Preface

This Master Thesis was carried out from December 2008 to June 2009 and has been a collaboration between Sony Ericsson Mobile Communications AB and the Division of Machine Design, Faculty of Engineering, Lund University. The project objective was to perform a study on how 3D-glass can be used to create an attractive and distinctive keypad for future mobile phones, and it is the final part of the Master's Program in Mechanical Engineering with Industrial Design at Lund University.

First of all, I would like to thank my supervisor at SEMC, Georgeta Anton (Staff Engineer - Mechanical Development), for her support and engagement throughout the project, and my manager at SEMC, Christian Axelsson (Manager – Mechanical Development), for giving me the opportunity to perform my Master Thesis within an interesting and unexplored technology area. I would also like to express my gratitude towards other employees at SEMC who contributed to my work by answering questions and giving valuable inputs. Thank you all for helping me complete this Master Thesis.

I also would like to thank my supervisor at Lund University, Karl-Axel Andersson (Visiting Senior Lecturer – Division of Industrial Design) for valuable comments and discussions regarding my work.

Last but not least, I would like to thank my family and my friends for their great support during this Master Thesis and the preceding four years of graduate studies. Without you, none of this would have been possible.

Lund, June 2009

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Abstract

The competition regarding market shares in the mobile handset industry is tough. Today the mobile phone is more and more becoming a personal accessory and trends in shape, color and material are changing rapidly. The keypad is one of a phone's many components which the end user gets in touch with first. It is used to activate the phone, and it is what the user feels and looks at initially. SEMC believes that offering a product made with new, exciting materials and unique shapes would give the company an added value on the mobile phone market.

Therefore, the objective of this Master Thesis has been to perform a study on how 3D-glass can be used to develop an attractive and distinctive keypad, and thereby create a more uniform glass impression for the entire front on future mobile phones of SEMC. Limitations, challenges, possibilities and advantages regarding keypad design and production have been examined. The result from the study is meant to increase the knowledge of this area to the level where a decision can be made whether a 3D-glass keypad is a realistic feature or not for future mobile phone concepts.

The project consists of three main phases - a theoretical study phase followed by an empirical study phase and a test phase. During the theoretical study phase two pre-studies were carried out; one within glass materials and one within keypad design. The empirical study phase included close contact with suppliers in the glass forming industry and keypad suppliers. Different production methods and combination of suppliers were considered, the keypad design chosen as a base was alternated, the artwork was revised and several possible aesthetic applications and after treatments of the glass keys were evaluated.

After this realization phase, the physical 3D-glass keypad samples were then evaluated through a number of tests performed in the test lab at SEMC in Lund. The outcome of the tests was analyzed and a final evaluation of all the different concepts was performed.

Ultimately, the project resulted in a design guideline, where recommendations for 3D-glass as a design material for keypads were made, as well as suggestions on areas for further studies.

Keywords:
Sony Ericsson Mobile Communications
3D-glass
Keypad
Manufacturing process
Test & Verification
Design guideline

Sammanfattning

Konkurrensen inom mobiltelefonsbranschen är enormt stor. De senaste åren har mobiltelefonen alltmer blivit en produkt som speglar människors personlighet, där kraven ökar och trender inom form, färg och material ändras hela tiden. En telefons tangentbord är en viktig del, då den används frekvent och är det element som användaren ofta kommer i kontakt med först. Att utforska nya material och designmöjligheter inom det här området är därför något som både är intressant och viktigt för Sony Ericsson. Genom att erbjuda en produkt tillverkad av nya och spännande material i unika former hoppas man att företaget ska få ett ökat värde på marknaden och dessutom särskilja sig från konkurrenterna,

Syftet med det här projektet har varit att studera hur tredimensionellt format glas kan användas för att skapa ett attraktivt och distinkt tangentbord. Förhoppningen är att ett sådant tangentbord ska bidra till att ge framtida telefoner ett enhetligt intryck, men såväl front som LCD och tangentbord tillverkat av glas. Definitionen på 3D-glas har fastställts som ett glas med icke enhetlig tjocklek, komplexa former och dubbelkrökta ytor. Begränsningar, utmaningar, möjligheter och fördelar inom design och tillverkning har utforskats, med tanken att öka kunskapen inom området till en nivå där beslut kan fattas kring huruvida ett tangentbord i tredimensionellt glas är ett realistiskt koncept för framtida mobiltelefoner eller inte.

Studien har huvudsakligen genomförts i tre delar:

- En teoretisk studiefas
- En empirisk studiefas
- En test- och verifieringsfas

Under den inledande teoretiska studiefasen utfördes två förstudier. Den första var inom glas, där information om olika glasmaterial och tillverkningsmetoder samlades in via litteratur, Internetkällor, interna företagsrapporter och tidigare genomförda glasstudier. Även potentiella leverantörer kontaktades och bidrog med värdefull kunskap. Den andra förstudien gällde tangentbordsdesign, där erfarenheter och riktlinjer upprättade av Sony Ericsson var den främsta informationskällan. Tillsammans med önskemål och idéer från ett antal interna företagsavdelningar utgjorde förstudierna en bra bas för det fortsatta projektet.

Den empiriska studiefasen inkluderade nära kontakt med företag inom glastillverkningsindustrin och olika tangentbordsleverantörer. Olika produktionsmetoder studerades närmre, en existerande tangentbordsdesign valdes ut och modifierades för att passa glas bättre, designen av knapparnas ikoner reviderades och ett flertal estetiska koncept och ytbehandlingsmetoder utvärderades. Även kostnader granskades i det här stadiet. Insamlade fakta och information kom här huvudsakligen från diskussioner med olika leverantörer och därför var deras kompetens och erfarenhet av liknande projekt en viktig och avgörande aspekt för resultatet av studien. Beslut fattades om att två olika

produktionsmetoder skulle användas och utvalda leverantörer tillverkade de fysiska proverna av tangentbord med glasknappar. Totalt togs 16 stycken olika koncept fram, med varierande tillverkningsmetod, typ av glas, ytbehandling och applicering av ikoner.

