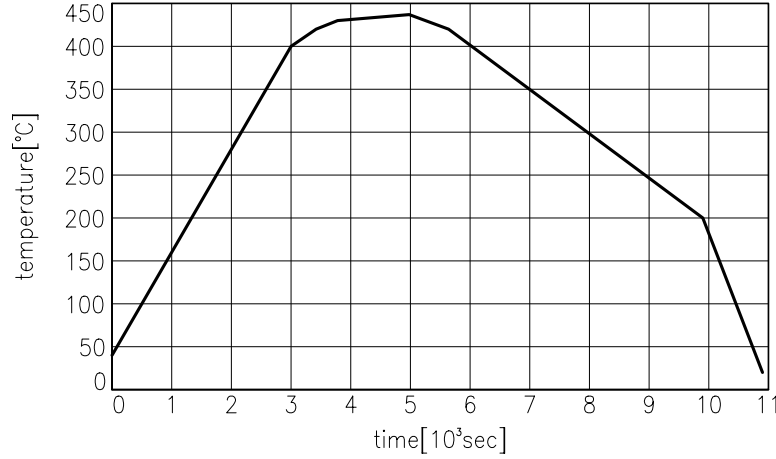


Figure 3: Time-temperature curve of a frit oven

2.1 Thermo elastic theory

In thermo elastic stress analysis the stress also depends on the thermal strain:

$$\boldsymbol{\sigma} = \mathbf{D} (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{th}) \quad (1)$$

where $\boldsymbol{\sigma}$, written as a vector $\boldsymbol{\sigma} = (\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{xz}, \sigma_{yz})^T$, is the stress tensor, $\mathbf{D}$ is the stiffness matrix and $\boldsymbol{\varepsilon} = (\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{xy}, \varepsilon_{xz}, \varepsilon_{yz})^T$ and $\boldsymbol{\varepsilon}^{th} = (\varepsilon^{th}, \varepsilon^{th}, \varepsilon^{th}, 0, 0, 0)^T$ are the actual and thermal strain vectors respectively.

The matrix $\mathbf{D}$ can be written as:

$$\mathbf{D} = \begin{pmatrix} K + \frac{4}{3}G & K - \frac{2}{3}G & K - \frac{2}{3}G & 0 & 0 & 0 \\ K - \frac{2}{3}G & K + \frac{4}{3}G & K - \frac{2}{3}G & 0 & 0 & 0 \\ K - \frac{2}{3}G & K - \frac{2}{3}G & K + \frac{4}{3}G & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G & 0 & 0 \\ 0 & 0 & 0 & 0 & 2G & 0 \\ 0 & 0 & 0 & 0 & 0 & 2G \end{pmatrix} \quad (2)$$

where K is the bulk modulus and G the shear modulus. The relations of these moduli with the Young's modulus E and the Poisson's ratio ν are:

$$\begin{aligned} K &= \frac{E}{3(1-2\nu)} \\ G &= \frac{E}{2(1+\nu)} \end{aligned} \quad (3)$$

In elastic calculations the residual stresses are caused by the difference in thermal expansion coefficient of the two glasses as can be seen from equation 1, where the thermal strain $\boldsymbol{\varepsilon}^{th}$ depends on the thermal expansion coefficient:

$$\boldsymbol{\varepsilon}^{th} = \int_0^t \alpha(T) \dot{T} dt \quad (4)$$

All variables in equations 1, 2 and 3, except the thermal strain ϵ^{th} , are not depending on time. This means that only one elastic calculation of the stresses needs to be made: the temperature step from the frit crystallization temperature to room temperature.

2.2 Thermo viscoelastic theory

Near the glass transition temperature the material behaviour of glass changes from elastic to viscoelastic. Hence, at higher temperatures the elastic analysis is of limited use because the viscoelastic behaviour of the glass is not taken into account.

Next, some concepts of the thermo viscoelastic behaviour of glass will be discussed. For an extensive discussion see for instance Uhlmann and Kreidl [2] and Scherer [3].

Glass transition Most liquids crystalize readily when cooled below their freezing points. If a liquid with a high viscosity is rapidly cooled, the high viscosity inhibits crystallization. The liquid structure is retained well below the freezing point. Materials with a liquid structure are called glass. The temperature where the liquid structure changes to a solid structure is called the glass transition temperature T_g . T_g is illustrated in figure 4 as the temperature where the line of expansion of the

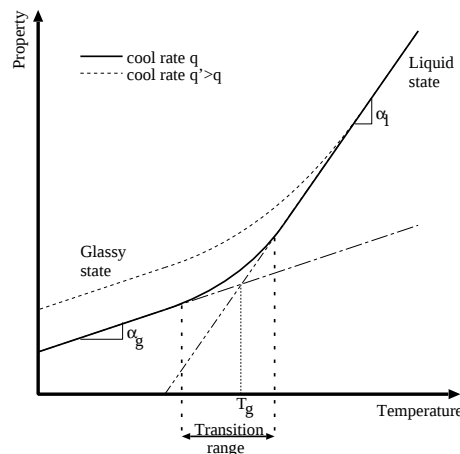


Figure 4: The glass transition range

solid state crosses the line of expansion of the liquid state. In practice the glass transition is not as sharp as the dotted lines of expansion in figure 4. In practice, the material cooled with cooling rate q will follow the continuous line. As can be seen in figure 4, T_g depends on the cooling rate q .

Structural relaxation Consider figure 5 with the property volume. The volume of glass following a small temperature change ($T_2 - T_1$) is time dependent in the transition range. The glass is not in equilibrium. At an isothermal hold at $T = T_1$,

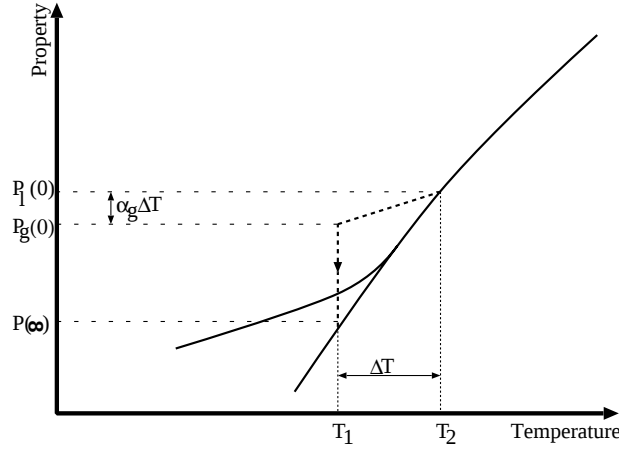


Figure 5: The behaviour of a property of glass in the transition region

the volume relaxes toward the equilibrium liquid value $V_l(\infty)$:

$$\frac{V(t) - V_l(\infty)}{V_g(0) - V_l(\infty)} = M_v(t) = \frac{T_f(t) - T_2}{T_1 - T_2} \quad (5)$$

where $V_g(0)$ is the volume immediately following the temperature change. The response function of the property exhibits a long tail.

An equation often used to describe this behaviour of properties in the glass transition range is:

$$M_p(t) = e^{-\left(\frac{t}{\tau}\right)^\beta} \quad (6)$$

where β is between 0 and 1 and typically $\beta \approx 0.5$. For ease of further computations, equation 6 can be accurately fit with a sum of a series of exponential functions:

$$M_p(t) = \sum_{i=1}^n c_i e^{-\frac{t}{\tau_i}} \quad (7)$$

where c_i are the weights of the structural relaxation times τ_i .

Stress relaxation The stresses are a function of the shear modulus G which is time dependent. The stress relaxation function is an empirical expression of the form of equation 6. The stress relaxation function can also be modelled by a discrete spectrum of relaxation times:

$$GM_s(t) = Ge^{-\left(\frac{t}{\tau}\right)^b} \quad (8)$$

$$\approx G \sum_{k=1}^m w_k e^{-\frac{t}{\lambda_k}} \quad (9)$$

where w_k are the weights of the stress relaxation times λ_k which corresponds to the measured stress relaxation curve. The bulk modulus K is assumed to be constant to go along with the assumption of elastic dilational behaviour adopted by Scherer and Rehson [4].

Thermo rheological simplicity (TRS) The rate of stress relaxation increases rapidly with temperature. In figure 6 the normalized stresses are plotted against a $\log t$ scale for different temperatures. For a TRS material the curves have the same shape when they are plotted on a $\log t$ scale.

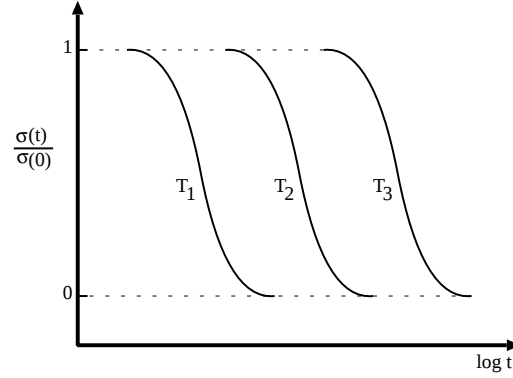


Figure 6: Stress relaxation curves at various temperatures
($T_1 > T_2 > T_3$)

The glass used in this study is a TRS material. The assumption of TRS is equivalent to requiring that the relaxation times τ_i have the same temperature dependence.

Reduced time TRS allows one to use relaxation times τ_{ref} measured at a suitable reference temperature T_{ref} . The temperature dependence is incorporated in a new variable, the reduced time:

$$\xi = \int_0^t \frac{\tau_{ref}}{\tau(T(t'))} dt' \quad (10)$$

Substitution of equation 10 in equation 6 results in:

$$M_p(\xi) = e^{-\left(\frac{\xi}{\tau_{ref}}\right)^\beta} \quad (11)$$

Relaxation times depend not only on temperature but also on thermal history. The measured relaxation times $\tau_{i,ref}$ can be shifted with a Arrhenius function:

$$\frac{\tau_i}{\tau_{i,ref}} = e^{\left\{-\frac{H}{R} \left[\frac{1}{T_{ref}} - \frac{x}{T} - \frac{(1-x)}{T_f} \right] \right\}} \quad (12)$$

where H the activation energy, R the ideal gas constant, x a constant in the range $0 < x < 1$ and T_f the fictive temperature.

Fictive temperature If a glass sample is cooled with cooling rate q from a high temperature, its equilibrium changes from (1) to (2) as shown in figure 7. An alternative way to reach this value is to cool the sample very slowly in the equilibrium

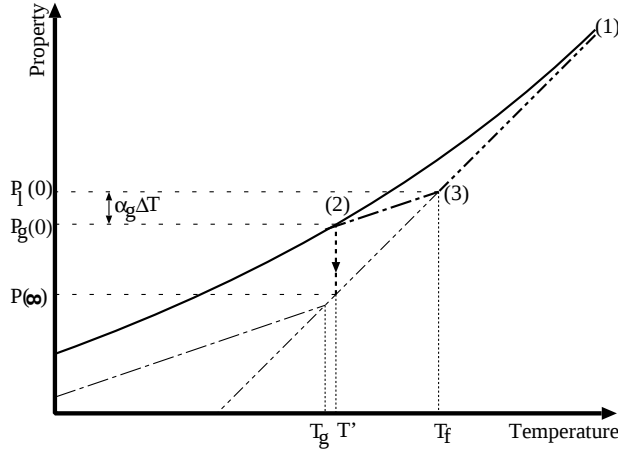


Figure 7: The glass transition range in detail

liquid state from (1) to (3) until $T = T_f$. After this, the sample is instantaneously quenched (3) $\rightarrow$ (2) to temperature T' . Due to this sudden drop in temperature no structural rearrangement can occur. The sample is a solid material but has a liquid structure. The fictive temperature is the temperature which corresponds to the structure of the liquid in equilibrium just before it is quenched down to the actual temperature. The fictive temperature is given by:

$$T_f(t) = T(t) - \int_0^t M_p [\xi(t) - \xi(t')] \frac{dT(t')}{dt'} dt' \quad (13)$$

where M_p is the relaxation function.

A more efficient algorithm to calculate the fictive temperature is the algorithm proposed by Markovsky and Soules [5]. In their algorithm they write $M_p(\xi)$ in equation 13 in the form of equation 7 and introduce partial fictive temperatures T_{fi} . The partial fictive temperatures T_{fi} have to satisfy a differential equation which is integrated in time. The numerical algorithm is as follows:

$$T_{fi}(t) = \frac{T_{fi}(t - \Delta) + T(t) \left(\frac{\Delta t}{\tau_i} \right)}{1 + \frac{\Delta t}{\tau_i}} \quad (14)$$

$$\tau_i = \tau_{i,ref} \exp \left\{ -\frac{H}{R} \left[\frac{1}{T_{ref}} - \frac{x}{T} - \frac{(1-x)}{T_f} \right] \right\} \quad (15)$$

$$T_f(t) = \sum_{i=1}^N c_i T_{fi}(t) \quad (16)$$

$$T_{fi}(0) = T_0 \quad (17)$$

Free thermal volume Once the fictive temperature is known, the volume of glass can be calculated by:

$$\frac{1}{3} \frac{V(t) - V(0)}{V(0)} = \int_{T_0}^{T_f(t)} \alpha_l(T') dT' + \int_{T_f(t)}^T \alpha_g(T') dT' \quad (18)$$

where α_l and α_g are the linear thermal expansion coefficients of the liquid and glass respectively.

Equation 18 provide the linear thermal strain ε^{th} for the finite element analysis:

$$\varepsilon^{th} = \frac{1}{3} \frac{\Delta V}{V(0)} \quad (19)$$

Viscoelastic stress analysis A viscoelastic counterpart of equation 1 is:

$$\boldsymbol{\sigma}(t) = \int_0^t \mathbf{D}(t-t') \frac{d}{dt'} [\boldsymbol{\varepsilon}(t') - \boldsymbol{\varepsilon}^{th}(t')] dt' \quad (20)$$

where t is the actual time and t' the time in the past.

The shear modulus G in equation 2 is replaced by its time dependent analogue $GM_s(t)$ as stated in equation 9. The bulk modulus K will be assumed constant to go along with the assumption of elastic dilational behaviour adopted by Scherer and Rekhson [4].