Efter denna realiserande fas genomfördes en test- och verifieringsfas, där de framtagna tangentborden utvärderades genom en rad olika tester. Glasknapparnas motståndskraft gentemot bland annat termisk chock, UV-strålning, slag och slitage undersöktes och resultaten av testerna analyserades baserat på givna kravspecifikationer. De olika tillverkningsmetodernas fördelar respektive nackdelar vägdes mot varandra och en utvärdering av de olika koncepten utfördes, där aspekter som kostnad, designbegränsningar och lämplighet för massproduktion vägdes in.

Tillsammans med den vunna kunskapen från de teoretiska och empiriska faserna sammanställdes testresultaten, och riktlinjer för design med 3D-glas presenterades liksom förslag på områden för fortsatta studier.

Terminology

Below is a description of acronyms and abbreviations used in this report.

BtB	Board to Board
CDC	Creative Design Center. An organization within SEMC.
DUT	Device Under Test
FEM	Finite Element Method
LED	Light-Emitting Diode
MDS	Metal Dome Sheet
PBA	Printed Board Assembly
PCB	Printed Circuit Board
SEMC	Sony Ericsson Mobile Communications AB
TPU	Thermoplastic Polyurethane
TRM	Technology Road Map
TWG	Technology Working Group. An organization within SEMC.
UI	User Interface. An organization within SEMC.

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1. Introduction

The following chapter introduces the background of the Master Thesis, as well as defines the project objective, the problem statement and the project scope.

1.1 Sony Ericsson Mobile Communications AB

Sony Ericsson Mobile Communications AB (SEMC) is a global provider of mobile multimedia devices, including feature-rich phones, accessories and PC cards. The products combine powerful technology with innovative applications for mobile imaging, music, communications and entertainment. The net result is that Sony Ericsson is an enticing brand that creates compelling business opportunities for mobile operators and desirable, fun products for the end users [1].

The company was founded in 2001 and is a joint venture between Telefonaktiebolaget LM Ericsson and Sony Corporation. SEMC is owned equally by Ericsson and Sony and announced its first joint products in March 2002 [1]. The company mission is to establish Sony Ericsson as the most attractive and innovative global brand in the mobile handset industry [2].

The mobile handset market is customer driven and the consumers demand the latest in design and functions, which require a rapid and innovative technological development. The competition is high and it is important to stay ahead. Regarding the strategic direction, SEMC believe that they must grow to survive and differ from the competitors in order to generate defendable market positions [3].

1.2 Project background

As mentioned above, the competition regarding market shares in the mobile handset industry is tough. The main target is to satisfy the customers (the purchasers) as well as the consumers (the end users). Today the mobile phone is more and more becoming a personal accessory and trends in shape, color and material are changing rapidly [4]. Therefore, it is of great interest and importance for SEMC to explore new grounds regarding future materials, design features, production methods etc. In order to do this, knowledge about how product design and trends affect the manufacturing processes and mechanical design with regards to material is essential.

The keypad is one of a phone's many components which the end user gets in touch with first. It is used to activate the phone, and it is what the user feels and looks at initially. Being that first impressions last, keypad design is of great importance and requires understanding of several disciplines, such as user interface, ergonomics, industrial design and mechanics [5].

Today, SEMC primarily works with different types of plastics and metals, but is now anxious to look at new materials. A possible alternative could be glass. Several studies and tests have been performed, where glass has been used on the back side of the phone as well as for the LCD. To be able to present an entire glass mobile phone concept sometime in the future, it is now interesting to explore the possibilities of using glass keypads, in particular glass keypads with non-uniform thickness keys. SEMC believes that offering a product made with new, exciting materials and unique shapes would give the company an added value on the mobile phone market.

1.3 Project stakeholders

This Master Thesis was commissioned by the Mechanical Development Department at SEMC in Lund. The project emerges from the department's wish to identify new materials for keypad design and together with two other company divisions they are the main stakeholders of the project. Below follows a short description of these three divisions.

1.3.1 Mechanical Development Department

The Mechanical Development Department at SEMC strives to be recognized as a dedicated and reliable supplier of first-class mechanical design. Their mission is to "provide innovative high volume manufacturable designs, which meet the product quality and performance requirements at the right cost" [6]. The teams of mechanical designers play an essential role, as they transform the proposals from CDC into realistic and technical solutions. Their 3D designs are later used by the suppliers when manufacturing the actual products. The department is also involved in deciding the color, the material and the structure of the final mobile phone.

1.3.2 CDC - Creative Design Center

The Creative Design Center at SEMC has the task of forming the mobile phones. Their mission is "to create innovative and attractive designs, made easy for the consumers to embrace and utilize". Form follows function as well as desire, and a mindset combining reason and emotion is to result in designs focused on the human being.[1] Every year CDC presents four so called trendencies, which are a compilation of research material regarding up and coming trends. The trendencies are based on visits to front edge cities, visits to different fairs, a range of trend scouting etc. Together with design briefs presented by the Product Planning Department the trendencies work as inspiration and guidance when creating proposals concerning colors, materials and structures for new mobile phone concepts.

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[1] Meeting with Jens Strandberg, Design Producer, Color & Material, CDC 2009-03-17

1.3.3 TWG Mechanics and Building Concepts

The Technology Working Groups (TWG) are cross-site and cross-functional groups which act globally to enable overall coordination of technology strategies within SEMC [7]. Briefly, they can be described as virtual networks of experts. An important output from their activities is the Technology Roadmaps (TRM). These core plans are SEMC's way of foreseeing what kind of technology the company will need in the future and plans to introduce.

The TWG Mechanics and Building Concepts (TWG M&BC) scope includes material and manufacturing technology as well as design strategies. In their TRM for 2008-2011, introducing new and innovative "wow" factor design materials like glass is listed as an important focus area, with the purpose to support brand building [8].

1.4 Project objective

The objective of the Master Thesis is to perform a study on how 3D-glass can be used to create an attractive and distinctive keypad for the future mobile phones of SEMC. The specified purpose of the study is to present a guideline for the design and manufacturing of a 3D-glass keypad. Limitations, challenges, possibilities and advantages regarding keypad design and production will be examined. The result from the study is meant to increase the knowledge of this area to the level where a decision can be made whether a 3D-glass keypad is a realistic feature or not for future mobile phone concepts. For this Master Thesis, the definition of 3D-glass is "glass with non-uniform thickness, complex shapes and double curved surfaces".

1.5 Problem statement

The main research question of the Master Thesis is:

- Is it realistic to implement 3D-glass keypads on future mobile phones of Sony Ericsson Mobile Communications?

Other questions to be answered by the Master Thesis are:

- Which types of glass could be suitable for keys with non-uniform thickness?
- Which manufacturing processes could be suitable for keys with non-uniform thickness?

- Which are the possibilities within the design and shape of keys made from glass?
    - What backside coatings could be suitable?
    - Which after treatment methods are available and how will they affect the appearance of the keys?
    - How does tinted glass change the appearance qualities?
    - Is it possible to engrave icons into the glass keys and if so, what will the optical effect be?
    - Which shapes and design features should be used to emphasize the glass' positive qualities?
    - How high would the costs be in comparison with plastic keys?

1.6 Project scope

As mentioned above, the scope of the Master Thesis is the research area of 3D-glass keypads, where 3D-glass is used as a design material for decorative and distinctive purposes. The reason for the study area is first and foremost that this area is a new and unexplored ground, within SEMC as well as within the rest of the mobile phone industry. Glass itself is an interesting and challenging area. Below follows a list of some chosen focus points and limitations.

1.6.1 Time frame and economical resources

Since being a Master Thesis, the project is limited in time. The time plan is set from December 2008 to May 2009, but when working with a development process one must always be prepared for the possibility of unexpected twists and delays. The economical resources are also somewhat limited and the ambition is to keep all costs as low as possible, without compromising too much to jeopardize a positive outcome of the study.

1.6.2 Glass material

The specific glass material to be used for the produced glass samples will be decided through consultation with experienced glass- and/or keypad suppliers. The study will focus on two varieties of glass – transparent glass and tinted, transparent glass.

1.6.3 Production and suppliers

In order for the outcome of the study to be as realistic as possible regarding mobile phone production possibilities, only industrialized production methods are evaluated. If possible, more than one production method will be used to enable a comparison between different manufacturing techniques.

Glass is a relatively new design material for SEMC and the mobile phone industry, and, as expected, SEMC's current keypad suppliers do not have substantial knowledge, experience and research activity within the 3D-glass forming area. Hence, in order to produce high quality 3D-glass key samples using industrialized production methods, suppliers in the glass forming industry will be contacted. However, these suppliers have no or insignificant knowledge regarding manufacturing keypad rubber mats or keypad assemblage. Therefore, it is expected that cooperation between a SEMC existing keypad supplier and an external supplier from the glass forming industry will be the best alternative possible for this study.

Since more general studies within the 3D-glass area previously have been performed at SEMC, some contact with suppliers, mainly from the glass molding industry, is already established. Due to the limited time plan for the Master thesis and the positive outcome from previous projects when cooperating with these suppliers, no additional suppliers completely new to SEMC will be contacted.

1.6.4 Design concept

To be able to perform critical tests on the glass keypad samples, a keypad design from an existing SEMC mobile phone will be used as a base for the study. The keypad design in question will be alternated to better suite glass keys and the production process of choice. Due to limitation in time and resources only one keypad design with glass keys will be developed and realized within the study. However, in order to look at various effects that the design and its features have on the characteristics of the glass, different combinations of artwork application and backside coatings will be tested.

1.6.5 Test and verification

A number of tests will be performed on the glass keypad samples. They will be carried out at the Department for Testing and Verification at SEMC in Lund and be based on the SEMC Test Specification.

The tests performed will be of limited range and focus is set on the tests that are considered the most critical for this study. If proceeding with further studies within the 3D-glass keypad area, more profound testing and analyzing might be recommended.

The test samples will be implemented on the chosen mobile phone model during testing and the results will then be compared to the results obtained from testing the corresponding plastic keypad.

2. Methodology

The following chapter presents the research methodology used within the Master Thesis. It also describes the individual steps of the applied method.

2.1 Applied method

"A product development process is the sequence of steps or activities which an enterprise employs to conceive, design and commercialize a product"(Ulrich & Eppinger 2008, s.12). Since every project is unique, it is often difficult to completely follow a pre-defined and fixed method found in product development literature, e.g. the process described in "Product Design and Development" by Ulrich & Eppinger. The research approach applied in this Master Thesis includes a number of steps chosen to fit this specific project, but many of these are influenced by the Ulrich & Eppinger methodology.

To start with, the project objective and the project scope were drawn up, in order to get a good foundation for the continuing work. An early time plan was also put together, including all expected crucial steps of the study.