Because both the thermal strain and the elastic modulus relax with time in the glass transition range, it is convenient to build up the stress-strain relations in increments. In this report the derivation of Soules et al. [6] is followed. The partial shear stress at time t is given by:

$$\sigma_k(t) = 2G \int_0^t e^{-\frac{\xi(t)-\xi(t')}{\lambda_{k,ref}}} d\varepsilon' \quad (21)$$

where $d\varepsilon'$ refers to the change in the difference between actual and thermal strain. Writing the integral of equation 21 from 0 to $t - \Delta t$ plus the integral from $t - \Delta t$ to t , yields to:

$$\sigma_k(t) = 2Ge^{-\frac{\xi(t)}{\lambda_{k,ref}}} \left[\int_0^{t-\Delta t} e^{\frac{\xi(t')}{\lambda_{k,ref}}} d\varepsilon' + \int_{t-\Delta t}^t e^{\frac{\xi(t')}{\lambda_{k,ref}}} d\varepsilon' \right] \quad (22)$$

The partial shear stress component at the previous time step $t - \Delta t$, is given by:

$$\sigma_k(t - \Delta t) = 2Ge^{-\frac{\xi(t)-\Delta\xi(t)}{\lambda_{k,ref}}} \int_0^{t-\Delta t} e^{\frac{\xi(t')}{\lambda_{k,ref}}} d\varepsilon' \quad (23)$$

Substitution of equation 23 into equation 22 yields to:

$$\sigma_k(t) = e^{-\frac{\Delta\xi(t)}{\lambda_{k,ref}}} \sigma_k(t - \Delta t) + 2Ge^{-\frac{\xi(t)}{\lambda_{k,ref}}} \int_{t-\Delta t}^t e^{\frac{\xi(t')}{\lambda_{k,ref}}} d\varepsilon' \quad (24)$$

Assuming $\frac{d\varepsilon'}{d\xi}$ is constant between $t - \Delta t$ and t , results in:

$$\sigma_k(t) = 2Gh_k \Delta\varepsilon + e^{-\frac{\Delta\xi(t)}{\lambda_{k,ref}}} \sigma_k(t - \Delta t) \quad (25)$$

where

$$h_k = \left(1 - e^{-\frac{\Delta\xi}{\lambda_{k,ref}}} \right) \left(\frac{\lambda_{k,ref}}{\Delta\xi} \right) \quad (26)$$

and

$$\frac{\Delta\xi(t)}{\lambda_{k,ref}} = \int_{t-\Delta t}^t \frac{1}{\lambda(T(t'))} dt' \quad (27)$$

With equation 25 the change in shear components of stress is given by the following recursive relation:

$$\Delta\sigma_k = 2Gh_k [\Delta\varepsilon - \Delta\varepsilon^{th}] - \left(1 - e^{-\frac{\Delta t}{\lambda_k}}\right) \sigma_k(t - \Delta t) \quad (28)$$

Equation 28 is convenient for incremental analysis since it uses the value of σ_k from the previous time step. According to equation 28 the change in stress in the time step Δt is that due to a sudden change in strain, with elastic modulus modified slightly by h_k , minus the portion of the previous stress which relaxed during Δt .

The total change in stress is given by:

$$\Delta\sigma = \mathbf{D} [\Delta\varepsilon - \varepsilon^{th}] - \sum_{k=1}^m \left(1 - e^{-\frac{\Delta t}{\lambda_k}}\right) \sigma_k(t - \Delta t) \quad (29)$$

where $\mathbf{D}$ is given in equation 2 with G replaced by $G \sum_{k=1}^m h_k$.

In the transition range, the stresses are changing rapidly. For accurate results a small time step should be used. Once the glass has been cooled to temperatures well below the glass transition range much larger time steps can be used to reach the final temperature.

3 Numerical method

The theory of viscoelasticity as described in chapter 2 is incorporated in the finite element code MARC [1]. To reduce calculation time, only a quarter of the sample is analysed. This is possible due to symmetry as can be seen in figure 2. The analysed quarter is the first quadrant of the XZ -plane. The blocks of glass have both a rectangular shape with rib length in x and y direction $b_x = b_y = 5\text{mm}$ and in z direction $b_z = 7\text{mm}$.

3.1 Discretization of the geometry

A quarter of the two blocks of glass are discretized into 1215 nodes and 1024 elements. The discretized model is shown in figure 8. The elements have a rectangular shape and the division of the elements is greater at the edges of the model. A finer mesh at the surface is chosen because larger stress gradients are likely to occur near the surface of the glass.

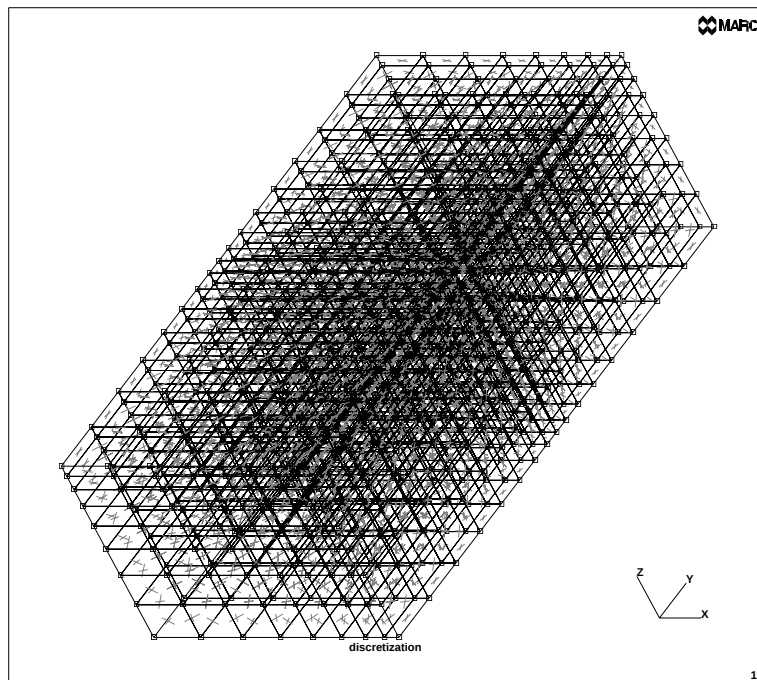


Figure 8: Discretization of the two blocks

3.2 Boundary conditions

In the model used, only mechanical boundary conditions exist.

The left side of the model in figure 8 is the YZ -plane. The points in this plane of symmetry have symmetric boundary conditions. They can not translate in a di-

rection perpendicular to the plane of symmetry. Therefore, the nodal displacements of the nodes in the YZ -plane are suppressed in the X direction.

The bottom side of the model, the XY -plane, is also a plane of symmetry. The nodal displacements of the nodes in the XY -plane are suppressed in the Z direction.

To remove the possibility of a rigid body mode translation in Y direction, the translation in Y -direction of the center node at the origin is suppressed.

3.3 Material parameters

The numerical calculations in this report are carried out for one set of glasses. G440 screen glass and G382 cone glass. The material parameters are constant in the simulation. The material parameters of the two glasses can be found in table 1.

Material parameter	Glass type	G440	G382
Young's modulus	$E[\text{N/mm}^2]$	7.1E+4	6.36E+4
Poisson's ratio	ν	0.241	0.235
Thermal expansion coefficient(glass)	$\alpha_g [1/^\circ\text{C}]$	10.35E-6	10.15E-6
Thermal expansion coefficient(liquid)	$\alpha_l [1/^\circ\text{C}]$	31.05E-6	30.45E-6
Narayanaswamy's constant	x	0.532	0.561
Activation energy	$H[\text{kJ/mol}]$	517.9	490.5
Ideal gas constant	$R[\text{J}/(\text{mol K})]$	8.31451	

Table 1: Material parameters (Van den Brink [7])

In the calculations done in this report the assumption $\alpha_l = 3\alpha_g$ is made according to the rule of thumb from Scholze [8](p.169). However, recent measurements by Van den Eijnde [9] of the thermal expansion coefficient in the liquid state show that it is about twice as big as in the solid state.

For viscoelastic calculations data is needed for structural and stress relaxation. The relaxation functions, equation 7 and 9, are written as a sum of exponentials. The parameters of the exponential series: c_i , τ_i and w_k , λ_k , are given in table 2 and 3 respectively. The exponential series have six terms, $n = m = 6$.

3.4 Nominal process parameters

In this report the variation of process parameters are also subject of this study. All changes in the process parameters are compared with a nominal model. The nominal situation of the process parameters is discussed in this subsection.

Fictive temperature One of the ‘material’ parameters, which is not mentioned in section 3.3, is the initial value of the fictive temperature T_f . Because the fictive temperature is dependent on earlier processes and also subject of this study, it is considered a process parameter.

G440	structural relaxation $T_{ref} = 553.0^{\circ}\text{C}$		stress relaxation $T_{ref} = 524.0^{\circ}\text{C}$	
i, k	c_i	$\tau_i[\text{s}]$	w_k	$\lambda_k[\text{s}]$
1	0.0077	0.0116	0.14437	0.86215
2	0.0319	0.296	0.19066	7.0119
3	0.0936	2.702	0.40131	39.163
4	0.2299	15.91	0.25045	184.18
5	0.4041	68.61	0.01290	730.27
6	0.2328	228.9	0.00010	5906.0

Table 2: Data for structure and stress relaxation in G440 screen glass (Van den Brink [10])

G382	structural relaxation $T_{ref} = 478.0^{\circ}\text{C}$		stress relaxation $T_{ref} = 463.0^{\circ}\text{C}$	
i, k	c_i	$\tau_i[\text{s}]$	w_k	$\lambda_k[\text{s}]$
1	0.0130	0.0152	0.10706	0.75785
2	0.0462	0.5631	0.15095	5.5297
3	0.1200	6.536	0.33388	32.025
4	0.2496	46.78	0.36027	149.51
5	0.3691	251.0	0.04698	464.79
6	0.2021	1113.0	0.00010	3091.4

Table 3: Data for structure and stress relaxation in G382 cone glass (Van den Brink [10])

The fictive temperature is the temperature of the structure of the material. If the fictive temperature and thus the structure is changed in earlier processes, then the material used during the frit process has different properties.

The nominal value of the initial fictive temperature is 513.1°C for G440 screen glass and 453°C for G382 cone glass. These values are based on a cooling speed of $0.03185^{\circ}\text{C/s}$ which is used in the production of a normal production screen and cone. In this model the fictive temperature is assumed uniform; in reality there will be a non uniform fictive temperature distribution over the thickness of the glass.

Thermal (frit) process During the frit process the CRT is heated in an oven. The temperature curve for the frit process is already mentioned in section 2 and can be found in figure 3.

In the numerical simulation the temperature of the model is uniform and equals the temperature of the frit oven. The uniform temperature in the two blocks of glass exclude stresses introduced by a thermal gradient.

Frit The frit is a ceramic paste which hardens at its crystallization temperature. It is assumed that crystallization occurs at approximately 430°C. However no exact data of the frit crystallization is present.

In the simulation no physical frit is modelled between the two blocks of glass. Only one property of the frit is modelled, the ability to transfer stresses between the two blocks of glass.

During the frit process the stress free blocks of glass are heated in an oven. Due to a mismatch in thermal expansion coefficient and structural relaxation, the blocks differ in volume changes. The frit is not hardened below 430°C so no stresses are introduced below this temperature. At 430°C the frit is assumed to be crystallized and to connect the two blocks of glass. From now on stresses are introduced due to different volume changes between the screen and cone glasses.

4 Results

4.1 Origin of thermal stresses

In the frit process two types of glass follow a thermal process. During this thermal process the two blocks of glass change in volume. The volume changes are not only caused by heating or cooling but also by structural relaxation.

Free thermo elastic expansion Due to heating and cooling the material will expand or contract linearly with temperature. This behaviour is described by equation 4.

In the frit process the thermo elastic expansion is plotted in figure 9 with dashed lines. Notice that it has the same form as the time-temperature curve in figure 3.

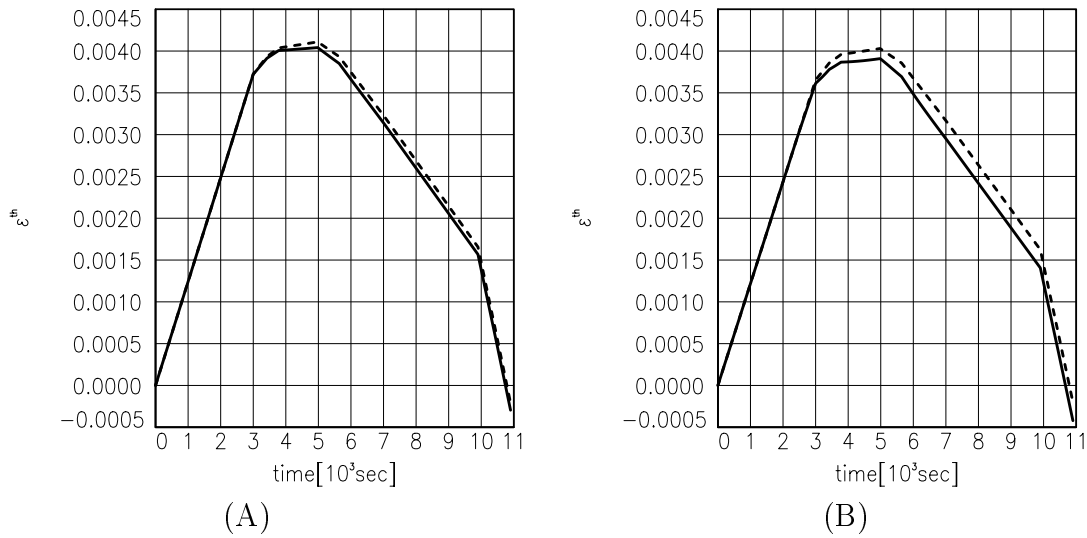


Figure 9: Thermo elastic strain during the frit process of the screen(A) and cone(B) glass. The dashed lines represent the thermo elastic expansion and the solid line the expansion with structural relaxation.

Free thermo viscoelastic expansion In the viscoelastic analysis the strain during the frit process is less than the strain calculated in an elastic simulation. In figure 9 the viscoelastic strain is plotted with a solid line.

Equation 18 can be written as:

$$\varepsilon_{i+1}^{th} = \alpha_g (T_{i+1} - T_i) + (\alpha_l - \alpha_g) (T_{f_{i+1}} - T_{f_i}) \quad (30)$$

where $i+1$ represents the actual time and i the solution at the previous time step. In equation 30 the first part of the right hand side is the elastic expansion in the glassy state. The second part of the right hand side is the effect of structural relaxation.

With equation 30 the expansion due to heating or cooling and structural relaxation can be calculated. At temperatures near and in the glass transition range structural relaxation occurs. Due to structural relaxation the structure changes towards a more stable equilibrium state. During this process the fictive temperature T_f decreases and this results in a decrease of the thermal strain ϵ^{th} calculated with equation 30.