The actual project consists of three main phases - a theoretical study phase followed by an empirical study phase and a test phase. Ultimately, the project is to result in a design guideline where recommendations for 3D-glass as a design material for keypads are made as well as suggestions on areas for further studies.

During the theoretical study phase two pre-studies were carried out; one within glass materials and one within keypad design. These pre-studies were based on knowledge gathered through literature studies and searching the Internet. Other sources of information were experiences gained from earlier projects and technical studies within the same or similar areas and important input from communicating with suppliers. Together with requirements and ideas from the previously mentioned internal stakeholders and representatives from several other SEMC departments, this phase functioned as a solid base for the empirical studies and the realization of the project.

The empirical study phase included close contact with suppliers in the glass forming industry and keypad suppliers. Different production methods and combination of suppliers were considered, the keypad design chosen as a base was alternated, the artwork was revised and several possible aesthetic applications and after treatments of the glass keys were evaluated. Most facts and information collected during this phase came from discussions with the suppliers. Therefore, the competence and experience of the suppliers was essential for the outcome of the project.

After this realization phase, the 3D-glass keypad samples were then evaluated through a number of tests performed in the test lab at SEMC in Lund. The outcome of the tests was analyzed and, together with the gained knowledge from the theoretical and the empirical studies, documented and put together in this report.

2.2 Method criticism

When performing a research- and development study it is important to stay objective and constantly question the validity and accuracy of the applied method. Another essential aspect to consider is the reliability of ones sources of information. Hence, the following paragraphs describe and analyze the different applied procedures and information gathering methods used throughout the Master Thesis.

2.2.1 "Expert opinions"

As previously mentioned a frequent source of information has been input from employees at various departments at SEMC and input from external suppliers. Most of the information has been gathered via verbal conversations and e-mail based interviews. While receiving information from a primary source is considered positive, it is also hard to verify the validity of the knowledge. Therefore, the potential risks regarding this method have been continuously noted during the project.

2.2.2 Published sources of information

Some of the information for the theoretical study has been gathered from published literature, but most data comes from various websites and the SEMC intranet. In the same way as when regarding the "expert opinions", only sources that are considered reliable and trustworthy have been utilized.

2.2.3 Product development procedure

Although not following any specific theoretical product development method, the development process within the Master Thesis has naturally been influenced by such. The main source of product development methodology has been that of Ulrich & Eppinger, which is the method taught at the Faculty of Engineering at Lund University. However, the implementation of the project has extensively been affected by the commissioners of the study and their experience from the product development process of SEMC. The combination of the pre-defined method and the SEMC way was therefore considered to be suiting for the Master Thesis.

2.2.4 Decision making procedure

Naturally, many important decisions were made throughout the different phases of the study. Choices were continuously made concerning the scope of the project, suitable suppliers, keypad design, test procedure etc. These decisions were all based on the information gathered during the study and were always evaluated considering the current situation.

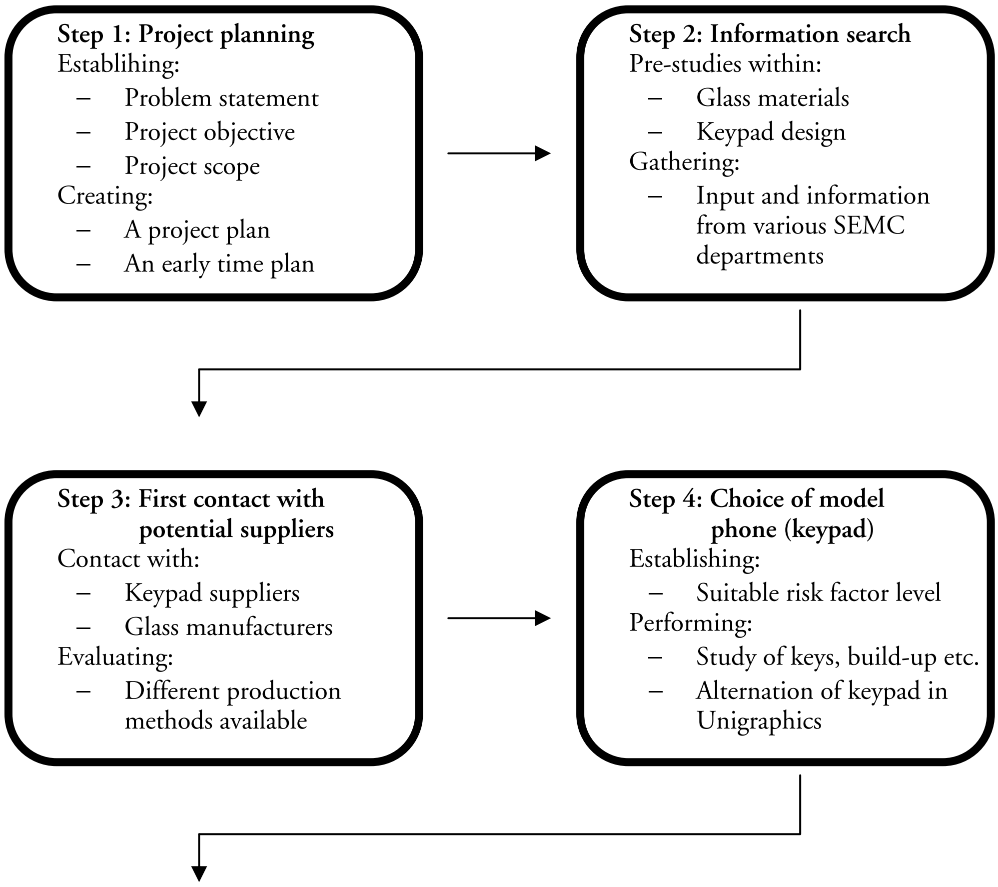
2.2.5 Testing procedure

The tests that have been performed on the glass keypad samples follow the standard testing procedure set up by SEMC. To be able to compare the results of the tests with some reference values, the tests carried out on the glass keypad samples were the same as those performed on the original model phone.

2.3 Applied method – step by step

To get a better view of the individual steps performed within the Master Thesis, a figure representing each step at a time is presented below.

As previously mentioned, a time plan was established as estimation to when in time the different steps would occur. This early time plan can be found in appendix A, together with additional comments.



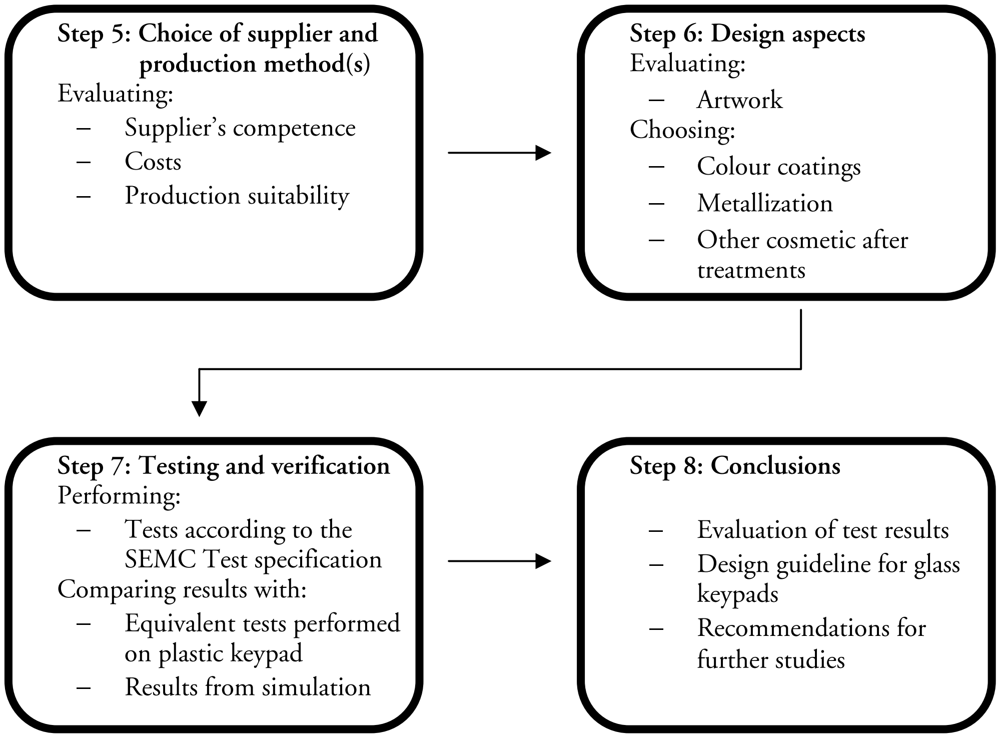


Figure 2.1: Project process steps

3. Theoretical Studies

The following chapter presents the outcome of the two performed pre-studies.

3.1 Pre-study within glass materials

A general pre-study on the area of glass was performed at an early stage of the project. Different glass materials were analyzed as well as possible production methods for 3D-glass keys. Available hardening procedures and potential alternatives for application of the artwork and backside coatings were also studied.

3.1.1 Glass materials

Glass is a quotidian material used for various applications, e. g. drinking glasses, windows and optical lenses. It is a hard yet brittle material, with a high resistance against chemical influences. It is heat-resistant but at the same time sensitive to thermal shock.

According to the Glass Research Institute (Glafo), glass is defined as follows [9]:

- A (non-organic) melt, fixed in a solid state where no crystallization has occurred.
- A material that has the material property of an area of transformation.
- A non-crystalline, solid material.

Like all other materials glass has its own typical qualities, which determines the materials scope of use. The most distinguishing characteristic of glass is its transparency, which allows light to pass through the material without distortion. The strength of a glass material is affected by e. g. scratches on the surface or inner tensions emerging during the manufacturing process (Falk et al. 2005).

From a manufacturing point of view, an important quality is the glass' formability when heated to liquid state. The formability stretches within a wide temperature range, which makes it possible to shape glass through numerous manufacturing processes. The glass' qualities are adaptable to suite different applications and the properties are decided by the composition and proportion of the included raw materials.

The most important glass raw material is sand, which mainly consists of silicon dioxide. Different sorts of glass can then be created together with various flux materials and stabilizers (Falk et al. 2005). Below follows a short description of a few common glass materials.

Quartz glass is the most basic type of all glasses, made from silicon dioxide alone. Because of this, melting quartz glass requires a temperature over 1 700 °C. Quartz glass has a very low coefficient of thermal expansion and thereby a high thermal shock resistance, which allows it to withstand temperatures up to 1 400 °C during short periods of time. It also has high chemical resistance qualities and is often used as a special glass, for e. g. lighting installations with UV radiation, optical fibers and some laboratory glassware (Falk et al. 2005).