The glass transition range of the screen glass is much higher on the temperature scale than the glass transition range of the cone glass. This will result in more structural relaxation of the cone glass than that of the screen glass as can be seen in figure 9. With figure 3 and 9 it can be seen that structural relaxation of screen and cone glass occurs at temperatures above 400°C and 350°C respectively.

Elastic stresses In elastic calculations the stresses in the blocks of glass occur due to a mismatch in TEC. The blocks of glass enter the frit process in a stress free situation. Due to the uniform heating no stresses are introduced by a thermal gradient. The blocks of glass are not connected and can expand freely.

At the frit crystallization temperature of 430°C the frit is assumed to withstand stresses. The blocks of glass are connected and the difference in thermal expansion or contraction will introduce stresses.

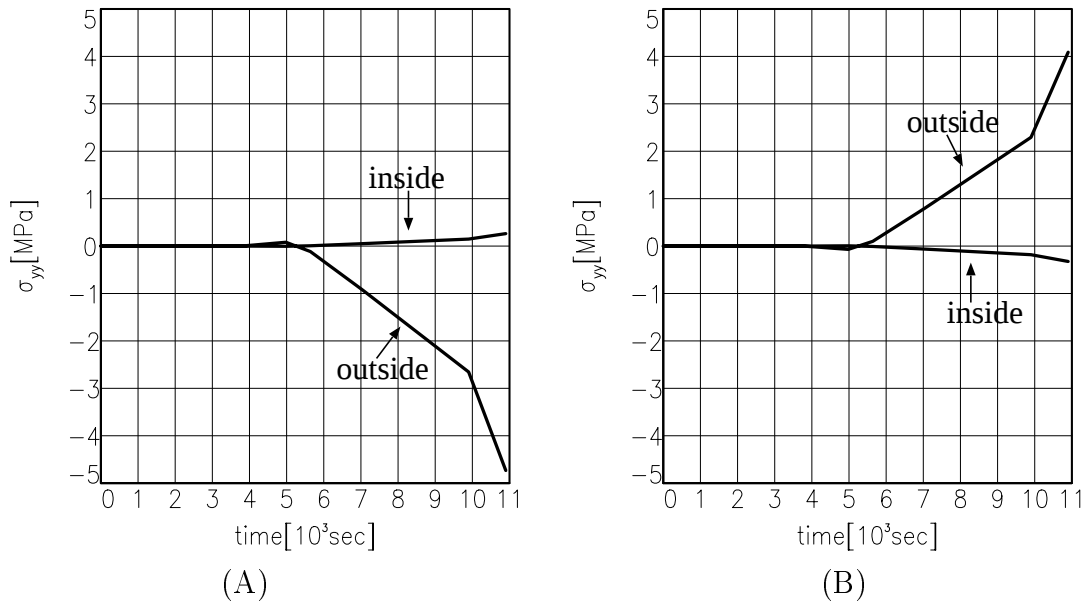


Figure 10: Stresses in Y-direction in the screen(A) and cone(B) glass in an elastic calculation.

In figure 10 the stresses at the surface¹ (outside) and inside² of the blocks are plotted. The blocks are stress free until crystallization of the frit occurs at $t = 3780$ s.

¹ $x = 5\text{mm}$, $z = 3.5\text{mm}$ and $y_s = -2.96875 \cdot 10^{-1}\text{mm}$ for G440 screen glass and $y_c = 0.6875\text{mm}$ for G382 cone glass.

² $x = 0\text{mm}$, $z = 0\text{mm}$ and $y_s = -2.96875 \cdot 10^{-1}\text{mm}$ for G440 screen glass and $y_c = 0.6875\text{mm}$ for G382 cone glass.

The temperature of the glass is still increasing to 437°C. The TEC of the screen glass is greater than the TEC of the cone glass. This will result in a situation as sketched in figure 11(A). The stresses at the outside in screen and cone glass are respectively tensile and compressive as can be seen in figure 10.

During cooling the process changes. Because of the higher TEC of the screen glass it will shrink more than the cone glass as sketched in figure 11(B). In an elastic calculation the stresses introduced during heating from 430°C till 437°C will disappear during cooling from 437°C till 430°C.

Cooling further to room temperature the situation of figure 11(B) will continue. The compressive and tensile stresses in the screen and cone glass respectively will increase.

At the plane of symmetry (inside) almost no strain and thus no stress will occur. On the surface the deformation is large and the highest stresses will be introduced here.

Figure 31 in appendix B shows the distribution of the residual stresses in the glass in Y-direction. The evolution of stresses at the entire surface of screen or cone glass are similar to the described evolution of stresses in this paragraph. During the frit process the distribution of stresses is unchanged.

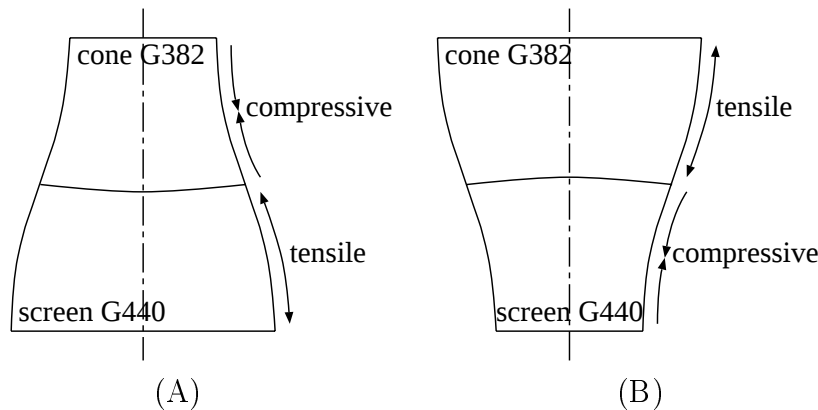


Figure 11: Sketch of the deformation of a screen and cone glass during heating(A) and cooling(B) in a frit process.
 $(\alpha_{g_{screen}} > \alpha_{g_{cone}})$

Viscoelastic stresses In viscoelastic calculations the stresses in the blocks of glass are caused by to three effects. The first two effects are described by equation 30. This equation incorporates the effect of TEC mismatch and structural relaxation. The third effect is stress relaxation.

In figure 12 the stresses of the viscoelastic calculation are plotted. The stress evolution during the frit process can be divided into five parts.

1. Between $t = 0s$ and $t = 3780s$ the frit has not crystallized and the blocks of glass are not connected and stress free. However structural relaxation will

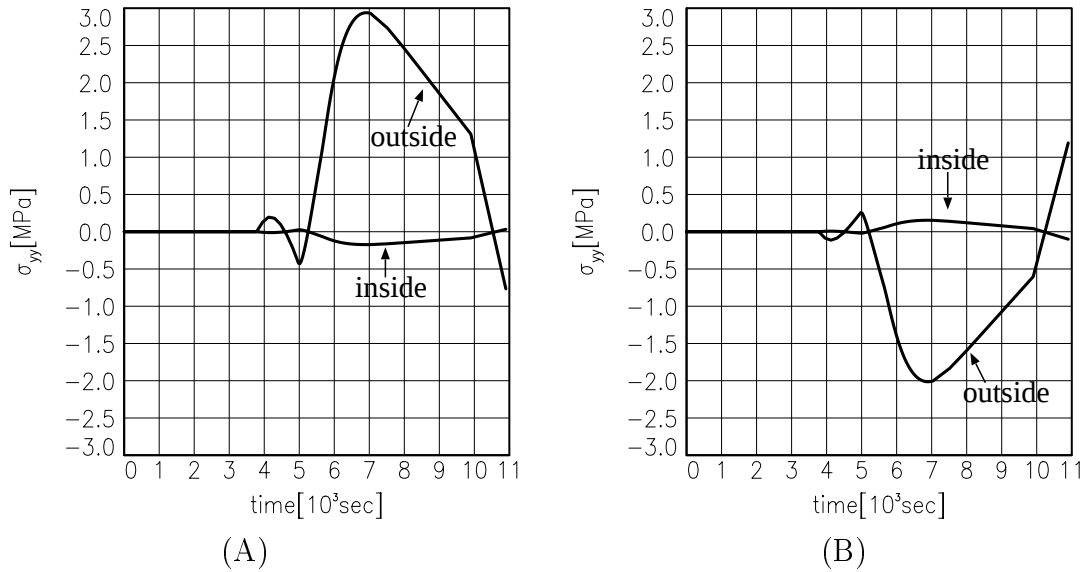


Figure 12: Stresses in Y-direction in the screen(A) and cone(B) glass in the nominal viscoelastic calculation.

occur due to the high temperatures as can be seen from the decrease in fictive temperature in figure 24.

- Between $t = 3780\text{s}$ and $t = 4123\text{s}$ the model is heated from $T = 430^\circ\text{C}$ to $T = 432^\circ\text{C}$. At $t = 3780\text{s}$ the frit is crystallized and the blocks of glass are connected. The stress evolution is caused by a difference in expansion or contraction.

The TEC of the screen glass is greater than the TEC of the cone glass. During heating the screen glass will expand more than the cone glass. The deformation of the blocks is as sketched in figure 11(A).

At these temperatures structural relaxation will also occur. The fictive temperature of the screen glass is greater than that of the cone glass. Because the actual temperature of the blocks is approaching the fictive temperature of the cone glass its structure approaches an equilibrium position as can be seen by the flattening of the curve in figure 13(A).

The fictive temperature is plotted in figure 13. Notice that in this time interval the decrease of the fictive temperature and thus the structural relaxation of the cone glass is greater than that of the screen glass as can be seen in figure 13(B).

Due to structural relaxation the volume will decrease. In this case the volume relaxation of the cone glass is greater than that of the screen glass. The effect of structural relaxation together with the effect of the mismatch in TEC will result in a deformation as sketched in figure 11(A). Because both effects intensify the situation of figure 11(A) the stresses are greater than in the elastic calculation.

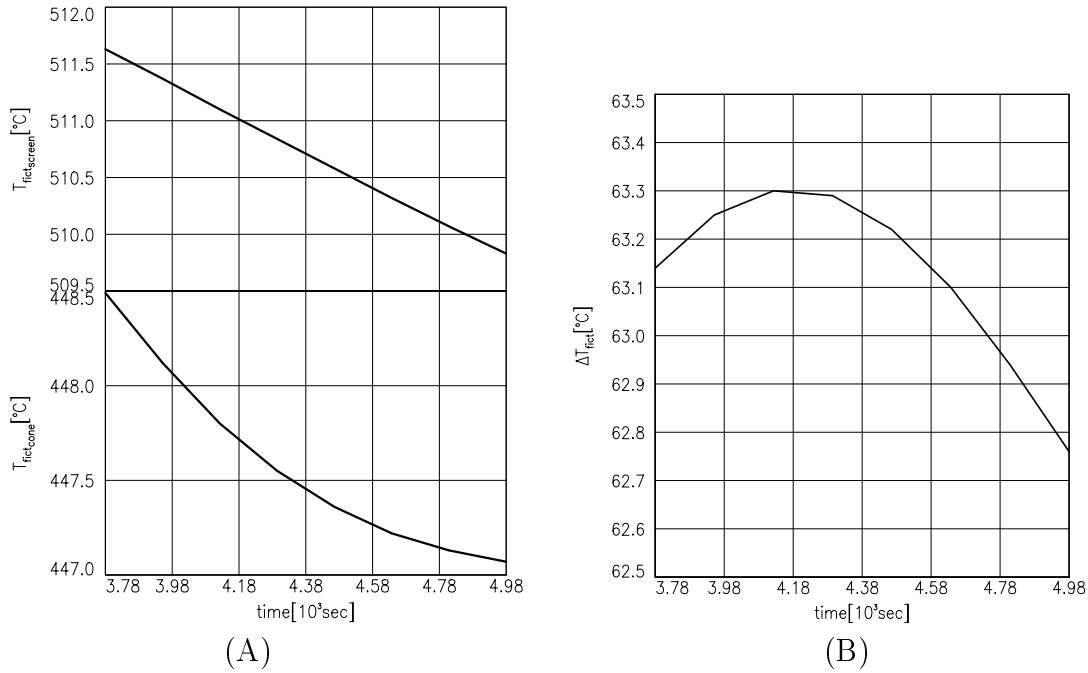


Figure 13: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during heating from 430°C to 437°C. (Part of figure 24 in appendix A.1)

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = 4123\text{s}$ in figure 12 would be higher.

- Between $t = 4123\text{s}$ and $t = 4980\text{s}$ the model is heated from $T = 432^{\circ}\text{C}$ to $T = 437^{\circ}\text{C}$. Due to the mismatch in TEC the screen glass will expand more than the cone glass.

Figure 13 shows that the decrease in fictive temperature of the cone glass reduces in this time interval while the decrease in fictive temperature of the screen glass continues. The fictive temperature of the cone glass approaches the actual temperature and the structure relaxes towards an equilibrium position. The fictive temperature of the screen glass is much greater than the actual temperature thus the screen glass will continue its structural relaxation. The screen glass will shrink more than the cone glass as sketched in figure 11(B).

Because the temperature increase is small the effect of TEC mismatch as sketched in figure 11(A) is smaller than the effect of structural relaxation as sketched in figure 11(B) and can be seen from equation 30. In this time interval the deformation of the blocks behaves like that in figure 11(B). The stresses at the outside in screen and cone glass reduce and increase respectively.

The third factor contributing to the stress evolution is stress relaxation. Due

to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = 4980\text{s}$ in figure 12 would be higher.

4. Between $t = 4980\text{s}$ and $t = 7040\text{s}$ the model is cooled from $T = 437^\circ\text{C}$ to $T = 350^\circ\text{C}$. Due to the mismatch in TEC the screen glass will shrink more than the cone glass. The deformation of the model due to the mismatch in TEC is sketched in figure 11(B).

In this time interval the temperature of the model is decreased rapidly. Because the actual temperature becomes much lower than the fictive temperature of the screen glass it will not relax anymore towards its structural equilibrium. Figure 14(A) shows that structural relaxation of the screen glass vanishes for $t > \pm 6000\text{s}$. However the cone glass continues to relax for lower temperatures until $t = \pm 7000\text{s}$.

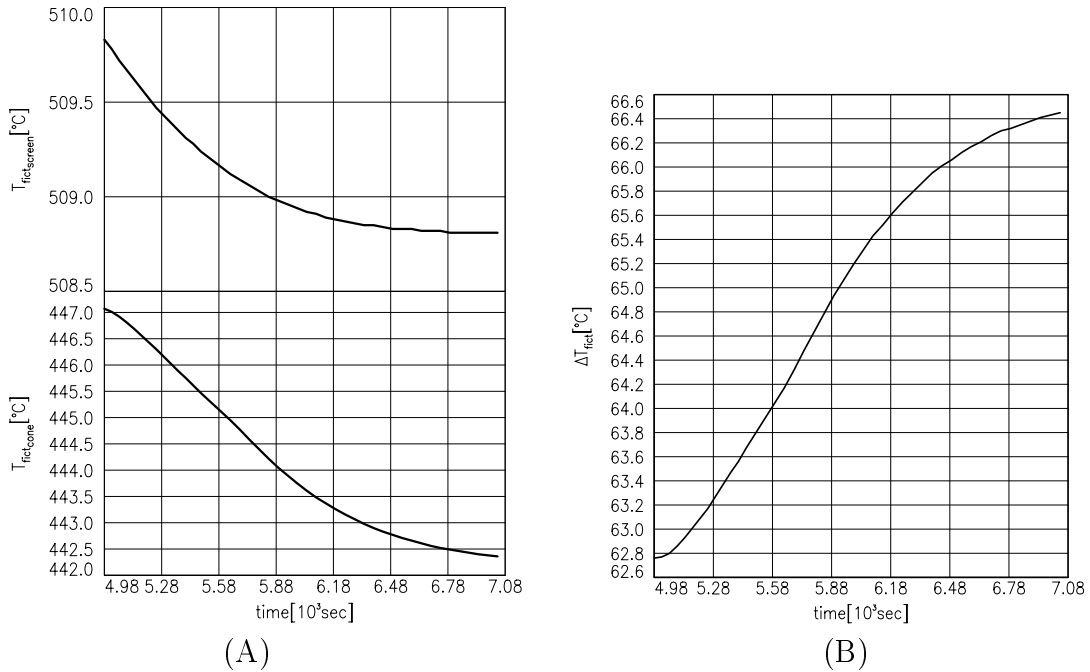


Figure 14: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during cooling from 437°C to 350°C . (Part of figure 24 in appendix A.1)

Figure 14(B) shows that the decrease of the fictive temperature of the cone glass is greater than the decrease of the fictive temperature of the screen glass. This means that the decrease of volume of the cone glass is greater than that of the screen glass. The deformation is as sketched in figure 11(A). Equation 30 shows that the influence of structural relaxation is larger than the influence of mismatch in TEC. The total deformation of the model is as sketched in

figure 11(A). This deformation will introduce tensile stresses in the screen glass and compressive stresses in the cone glass.

For $t > 7000$ s the decrease in fictive temperature and thus structural relaxation will also vanish for the cone glass. From this point on the influence of the effect of mismatch in TEC will increase. At $t = 6890$ s the effect of mismatch in TEC will be greater than the effect of structural relaxation and the deformation is as sketched in figure 11(B) and will reduce tensile and compressive stresses in the screen and cone glass respectively.

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = 6890$ s in figure 12 would be higher.

5. After $t = 7040$ s the model is cooled from $T = 350^\circ\text{C}$ to room temperature (20°C). At these ‘low’ temperatures no³ structural relaxation will take place. The stresses occur due to the mismatch in TEC. The screen glass will shrink more than the cone glass as sketched in figure 11(B). The stresses in the screen glass will decrease and the stresses in the cone glass will increase.

Notice that the evolution of the stresses in this time interval is almost the same as in the elastic calculation as plotted in figure 10. The only difference between the stresses in the elastic and the viscoelastic calculation in this time interval is the presence of stress relaxation in the viscoelastic calculation. Stress relaxation will reduce the absolute values of the stresses. By comparing the figures 10 and 12 one can see that the difference in stress over the time interval is slightly less in the viscoelastic calculation due to stress relaxation.

In figure 11, it can be seen that the deformation at the plane of symmetry (inside) is small compared to the deformation at the outside. Due to the small deformation at the inside of the blocks the stresses are also small at the inside. In the remainder of this report only stresses at the outside will be discussed because they are a major factor contributing to product failure.

Figure 32 in appendix B shows the distribution of the residual stresses in the glass in Y -direction. The evolution of stresses at the entire surface of screen or cone glass are similar to the described evolution of stresses in this paragraph. During the frit process the distribution of stresses is unchanged.

In appendix C the numerical accuracy of the calculation is discussed.

4.2 Variation of oven temperature

The frit process is a thermal process. The oven settings can be found in figure 3. The temperature in an oven is not uniform and the frit process can be influenced by this non-uniformity of the oven temperature. In this section the effect of a higher or lower temperature of the oven is discussed. Again the temperature in the glasses is uniform.

³Less than 1% of the change in the thermal expansion (ε_{i+1}^{th}) calculated with equation 30 is caused by structural relaxation in the first ‘few’ seconds of this time interval.

Increased maximum temperature of frit oven The oven temperature in figure 3 is increased with 5°C . The maximum temperature reached during this cyclis is 442°C . With the same cooling speed the blocks of glass are cooled to room temperature (20°C).

The initial temperature is also increased with 5°C to 45°C . This has no effect on the viscoelastic calculation of the stresses because at these low temperatures no structural relaxation will occur.

Due to the increase in temperature the frit crystallization temperature of 430°C will be reach at $t = 3600\text{s}$. The stresses at the outside are plotted in figure 15. The stress evolution during the frit process with increased maximum temperature can be divided into four parts.

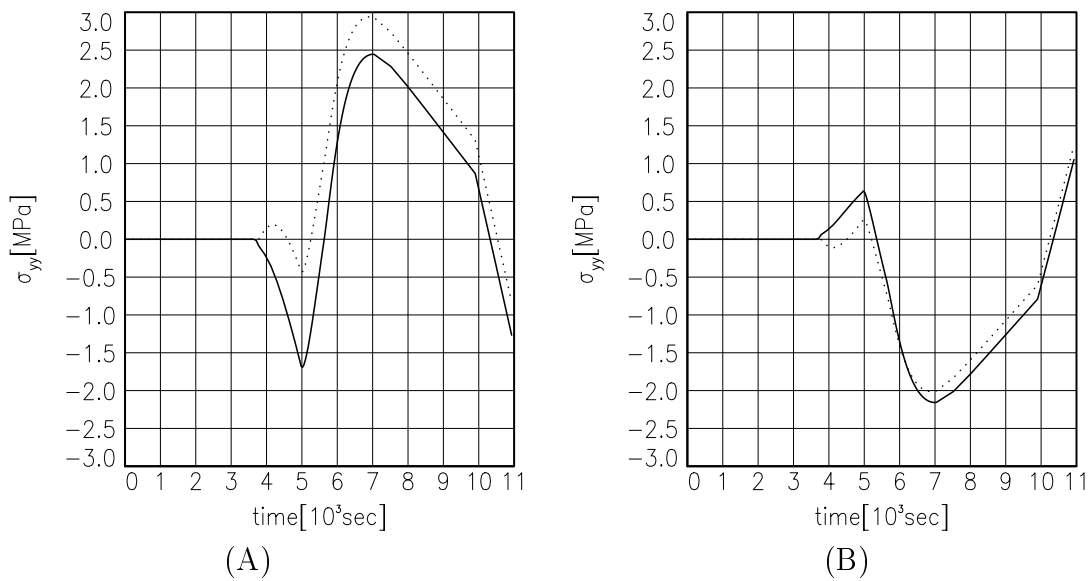


Figure 15: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with increased maximum temperature of 442°C .

1. Between $t = 0\text{s}$ and $t = 3600\text{s}$ the frit has not crystallized and the blocks of glass are not connected and stress free. However structural relaxation occurs due to the high temperatures as can be seen from the decrease in fictive temperature in figure 25.
2. Between $t = 3600\text{s}$ and $t = 4980\text{s}$ the model is heated from $T = 430^{\circ}\text{C}$ to $T = 442^{\circ}\text{C}$. At $t = 3600\text{s}$ the frit is crystallized and the blocks of glass are connected. The stress evolution is caused by a difference in expansion or contraction.

The TEC of the screen glass is greater than the TEC of the cone glass. During heating the screen glass will expand more than the cone glass. The deformation of the blocks is as sketched in figure 11(A).

At these temperatures structural relaxation will also occur. The fictive temperature of the screen glass is greater than that of the cone glass. Because the actual temperature of the blocks is approaching the fictive temperature of the cone glass its structure approaches an equilibrium position as can be seen by the flattening of the curve in figure 25(A).

By comparing figure 24 with figure 25 can be seen that due to the higher temperature than the nominal situation both glasses relax faster than the nominal situation. Due to the higher temperature the screen glass can relax to a more stable equilibrium state. This will result in a decrease of fictive temperature. The cone glass will relax to an equilibrium position at $T_f = \pm 448^\circ\text{C}$.

Notice that in this time interval the decrease of the fictive temperature and thus the structural relaxation of the screen glass is greater than that of the cone glass as can be seen in figure 25(B). Due to structural relaxation the volume will decrease. This will result in a deformation as sketched in figure 11(B).

Because the temperature increase is small the effect of TEC mismatch as sketched in figure 11(A) is smaller than the effect of structural relaxation as sketched in figure 11(B). This can be seen in equation 30. In this time interval the compression of the screen glass is greater than that of the cone glass. The resulting compressive and tensile stresses in the screen and cone glass are clearly visible in figure 15.

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = 4980\text{s}$ in figure 15 would be higher.

3. Between $t = 4980\text{s}$ and $t = \pm 7000\text{s}$ the model is cooled from $T = 442^\circ\text{C}$ to $T = \pm 350^\circ\text{C}$. Due to the mismatch in TEC the screen glass will shrink more than the cone glass. The deformation of the model due to the mismatch in TEC is sketched in figure 11(B).

In this time interval the temperature of the model is decreased rapidly. Because the actual temperature becomes much lower than the fictive temperature of the screen glass it will not relax anymore to its structural equilibrium. Figure 25(A) shows that structural relaxation of the screen glass vanishes for $t > \pm 6000\text{s}$. However the cone glass continues to relax for lower temperatures until $t = \pm 7000\text{s}$.

Figure 25(B) shows that the decrease of the fictive temperature of the cone glass is greater than the decrease of the fictive temperature of the screen glass. This means that the decrease of volume of the cone glass is greater than that of the screen glass. The deformation is as sketched in figure 11(A). Equation 30 shows that the influence of structural relaxation is larger than the influence of mismatch in TEC. The total deformation of the model is as sketched in figure 11(A). This deformation will introduce tensile stresses in the screen glass and compressive stresses in the cone glass.

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = \pm 7000\text{s}$ in figure 15 would be higher.

4. After $t = \pm 7000\text{s}$ the model is cooled from $T = 350^\circ\text{C}$ to room temperature (20°C). For $t > 7000\text{s}$ the decrease in fictive temperature and thus structural relaxation will also vanish for the cone glass. At these 'low' temperatures no structural relaxation will take place. The stresses occur due to the mismatch in TEC. The screen glass will shrink more than the cone glass as sketched in figure 11(B). The stresses in the screen glass will decrease and the stresses in the cone glass will increase.

Notice that the evolution of the stresses in this time interval is almost the same as in the elastic calculation plotted in figure 10. The only difference between the stresses in the elastic and the viscoelastic calculation in this time interval is the presence of stress relaxation in the viscoelastic calculation. Stress relaxation will reduce the absolute values of the stresses. By comparing the figures 10 and 12 one can see that the difference in stress over the time interval is slightly less in the viscoelastic calculation due to stress relaxation.

Due to a higher oven temperature the screen glass will relax more than in the nominal situation. The stress evolution at high temperatures will increase significantly due to the higher decrease in volume compared to the nominal situation. During cooling the effect of TEC mismatch and the increased structural relaxation of the screen glass intensify the stress evolution. The residual stresses increase in their absolute values due to the difference in stress level at $t = \pm 7000\text{s}$ compared to the nominal situation.

Decreased maximum temperature of frit oven The oven temperature in figure 3 is decreased with 5°C . The maximum temperature reached during this cyclis is 432°C . With the same cooling speed the blocks of glass are cooled to room temperature (20°C).

The initial temperature is also decreased with 5°C to 35°C . This has no effect on the viscoelastic calculation of the stresses because at these low temperatures no structural relaxation will occur.

Due to the increase in temperature the frit crystallization temperature of 430°C will be reach at $t = 4637\text{s}$. The stresses at the outside are plotted in figure 16. The stress evolution during the frit process with decreased maximum temperature can be divided into four parts.

1. Between $t = 0\text{s}$ and $t = 4637\text{s}$ the frit has not crystallized and the blocks of glass are not connected and stress free. However structural relaxation occurs due to the high temperatures as can be seen from the decrease in fictive temperature in figure 26.
2. Between $t = 4637\text{s}$ and $t = 4980\text{s}$ the model is heated from $T = 430^\circ\text{C}$ to $T = 432^\circ\text{C}$. At $t = 4637\text{s}$ the frit is crystallized and the blocks of glass

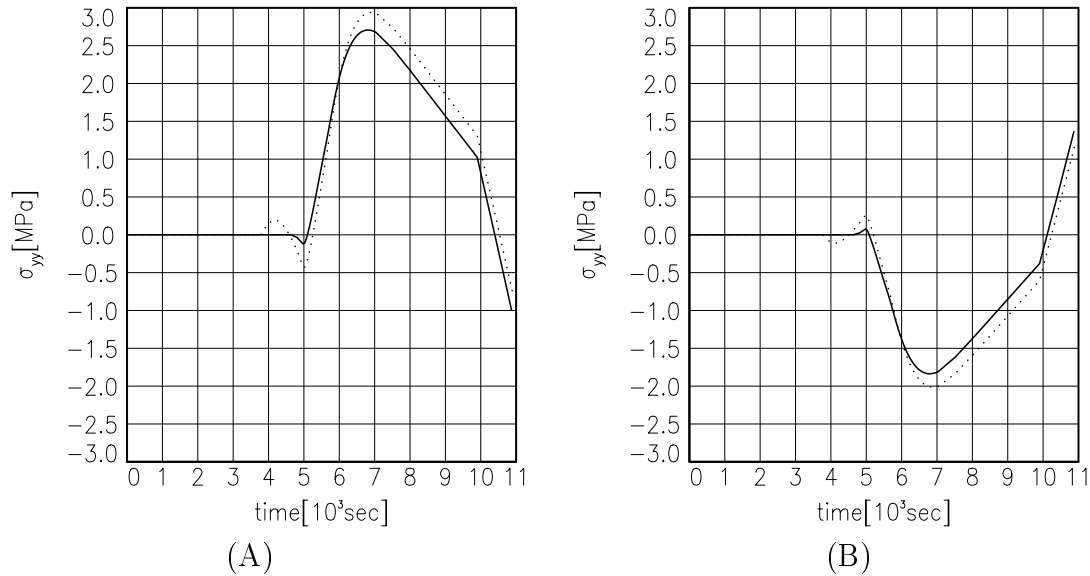


Figure 16: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with decreased maximum temperature of 432°C.

are connected. The stress evolution is caused by a difference in expansion or contraction.