Soda-lime glass is one of the most commonly used types of glass (Askeland, Donald R. 2001). More than 90 % of all manufactured glass is soda-lime glass, made from mainly silicon dioxide (sand), calcium oxide (lime) and sodium carbonate (soda) (Falk et al. 2005). These are all relatively inexpensive raw materials and soda-lime glass is used for many various applications, e. g. windows, glass containers, light bulbs, plain glass tableware and much more [10]. In effect, soda-lime glass also consists of smaller amounts of other materials, e. g. magnesium oxide, aluminum oxide and potassium oxide. Due to impurities within the raw materials, mainly from iron oxide, soda-lime glass often have a pale, greenish color tone (Falk et al. 2005)

Borosilicate glass is a type of glass primarily made from silicon dioxide and boron. The chemical compound with boron makes the glass less sensitive to thermal shock and increases the chemical resistance. A borosilicate glass has a high content of silicon dioxide and contains more than five percent by weight of boron, which gives the glass a low coefficient of thermal expansion. It is commonly used for numerous industrial applications, e. g. at laboratories and for traffic lights, but it is also used for making oven safe kitchen utensils (Falk et al. 2005).

3.1.2 Production methods

As mentioned in the previous section, glass materials have unique qualities, which allow many different production methods. To create hollow glass containers, bottles and jars it is common to use the industrialized glass blowing technique, and to get a complex 3D-shape with uniform thickness one can use the slumping technique, where a heated flat glass sheet is placed over a mould. Different molding techniques are also available, as well as casting and steeping of liquid glass (Falk et al. 2005).

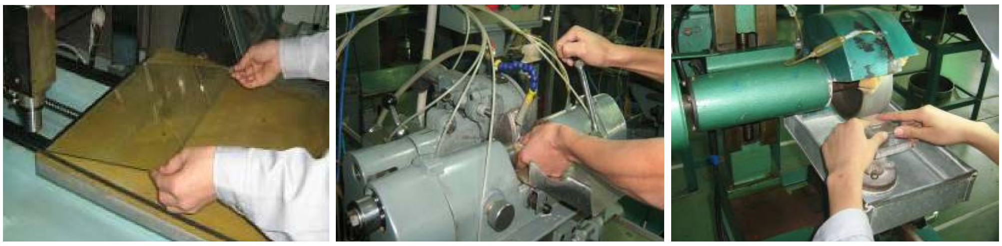
After evaluating input from suppliers within the glass forming industry, it was clear that there were primarily two production methods considered suitable for 3D-glass keys and this project; milling of flat glass and blank molding of glass rods. Below follows a short description of these two manufacturing processes.

Milling of flat glass
The milling of flat glass is a kind of mechanical after treatment performed on glass sheets or blocks, where special diamond tool mills are used to create 3D-shaped glass parts. A large glass sheet, with sufficient thickness, is cut into smaller parts to better suite the milling equipment. The customized glass sheets, which are kept at room temperature, are then milled into the desired shapes one by one, using a 2D-mill and chamfering

equipment. After this, the finished glass parts are cleansed and polished and if no further treatment is needed or wanted they are ready for a final inspection.

The 2D-milling process to create 3D-shapes allows spherical contours to some extent, but the dimensions are hard to control during the chamfering and polishing steps. It is also a very time consuming process, since every individual part is milled one by one. If more complex shapes are desired, CNC-grinding and polishing is needed, which is far more expensive than using standard milling equipment. Therefore, multilateral shapes and curved surfaces are not recommended when using the milling process. Another general limitation for this method is the minimum thickness of the glass, which cannot be thinner than 0,4 mm.[2]

The different steps of the milling process are shown in figure 3.1 below.



Cutting Milling Chamfering

Cleansing Polishing Inspection

Figure 3.1. The milling process

Blank molding of glass rods

Blank molding of glass is a special kind of pressure molding technique where re-heated glass rods are pressed into wanted shape by using an open metal molding tool. The term blank molding comes from that at minimum of one side will stay blank, i. e. it will be finished when coming out of the mold, with a surface as the original surface of the glass rod. The other side will have a rougher surface and needs to be grinded and polished

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[2] Mail conversation with Manager, later chosen Keypad supplier 2009-05-05

down to the wanted thickness. To reduce the costs, the grinded and polished side should be flat (not convex or concave).

During the molding process, glass rods are heated up to approximately 900°C, which makes the glass material soft but not liquid. An upper molding tool, defining the non-uniform shape of the glass, and a flat lower molding tool is fixed in a molding machine and the soft glass is then put between the tools. Both tools are heated up to approximately 500°C. After that the two tools are closed and the glass rod is cut and moved back into the oven. When coming out of the molding tool, the upper side of the glass is finished and no further treatment for this side is needed. The flat backside is then grinded and polished to get the right thickness of the parts. For the grinding and polishing process the parts are glued face down on metal plates. This is a state of the art process for all small, high precision or thin optical parts. After the grinding and polishing the parts are washed and then ready for final inspection.[3]

The different steps of the molding process are shown in figure 3.2 below. Five of the pictures show the steps as they could be carried out for this specific glass key project. Only the picture of the backside polishing gives a more general view on how small optical lenses are fixated onto a metal plate with hot wax, for grinding and polishing.

Heating of glass rod　Upper molding tool　Molding machine

Molded piece　Backside polishing　Finished keys

Figure 3.2. Blank molding of glass rods

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[3] Mail conversation with Manager, Glass molding company 2009-04-29

It is possible to blank mold parts that are finished on both sides when coming out of the molding tool. However, this is a more expensive process and the tolerance of the finished parts will be approximately ±0,3 mm, compared to a tolerance of ±0,1 mm for parts that are ground and polished on one side afterwards.[4] Double side molding also requires parts with a minimum thickness of more than 2 mm and is therefore not suitable for the 3D-glass keys. Another limitation of the molding process is the need to have slight extraction angles to be able to pull out the glass parts from the molding tool.