The TEC of the screen glass is greater than the TEC of the cone glass. During heating the screen glass will expand more than the cone glass. The deformation of the blocks is as sketched in figure 11(A).

At these temperatures structural relaxation will also occur. The fictive temperature of the screen glass is greater than that of the cone glass. Because the actual temperature of the blocks is approaching the fictive temperature of the cone glass its structure approaches an equilibrium position as can be seen by the flattening of the curve in figure 26(A).

By comparing figure 24 with figure 26, it can be seen that due to the lower temperature than the nominal situation both glasses relax slower than in the nominal situation. Due to the lower temperature the screen glass relaxes at a lower rate to a less stable equilibrium state than in the nominal situation. This will result in a decrease of fictive temperature which is less than that in the nominal situation. The cone glass will relax to an equilibrium position at $T_f = \pm 448^\circ\text{C}$. The temperatures are still high enough for the cone glass to relax to the equilibrium position of the nominal situation.

Notice that in this time interval the decrease of the fictive temperature and thus the structural relaxation of the screen glass is greater than that of the cone glass as can be seen in figure 26(B). Due to structural relaxation the volume will decrease. This will result in a deformation as sketched in figure 11(B).

Because the temperature increase is small the effect of TEC mismatch as

sketched in figure 11(A) is smaller than the effect of structural relaxation as sketched in figure 11(B) as can be seen in equation 30. In this time interval the compression of the screen glass is greater than that of the cone glass. The resulting compressive and tensile stresses in the screen and cone glass are clearly visible in figure 16. Due to the short time interval these stresses are very small.

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased.

3. Between $t = 4980\text{s}$ and $t = \pm 7000\text{s}$ the model is cooled from $T = 432^\circ\text{C}$ to $T = \pm 350^\circ\text{C}$. Due to the mismatch in TEC the screen glass will shrink more than the cone glass. The deformation of the model due to the mismatch in TEC is sketched in figure 11(B).

In this time interval the temperature of the model is decreased rapidly. Because the actual temperature becomes much lower than the fictive temperature of the screen glass it will not relax anymore to its structural equilibrium. Figure 26(A) shows that structural relaxation of the screen glass vanishes for $t > \pm 6000\text{s}$. However the cone glass continues to relax for lower temperatures until $t = \pm 7000\text{s}$.

Figure 26(B) shows that the decrease of the fictive temperature of the cone glass is greater than the decrease of the fictive temperature of the screen glass. This means that the decrease of volume of the cone glass is greater than that of the screen glass. The deformation is as sketched in figure 11(A). Equation 30 shows that the influence of structural relaxation is larger than the influence of mismatch in TEC. The total deformation of the model is as sketched in figure 11(A). This deformation will introduce tensile stresses in the screen glass and compressive stresses in the cone glass.

The third factor contributing to the stress evolution is stress relaxation. Due to stress relaxation the absolute values of the stresses are decreased. Without stress relaxation the peak stress at $t = \pm 7000\text{s}$ in figure 16 would be higher.

4. After $t = \pm 7000\text{s}$ the model is cooled from $T = 350^\circ\text{C}$ to room temperature (20°C). For $t > 7000\text{s}$ the decrease in fictive temperature and thus structural relaxation will also vanish for the cone glass. At these 'low' temperatures no structural relaxation will take place. The stresses occur due to the mismatch in TEC. The screen glass will shrink more than the cone glass as sketched in figure 11(B). The stresses in the screen glass will decrease and the stresses in the cone glass will increase.

Notice that the evolution of the stresses in this time interval is almost the same as in the elastic calculation plotted in figure 10. The only difference between the stresses in the elastic and the viscoelastic calculation in this time interval is the presence of stress relaxation in the viscoelastic calculation. Stress relaxation will reduce the absolute values of the stresses. By comparing the

figures 10 and 12 one can see that the difference in stress over the time interval is slightly less in the viscoelastic calculation due to stress relaxation.

Due to a lower oven temperature the screen glass will relax less than in the nominal situation. However the frit crystallization temperature is 430°C. This temperature will be reached at almost the end of the heating cycle. Due to the short time at high temperatures above 430°C almost no structural relaxation will take place. The stress evolution at high temperatures is neglectable compared to the nominal situation. During cooling the effect of TEC mismatch and the increased structural relaxation of the cone glass have an opposite effect and reduce stress evolution. The residual stresses increase in their absolute values due to the difference in stress level at $t = \pm 7000$ s compared to the nominal situation.

4.3 Variation of initial fictive temperature

The value and the distribution of the fictive temperature reflects the thermal history of the glass. Before screen and cone glass are fritted together they have had two previous thermal processes. The press and anneal process in which the glass is pressed in its geometric shape and stresses reduced respectively. The initial fictive temperature of the frit process can be changed due to differences in earlier processes.

In this subsection the effect of the thermal history variation by changing the initial fictive temperature is studied. Again the actual and fictive temperature in the glass are assumed uniform.

Increase of initial fictive temperature of G382 cone glass The initial fictive temperature of the cone glass is increased with 5°C to 458°C. The screen and cone glass are fritted with the nominal temperature curve of figure 3.

In figure 17 the stresses are plotted. The calculated fictive temperature curves can be found in figure 27. The initial fictive temperature and thermal process are the same thus the fictive temperature curve of screen glass is the same as in the nominal process.

Comparing figure 24 and 27 shows that due to the higher initial fictive temperature of the cone glass the process of structural relaxation is faster. This results in more deformation as sketched in figure 11(A).

Hence, the stresses in screen and cone glass evolves respectively in a more tensile and compressive way. The described effect on the stresses caused by an increased initial fictive temperature of the cone glass can be noticed by comparing figure 12 with 17.

Decrease of initial fictive temperature of G440 screen glass The initial fictive temperature of the screen glass is decreased with 5°C to 508.1°C. The screen and cone glass are fritted with the nominal temperature curve of figure 3.

In figure 18 the stresses are plotted. The calculated fictive temperature curves can be found in figure 28. The initial fictive temperature and thermal process are the

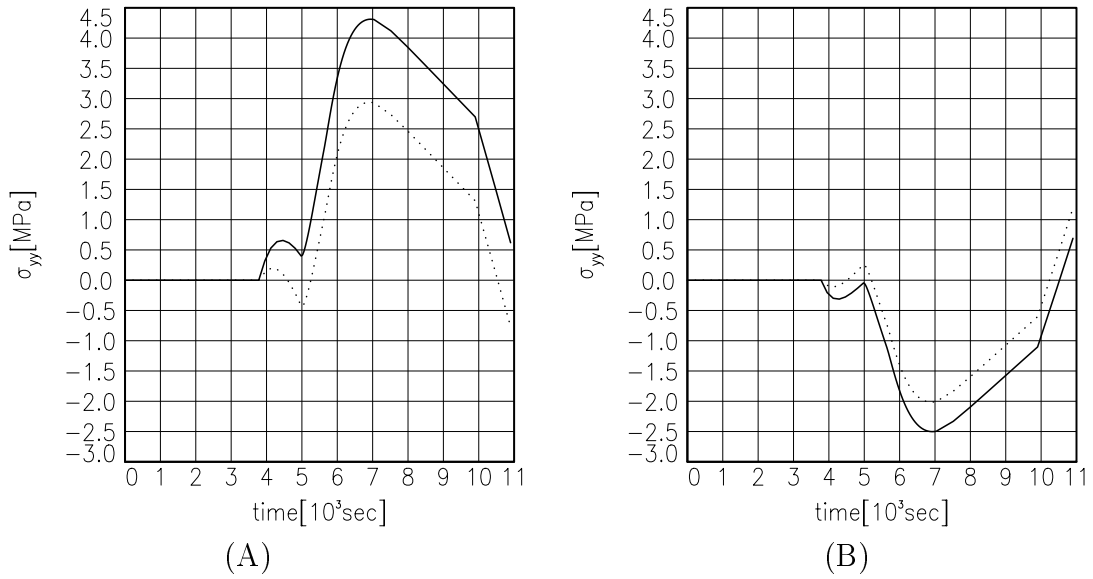


Figure 17: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with increased initial fictive temperature of G382 cone glass. $T_{f_{cone}} = 458^{\circ}\text{C}$.

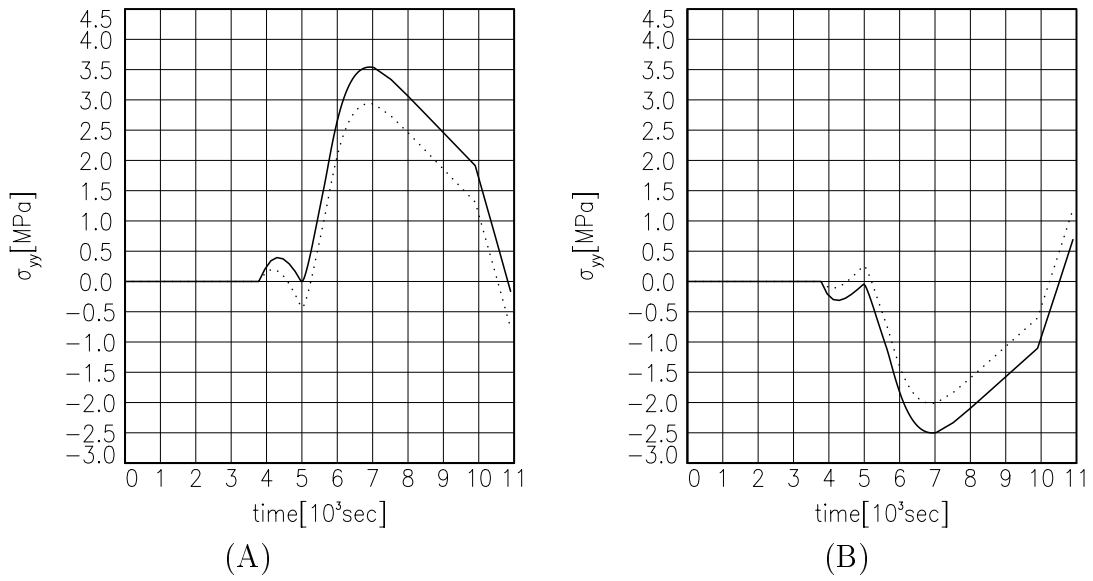


Figure 18: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with decreased initial fictive temperature of G440 screen glass. $T_{f_{screen}} = 508.1^{\circ}\text{C}$.

same thus the fictive temperature curve of cone glass is the same as in the nominal process.

Comparing figure 24 and 28 shows that due to the lower initial fictive temperature of the screen glass the process of structural relaxation is slower. The screen glass reaches its equilibrium state sooner due to the decreased initial fictive temperature and the decrease of fictive temperature slows down. This will result in more deformation as sketched in figure 11(A).

Hence, the stresses in screen and cone glass evolves respectively in a more tensile and compressive way. The described effect on the stresses caused by a decreased initial fictive temperature of the screen glass is found by comparing figure 12 with 18. Notice that the stress evolution during the frit process with increased initial fictive temperature of G382 cone glass is almost the same as the stress evolution during the frit process with decreased initial fictive temperature of G440 screen glass. The difference in stresses compared to the nominal situation is caused by the difference in fictive temperature of screen and cone glass. Increasing the initial fictive temperature of the cone glass by 5°C or decreasing the initial fictive temperature of the screen glass by 5°C will result in a decrease of the difference in fictive temperature between the screen and cone glass by 5°C . The calculated stresses are almost the same because the difference in fictive temperature is almost the same.

Reclaim of screen During manufacturing some CRT's are damaged at the cone. The screen is intact and can be reused to produce another CRT. These screens are called reclaim screens.

A reclaim screen has had already the thermal frit process. The thermal history of a reclaim screen is different compared to a 'fresh' screen. Figure 24 shows that the decrease of fictive temperature in the screen glass during the nominal frit process is 4.3°C .

The evolution of stresses during the frit process in a CRT with a reclaim screen and a 'fresh' cone can be compared with the viscoelastic calculation of a decreased initial fictive temperature of G440 screen glass. The decrease in initial fictive temperature of a reclaim screen is almost the same as the above described situation in paragraph *Decrease of initial fictive temperature of G440 screen glass*.

Decrease of initial fictive temperature of G382 cone glass The initial fictive temperature of the cone glass is decreased with 5°C to 448°C . The screen and cone glass are fritted with the nominal temperature curve of figure 3.

In figure 19 the stresses are plotted. The calculated fictive temperature curves are found in figure 29. The initial fictive temperature and thermal process are the same thus the fictive temperature curve of screen glass is the same as in the nominal process.

Comparing figure 24 and 29 shows that due to the lower initial fictive temperature of the cone glass the process of structural relaxation is slower. Due to the lower initial fictive temperature the equilibrium state of the cone glass will be reached sooner. This will result in more flattening of the fictive temperature curve. The cone glass

relaxes less than in the nominal situation and the deformation is more like the one sketched in figure 11(B).

Hence, the stresses in screen and cone glass evolves respectively in a more compressive and tensile way. The described effect of decreased initial fictive temperature of the cone glass on the stresses is found by comparing figure 12 with figure 19.

Increase of initial fictive temperature of G440 screen glass The initial fictive temperature of the screen glass is increased with 5°C to 518.1°C. The screen and cone glass are fritted with the nominal temperature curve of figure 3.

In figure 20 the stresses are plotted. The calculated fictive temperature curves is shown in figure 30. The initial fictive temperature and thermal process are the same thus the fictive temperature curve of cone glass is the same as in the nominal process.

Comparing figure 24 and 30 shows that due to the higher initial fictive temperature of the screen glass the process of structural relaxation will be faster. This will result in more deformation as sketched in figure 11(B).

Hence, the stresses in screen and cone glass evolves respectively in a more compressive and tensile way. The described effect of increased initial fictive temperature of the screen glass is found by comparing figure 12 with 20.

Notice that the stress evolution during the frit process with decreased initial fictive temperature of G382 cone glass is almost the same as the stress evolution during the frit process with increased initial fictive temperature of G440 screen glass. The difference in stresses compared to the nominal situation is caused by the difference in fictive temperature of screen and cone glass. Decreasing the initial fictive temperature of the cone glass by 5°C or increasing the initial fictive temperature of the screen glass by 5°C will result in an increase of the difference in fictive temperature between the screen and cone glass by 5°C. The calculated stresses are almost the same because the difference in fictive temperature is almost the same.

Reclaim of cone During manufacturing some CRT's are damaged at the screen. The cone is intact and can be used to produce another CRT.

A reclaim cone has had already the thermal frit process. The thermal history of a reclaim cone is different compared to a 'fresh' cone. Figure 24 shows that the decrease of fictive temperature in the cone glass during the nominal frit process is 10.7°C.

The evolution of stresses during the frit process in a CRT with a reclaim cone and a 'fresh' screen can be compared with the viscoelastic calculation of a decreased initial fictive temperature of G382 cone glass. The decrease in initial fictive temperature of a reclaim cone is about twice as much as the above described situation in paragraph *Decrease of initial fictive temperature of G382 cone glass*. The structural relaxation of the cone glass will be negligible compared to the relaxation of the screen glass. The deformation of the blocks is as sketched in figure 11(B) and will result in more compressive and tensile situation for screen and cone glass respectively as plotted in figure 19.

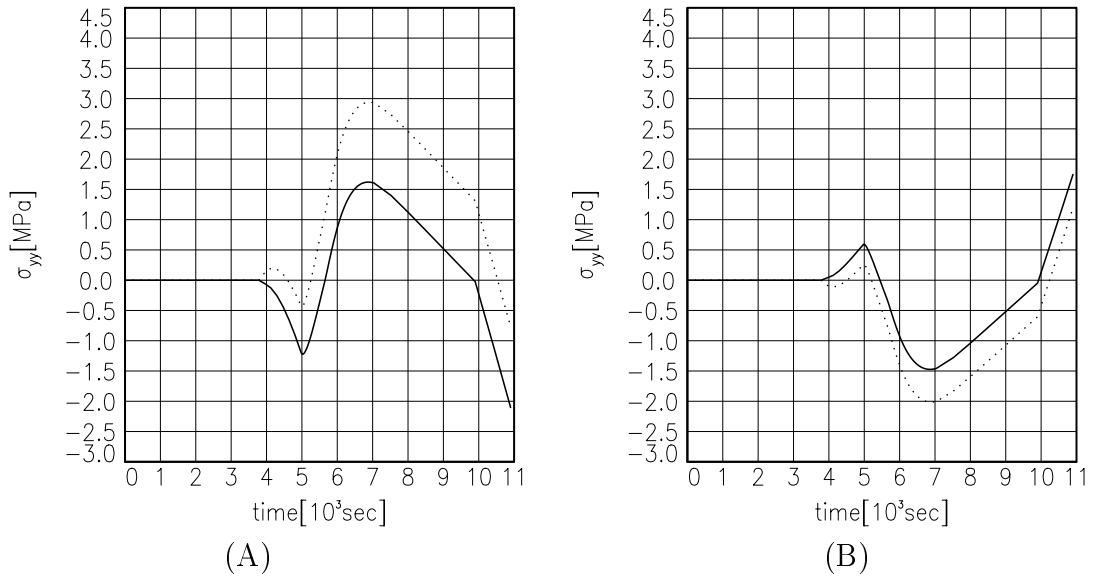


Figure 19: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with decreased initial fictive temperature of G382 cone glass. $T_{f_{cone}} = 448^{\circ}\text{C}$.

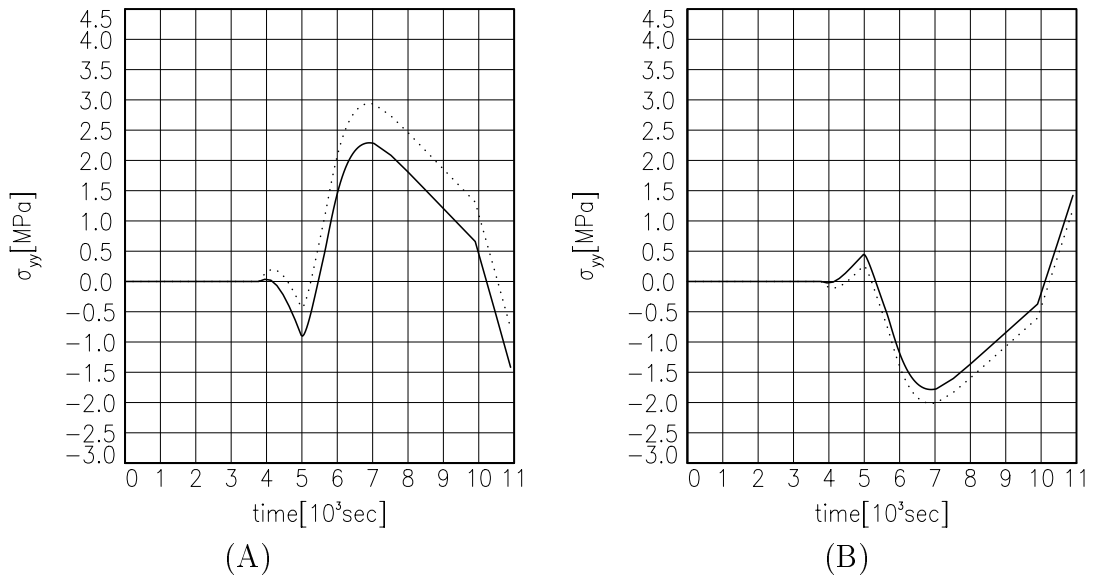


Figure 20: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with increased initial fictive temperature of G440 screen glass. $T_{f_{screen}} = 518.1^{\circ}\text{C}$.

4.4 Variation in frit crystallization

In all previous stress analysis the frit is assumed to crystallize instantaneously at $T = 430^\circ\text{C}$. However no precise data is available about frit crystallization. In this subsection the effect of frit crystallization on the stresses in the blocks of glass will be discussed.

The calculations in this subsection are carried out with different initial fictive temperatures than before. In this case the initial fictive temperatures for screen and cone glass are 524°C and 463°C respectively. The evolution of stresses in this situation can be compared by combining the situation with an increased initial fictive temperature of both screen and cone glass as described in section 4.3.

In this subsection the nominal oven settings are used. Again the temperature and fictive temperature in the glass is uniform.

Frit crystallization function Until now the frit is assumed to crystallize instantaneously. In reality the crystallization process will take some time. Therefore some viscoelastic calculations have been carried out using different assumptions of the crystallization process.

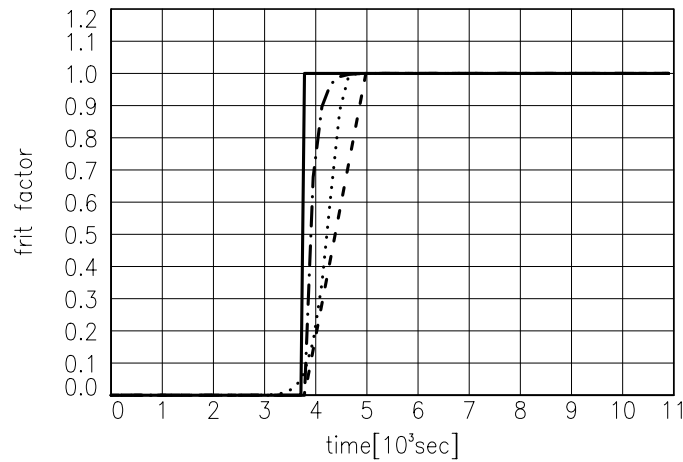


Figure 21: Frit factors plotted with a solid, dashed, dash-dotted and dotted line calculated from equations 31, 32, 33 and 34 respectively.

1. The nominal frit crystallization function is a step function:

$$\epsilon_{i+1}^{th} = u_{430^\circ\text{C}}(T)\epsilon_{i+1}^{th} \quad (31)$$

where ϵ_{i+1}^{th} is the solution of equation 30 and ϵ_{i+1}^{th} the thermal strain used in the viscoelastic calculation.

The frit crystallization function and the evolution of the stresses are plotted with a solid line in figure 21 and 22 respectively.

2. Another assumption for the behaviour of frit crystallization can be a linear one. Assume that the frit crystallization process starts at 430°C and the frit linear hardens until $T = 437^\circ\text{C}$. The frit crystallization function becomes:

$$\epsilon_{i+1}^{th} = \begin{cases} 0, & \text{if } T < 430^\circ\text{C} \\ (8.33 \cdot 10^{-4}t - 3.15)\epsilon_{i+1}^{th}, & \text{if } 430^\circ\text{C} \leq T < 437^\circ\text{C} \\ \epsilon_{i+1}^{th}, & \text{if } T \geq 437^\circ\text{C} \end{cases} \quad (32)$$

The frit crystallization function and the evolution of the stresses are plotted with a dashed line in figure 21 and 22 respectively.

3. Another assumption for the behaviour of frit crystallization can be a relaxation function towards full crystallization of the frit. Assume that the frit crystallization process starts at 430°C and the frit is for more than 99% crystallized at $T = 437^\circ\text{C}$. The frit crystallization function becomes:

$$\epsilon_{i+1}^{th} = \begin{cases} 0, & \text{if } T < 430^\circ\text{C} \\ \left(1 - e^{\frac{3780-t}{150}}\right) \epsilon_{i+1}^{th}, & \text{if } T \geq 430^\circ\text{C} \end{cases} \quad (33)$$

The frit crystallization function and the evolution of the stresses are plotted with a dash-dotted line in figure 21 and 22 respectively.

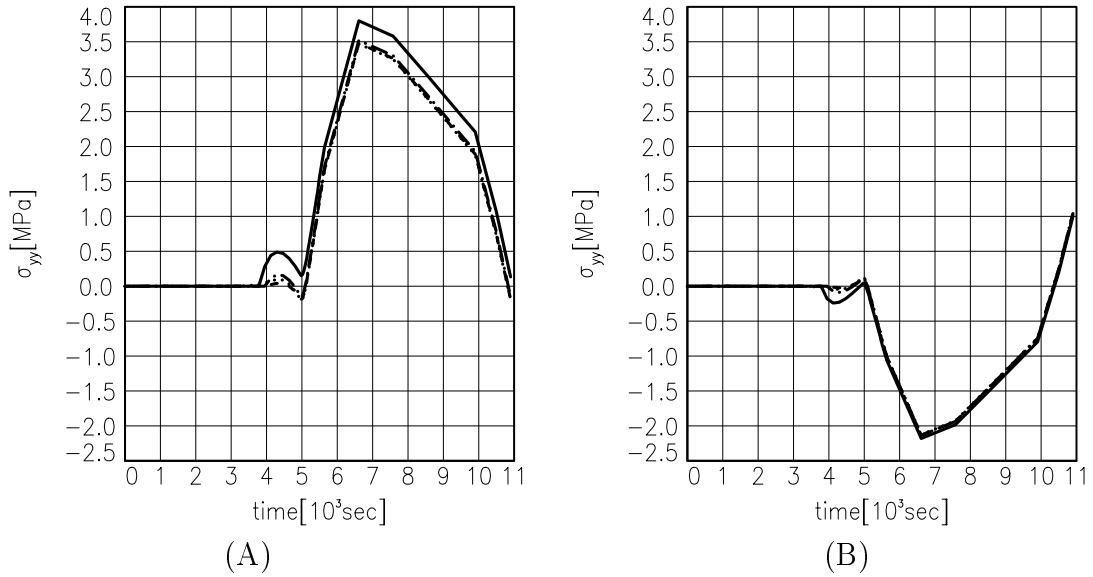


Figure 22: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with different frit functions. The plotted lines correspond with the lines in figure 21.

4. Another assumption for the behaviour of frit crystallization can be a relaxation function from no crystallization towards full crystallization of the frit. The

frit is for $\pm 7\%$ crystallized at $T = 430^\circ\text{C}$ and more than 99% crystallized at $T = 437^\circ\text{C}$. The frit crystallization function becomes:

$$\epsilon_{i+1}^{th} = \left(1 - e^{-\left(\frac{t}{4300}\right)^{20}}\right) \epsilon_{i+1}^{th} \quad (34)$$

The frit crystallization function and the evolution of the stresses are plotted with a dotted line in figure 21 and 22 respectively.

Figure 21 shows that the crystallization process described with equations 32, 33 and 34 are slower than the nominal crystallization process described by equation 31. The resulting stresses during the hardening of the frit will be smaller because the frit yields to the generated shear stresses. This effect is shown in figure 22.

The difference in stresses caused by the different assumptions of the frit crystallization has occurred before the maximum temperature of 437°C . After the maximum temperature at $t = 4980\text{s}$ in all four described situations the frit is fully⁴ crystallized and the evolution in stresses is the same as in the nominal process.

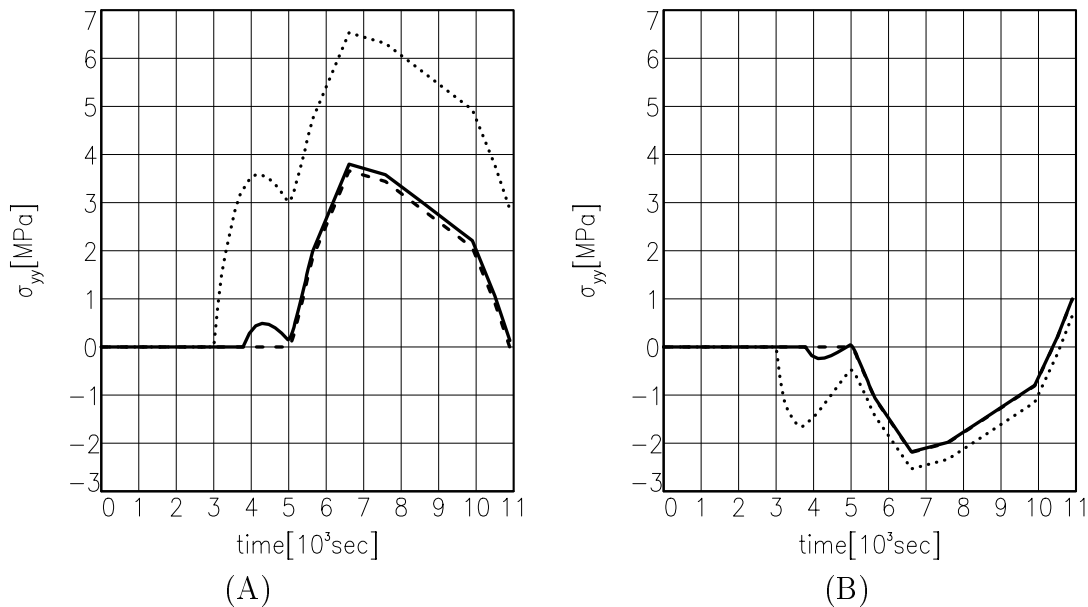


Figure 23: Stresses in Y-direction in the screen(A) and cone(B) glass in a viscoelastic calculation with different frit crystallization temperatures. The stresses plotted with a solid, dashed and dotted line occur due to a frit crystallization temperature of 430°C , 400°C and 437°C respectively.