3.1.3 After treatments and hardening procedures

In addition to the production processes, various after treatments can be applied to the glass parts. Within edge processing, the glass can be grinded and polished, giving the parts C-shaped edges, beveled edges, rounded corners and edge cut-outs. For the molding process this is considered as an after treatment, while for the milling process it is more a part of the actual manufacturing method.

Holes can be drilled with a diamond tool, creating round, oval or customized openings. It is also possible to perform micro-drilling with ultra sonic aided lapping. When it comes to surface treatments, the market offers several different applications, e. g. mirror coating, anti-reflective coating, sandblasting and screen-printing [11]. An anti-splinter coating can also be applied to the glass surface, which could prevent any unnecessary risks of getting injured if the glass where to break. This is however not a possible application for the 3D-glass keypad, since the individual glass keys are too small.[5]

To bring extra strength to the glass material there are two main hardening procedures; thermal hardening and chemical hardening.

Thermal hardening is a less expensive and much faster procedure than chemical hardening, but it only increases the heat shock resistance of the glass and not the hardness of the surface against damages and scratches. During thermal hardening, the glass is heated to a temperature above the transformation point of the glass, which depends on the material itself but also the size of the parts. After heating, the glass, which must be isotherm (have the same temperature in the center as on the surface), is then shocked with cold air. This procedure brings stress into the glass and it will now be more resistant to temperature shocks. The thermal hardening process is often used for glass doors or automotive windows.

To chemically harden glass material, the parts are lowered into a chemical bath, where small ions from the glass surface are changed with added ions of a bigger diameter. This brings strength into the glass and the chemical hardening process is commonly used for eyeglasses made of glass.[6]

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[4] Mail conversation with Manager, Glass molding company 2009-05-06

[5] Mail conversation with Manager, later chosen Keypad supplier 2009-05-05

[6] Mail conversation with Manager, Glass molding company 2009-04-29

3.1.5 Artwork application and backside coatings

One major advantage with glass keys is that the artwork can be applied on the backside of the keys. Thereby, the artwork is not subjected to any wear and tear and no top coat is needed. A top coat gives the keys a more rounded feel and not having to apply this means that the shape of the keys and the chamfers hopefully will be more distinct than that of injection-molded plastic keys.

The artwork can be applied in two ways; through laser etching or through laser engraving. The backside of the glass keys are either silkscreen printed with a thin layer of IR ink or subjected to vacuum metallization, which gives the surface a chromed effect. When using laser etching, the artwork appears by etching away the color- or the chromed coat, leaving a non-coated surface where the artwork is. This means that the laser only etches away the coating and the glass keys themselves are not subjected to any machining. To try to get an even deeper feel to the artwork, it is possible to use laser engraving. This means that the laser not only removes the backside coating but also engraves the artwork into the actual glass material.

Another possible aesthetical surface treatment is sand blasting, where the backside of the keys are grained with sand. This gives an opaque surface and could be an interesting design feature. However, the sand blasting process is not perfect and the effect might be a bit uneven. As an alternative, coarse polishing can be used to obtain an opaque surface, but this is a far more expensive and time consuming process.[7]

3.2 Pre-study within keypad design

Keypads are the main mobile phone feature utilized for functional inputs, e. g. telephony, text messaging and menu navigation control. This is usually an area of focus in user reviews. Within mechanics, keyboard related problems represent the biggest return rate driver. These quality problems burden SEMC money wise and naturally affect the overall quality perception of the company brand name [12].

Every year, the keyboard focus group (one of five focus groups within the Mechanics Department at SEMC) presents a design guideline to discuss and advice in matters concerning the design of keyboard systems. The keyboard focus group goal is to improve the quality of keypads by increased knowledge and experience in keyboard design within mechanics [13].

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[7] Mail conversation with Manager, later chosen Keypad supplier 2009-05-19

3.2.1 Difference between keyboard and keypad

This study focuses on the design and manufacturing of 3D-glass mobile phone keypads. It is sometimes easy to mix up the definition of a mobile phone keypad with that of a mobile phone keyboard. The keyboard design guideline mentioned earlier actually contains a subchapter regarding keypad design and separating the concepts can be somewhat confusing. Within SEMC, the two concepts are often considered to be equivalent and sometimes as parts of an overall keyboard system. However, to clarify the difference between the two concepts, within this Master Thesis the keyboard and the keypad have been defined as follows (using the build-up of the C903 mobile phone as an example):

The *keyboard* consists of a keyboard PCB, a dome foil (MDS), a light guide and sometimes a masking foil. The PCB is connected to the main PBA via a BtB connector. The *keypad* is placed on top of the keyboard and consists of a rubber mat with the actual keys glued on top. The dome is the part that connects a pressed down key with the PCB and it also gives the user tactile feedback.

Naturally the build-up of the keyboard and the keypad varies from some mobile phones to others. The one described above is just chosen as an illustrating example.

3.2.2 The C903 navigation keyboard and keypad

To increase the level of understanding regarding mobile phone structure, the design and build-up of the C903 navigation keyboard and keypad is used as an example, illustrated in figure 3.3 below.