Frit crystallization temperature Until now the frit is assumed to crystallize at 430°C . Two other viscoelastic calculations have been made with other frit crystallization temperatures.

⁴For more than 99%.

1. The frit crystallization temperature is 400°C at $t = 3000\text{s}$. The difference in stress evolution compared with the nominal situation is caused by the difference in structural relaxation and TEC between $T = 400^{\circ}\text{C}$ and $T = 430^{\circ}\text{C}$.

Figure 24(B) shows that structural relaxation and thus decrease in volume in the cone glass is greater compared to screen glass. During heating from 400°C at $t = 3000\text{s}$ to 430°C at $t = 3780\text{s}$ this will result in extra deformation like sketched in figure 11(A).

The stresses in screen and cone will be increased and decreased respectively. The evolution of the stresses in this calculation are plotted in figure 23 with a dashed line.

2. The frit crystallization temperature is 437°C at $t = 4980\text{s}$. Notice that the frit crystallizes at the maximum temperature of the frit process.

This situation can be compared with a decrease in maximum temperature as described in paragraph *Decreased maximum temperature of frit oven* in section 4.2. The frit is hardened at the highest temperature reached.

The evolution of the stresses in the this calculation are plotted in figure 23 with a dotted line.

5 Conclusions and recommendations

5.1 Conclusions

- Stresses occurring in the glass during the frit process are not only caused by difference in thermal expansion coefficient but mainly by structural rearrangement at higher temperatures.
- A relatively simple elastic model of glass is not sufficient to simulate the real frit process.
- Fritting with both higher and lower maximum oven temperature settings will decrease the absolute value of the residual stresses in the screen glass.
- Thermal history of the glass significantly influences the stress evolution during the frit process. Reason for this effect is the degree of compaction of the initial glass products; a rapid cooled ‘fresh’ glass will be subject to high compaction during subsequent thermal processes such as the frit process.
 - A reclaim screen will decrease the residual stresses. However the maximum stresses during cooling will increase. In some cases it is possible to change the sign of the residual stresses.
 - A reclaim cone will increase the residual stresses in the glass.
- The difference in frit crystallization dynamics near the maximum temperature of the frit process is negligible.
- Crystallization of the frit at lower temperatures causes the absolute values of the stresses to increase.
- The calculated residual stress is strongly dependent on the choice of the initial parameter initial fictive temperature and the frit process parameters oven temperature settings and frit crystallization dynamics. Therefore a careful validation of the boundary conditions and assumptions has to be made for reliable modelling.

5.2 Recommendations

- Simulations should be carried out on a real model of a CRT to compare the results in this report with the stress evolution in a real CRT model.
- New calculations should be made with the new measured data (Van den Eijnde [9]) of the thermal expansion coefficient in the liquid state.
- Calculations have to be carried out which include a non uniform transient temperature distribution in the glass.

- Calculations have to be carried out with other types of glasses. In this way the stress and structural relaxation behaviour of the glasses on the residual stresses can be investigated.
 - With different types of glasses the best combination can be determined to produce the desired residual stress level.
- Calculations should be carried out to investigate the influence of a non uniform initial fictive temperature distribution on the residual stresses in the glass.

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A Figures of fictive temperature

A.1 Influence of oven temperature

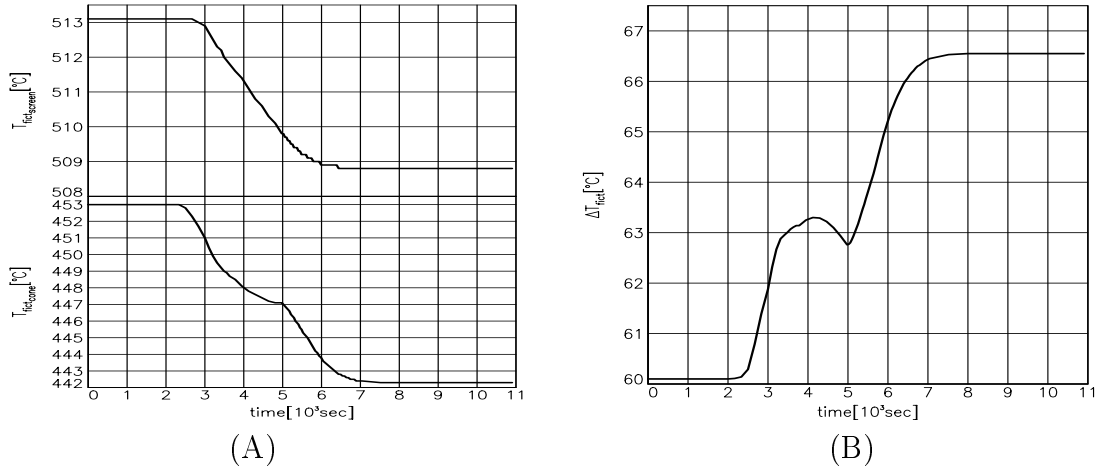


Figure 24: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the nominal frit process with top temperature 437 $^{\circ}\text{C}$ and frit crystallization temperature 430 $^{\circ}\text{C}$ at $t = 3780\text{s}$.

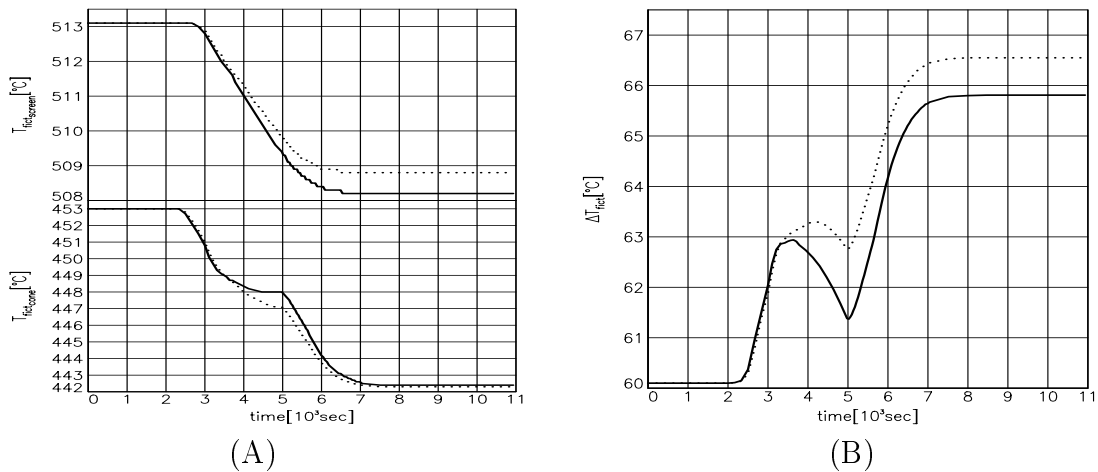


Figure 25: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process with increased top temperature 442 $^{\circ}\text{C}$. The frit crystallization temperature is 430 $^{\circ}\text{C}$ at $t = 3600\text{s}$.

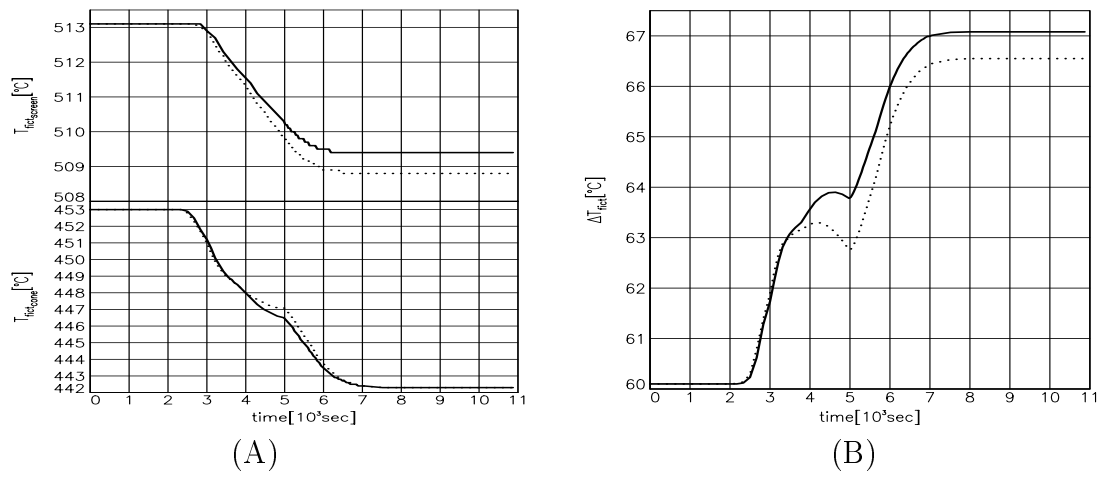


Figure 26: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process with decreased top temperature 432°C. The frit crystallization temperature is 430°C at $t = 4637$ s.

A.2 Influence of initial fictive temperature

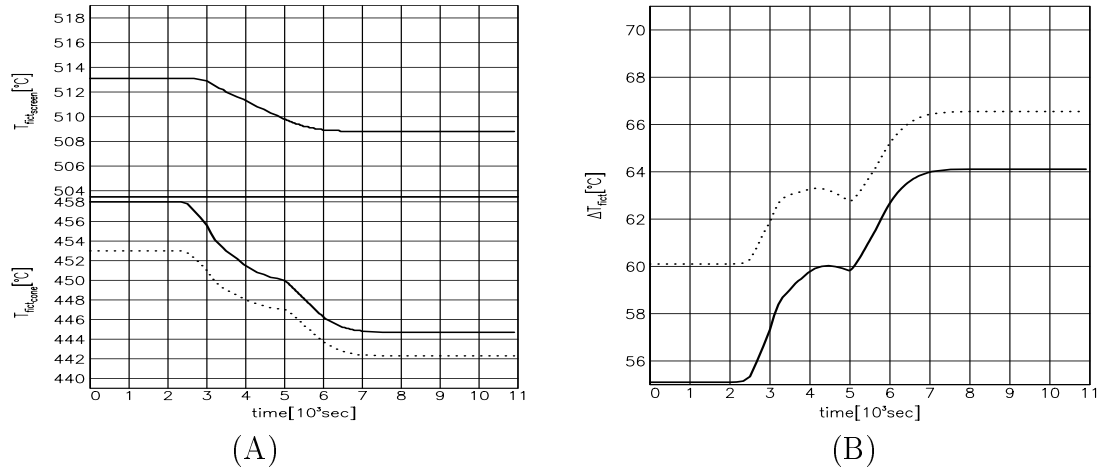


Figure 27: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process. The initial fictive temperature of the cone glass is 5°C higher than in the nominal situation.

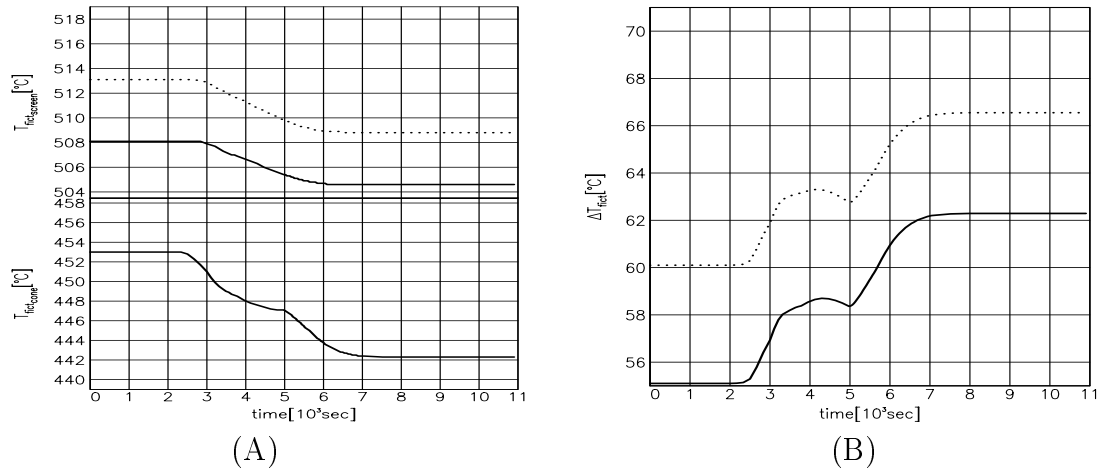


Figure 28: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process. The initial fictive temperature of the screen glass is 5°C lower than in the nominal situation.

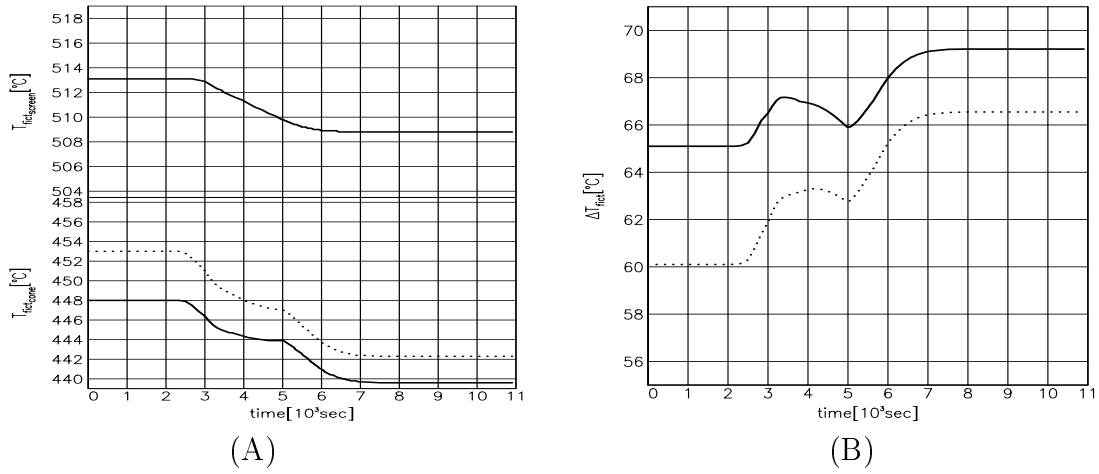


Figure 29: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process. The initial fictive temperature of the cone glass is 5°C lower than in the nominal situation.

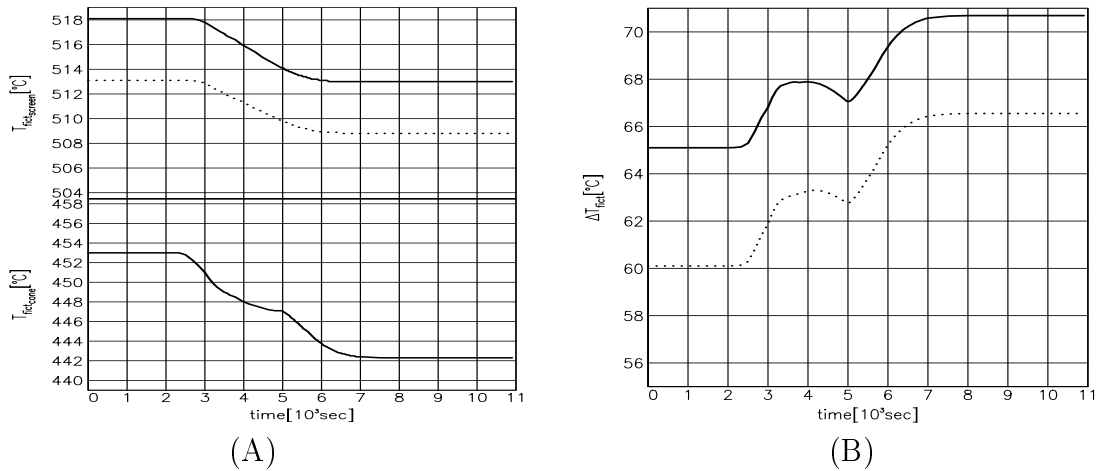


Figure 30: Fictive temperature in screen and cone glass(A) and the difference between the fictive temperature of screen and cone glass(B) during the frit process. The initial fictive temperature of the screen glass is 5°C higher than in the nominal situation.

B Distribution of stresses

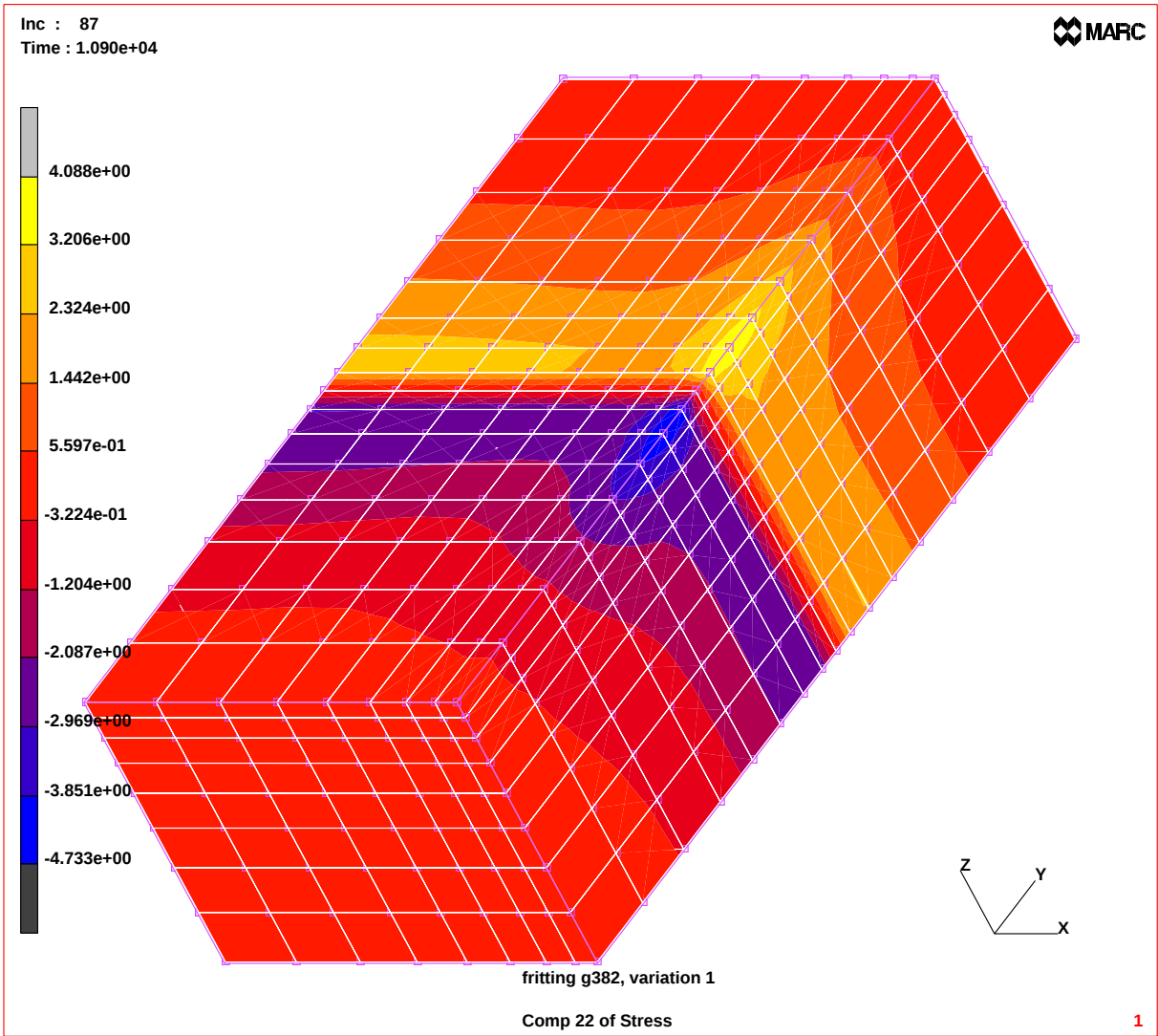


Figure 31: Residual stress distribution after an elastic frit simulation

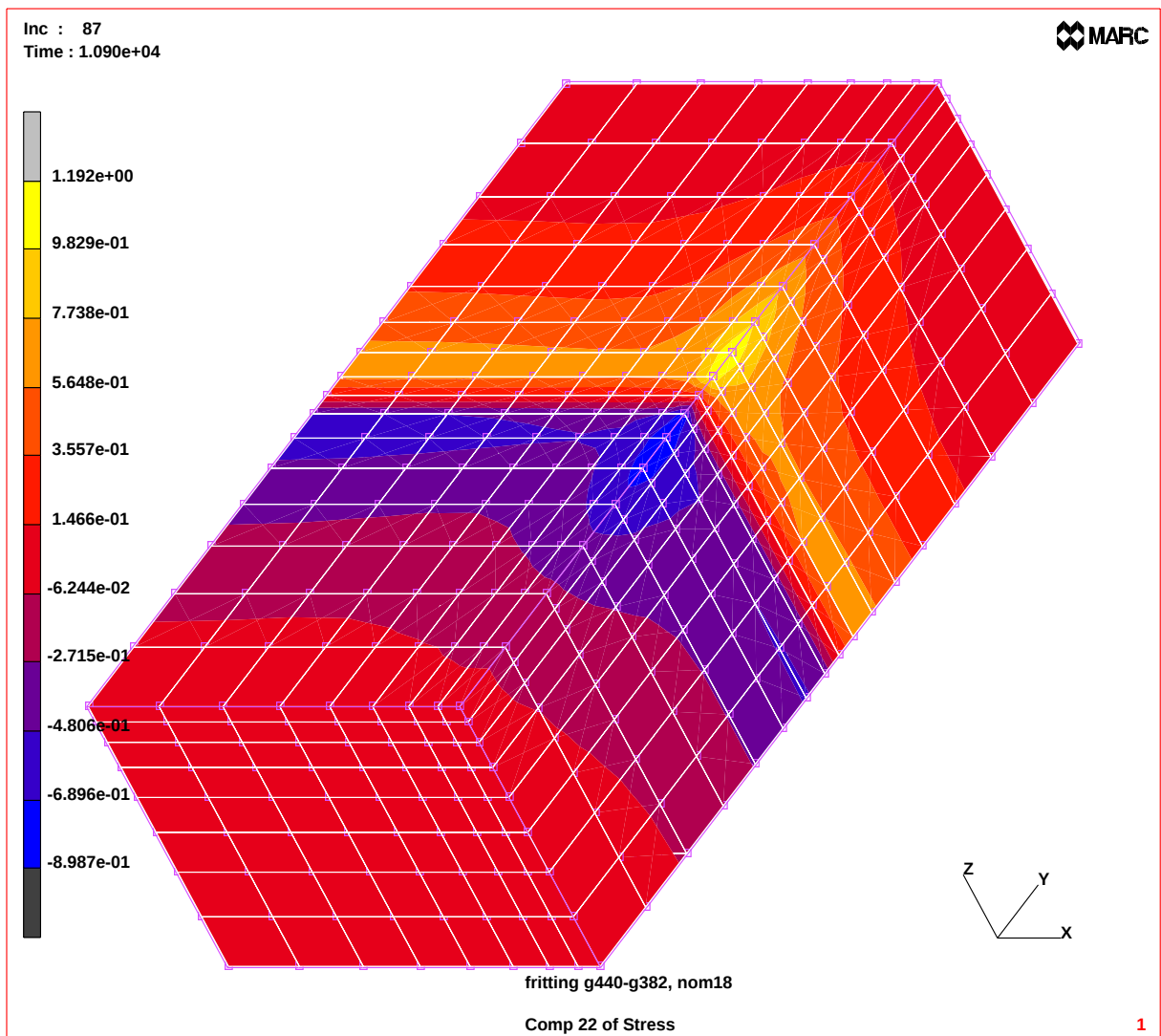


Figure 32: Residual stress distribution after a viscoelastic frit simulation

C Discretization error

In the simulation of the frit process by a finite element method, the unknown exact solution of the governing equations is approximated using a discretization method. Differential equations of the following form have to be evaluated:

$$y' = f(t, y) \quad (35)$$

The numerical solution of differential equation 35, using a first order implicit scheme is:

$$y_{n+1} = y_n + \Delta t f(t_{n+1}, y_{n+1}) \quad (36)$$

If y_n is exact, the discretization error in the solution at t_{n+1} of the differential equation 35 is:

$$y(t_{n+1}) = y_{n+1} + c_2(\Delta t)^2 + c_3(\Delta t)^3 + \dots \quad (37)$$

Integrating from y_0 the number of time steps needed to reach t_{n+1} is of order $\frac{1}{\Delta t}$. Then a discretization error occurs in y_n and the error in y_{n+1} with the scheme of equation 36 is:

$$y(t_{n+1}) = y_{n+1} + C_1(\Delta t) + C_2(\Delta t)^2 + \dots \quad (38)$$

Three time step sizes Δt , $\frac{1}{2}\Delta t$ and $\frac{1}{4}\Delta t$ are introduced. Substitution of these time step sizes in equation 38 results in three equations:

$$y(t_{n+1}) = y_{n+1}^{\Delta t} + C_1(\Delta t) + C_2(\Delta t)^2 + \dots \quad (39)$$

$$y(t_{n+1}) = y_{n+1}^{\frac{1}{2}\Delta t} + \frac{1}{2}C_1(\Delta t) + \frac{1}{4}C_2(\Delta t)^2 + \dots \quad (40)$$

$$y(t_{n+1}) = y_{n+1}^{\frac{1}{4}\Delta t} + \frac{1}{4}C_1(\Delta t) + \frac{1}{16}C_2(\Delta t)^2 + \dots \quad (41)$$

Eliminating $y(t_{n+1})$ in equations 39, 40 and 41 yields the following three equations:

$$y_{n+1}^{\frac{1}{4}\Delta t} - y_{n+1}^{\Delta t} = \frac{3}{4}C_1\Delta t + \dots \quad (42)$$

$$y_{n+1}^{\frac{1}{2}\Delta t} - y_{n+1}^{\Delta t} = \frac{1}{2}C_1\Delta t + \dots \quad (43)$$

$$y_{n+1}^{\frac{1}{4}\Delta t} - y_{n+1}^{\frac{1}{2}\Delta t} = \frac{1}{4}C_1\Delta t + \dots \quad (44)$$

In figure 33 the left hand side of equations 42, 43 and 44 are plotted for the difference in thermal strain ε^{th} between the screen and the cone glass. Notice that the error $\Delta\varepsilon^{th\Delta t} - \Delta\varepsilon^{th\frac{1}{4}\Delta t}$ is three times that of $\Delta\varepsilon^{th\frac{1}{2}\Delta t} - \Delta\varepsilon^{th\frac{1}{4}\Delta t}$ and $\Delta\varepsilon^{th\frac{1}{2}\Delta t} - \Delta\varepsilon^{th\Delta t}$ is halved if the time step size Δt is divided by two. Hence, the error in thermal strain ε^{th} is of order Δt as it should be.

If the difference in stresses for decreasing time step sizes is plotted in a figure the same effect can be noticed as in figure 33. The error reduces with a half if the step size is divided by two.

The decrease in discretization error proves that the numerical solution of the differential equation converges with order Δt , as expected by equation 38.

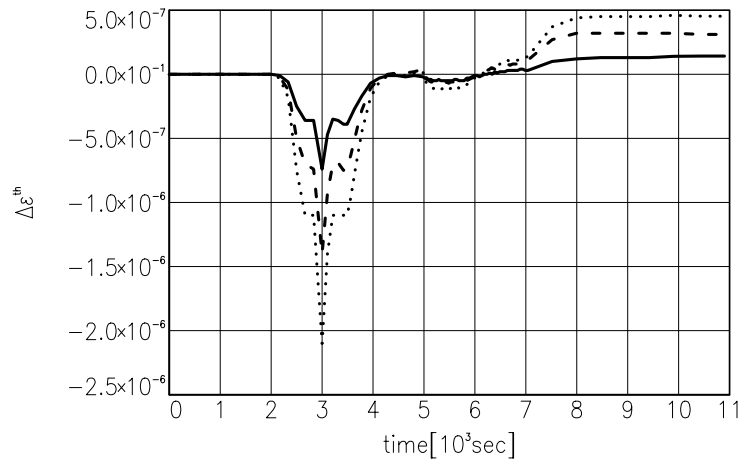


Figure 33: Difference in thermal strain ε^{th} between screen and cone glass calculated with different time step sizes. The solid line is the difference between the solutions calculated with time step $\frac{1}{2}\Delta t$ and $\frac{1}{4}\Delta t$. The dashed line is the difference between the solutions calculated with time step Δt and $\frac{1}{2}\Delta t$. The dotted line is the difference between the solutions calculated with time step Δt and $\frac{1}{4}\Delta t$.

Author M.P.M. Rhijnsburger
Title Viscoelastic modelling of stresses in glass
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