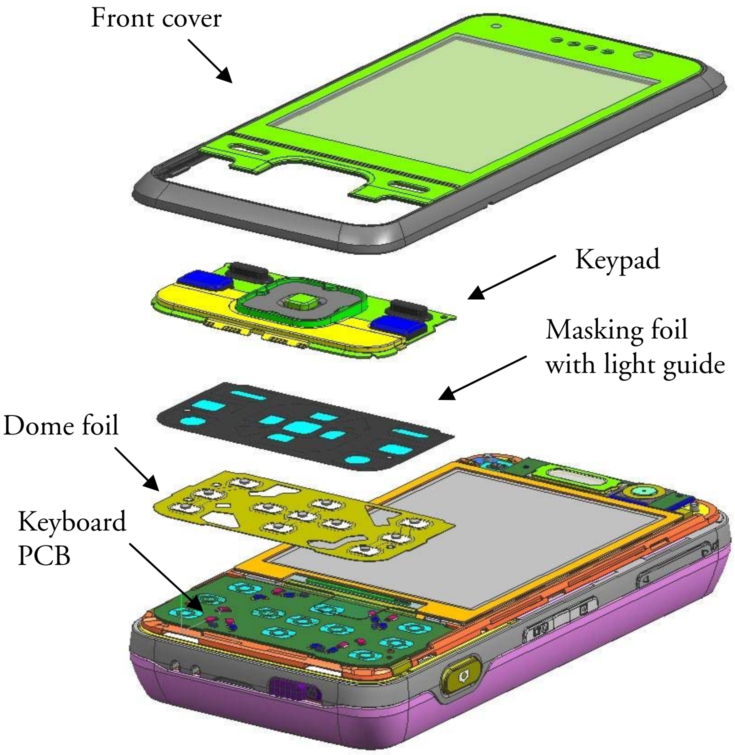


Figure 3.3. The C903 build-up

As mentioned in chapter 3.2.1, the keyboard PCB is connected to the main PCB via BtB connectors. On top of the keyboard PCB is a dome foil. When a key is pressed down, the dome connects it to the PCB and it also gives the key its "click feeling". A masking foil with a light guide is then placed on top, spreading the light from the LEDs evenly. The keypad is then mounted on top of the masking foil and last but not least, the front cover is snapped on, which keeps the keypad in place and makes the mobile phone a complete unit.

As mentioned earlier, the keypad consists of a rubber mat with the keys glued on top. The individual definitions of different navigation keys are presented in figure 3.4 below.

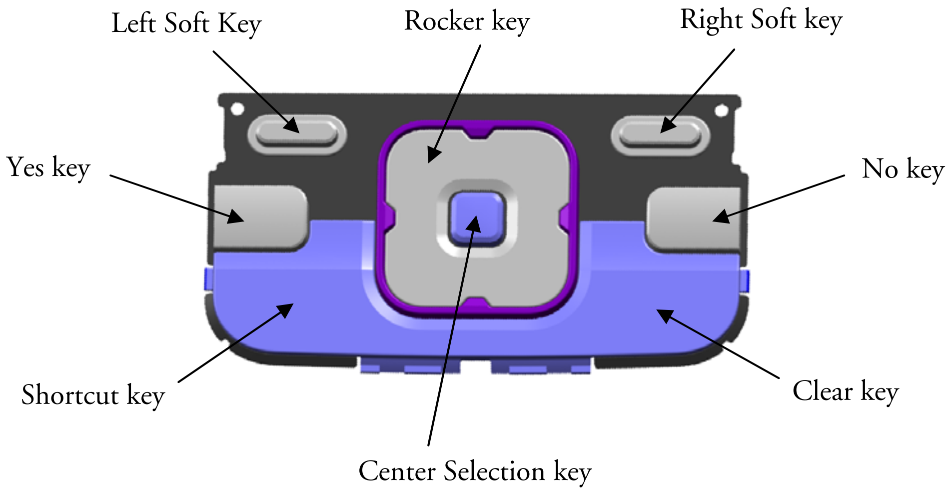


Figure 3.4. Navigation keypad

3.2.3 Keyboard design guideline

To enhance the quality and reliability of keyboard systems is a multi disciplinary work. It is sometimes difficult to sort out one single factor that significantly affects the performance of the system [13]. The keyboard design guideline therefore provides recommendations for actions to be taken on several different fields.

As mentioned earlier, one of the subchapters of the guideline focuses on keypad design. Today, SEMC uses four major types of keypad designs:

- **Hard Top keypad:** Each key is individually guided by an opening in the front cover.
- **Cluster keypad:** The keys are placed and guided on a plastic carrier. The front cover has only one big opening for the keypad.
- **Panel keypad:** Keys and front panel integrated in one assembly with a base of silicone, TPU or other soft material.
- **Film keypad:** Thin sheet UV-molded or stamped.

Using the C903 again as an example, its navigation keypad is a combination of a Hard Top keypad and a Cluster keypad (see figure 3.4). The left and right soft keys are individually guided by openings in the front cover. The yes key, the no key and the rocker key are partially guided by the front cover but also placed very close together with the larger U-shaped key (the clear key and shortcut key), forming a pad with only minor gaps between the keys.

For Hard Top keypads the guideline presents a number of recommendations regarding crucial dimensions, that e. g. could affect the stability of the key tops. For a Cluster keypad it is important that the keys do not interfere with each other as this could affect the click feeling. On the other hand, if the gaps are too big the keypad will lose its appearance of being one unit.

A complement to the keyboard design guideline is the thin keypad design guide. This document includes a focus group study regarding user's perception of quality and preferences with respect to keypads. The result of the study suggests that users prefer e. g. keys with tactile feedback, slightly raised keys and keys that are as big as possible. According to the same study, slanted keys, small round keys and flat keys are designs that users do not like [14].

Since the 3D-glass keypad will emanate from an already existing keypad these design suggestions are not regarded essential for the project, but naturally they are considered when working with the alterations. Although the study mainly focuses on material properties and manufacturing methods it is important for the overall picture to acknowledge the keypad design recommendations.

All keys are bonded to the rubber mat with glue. When applying the glue the guideline recommends using silk print if the key tops are transparent. This will distribute the glue better. However, the best solution presented is to apply a coat of color on the backside of the keys and only have the artwork translucent. This way, the glue will not be visible at all.

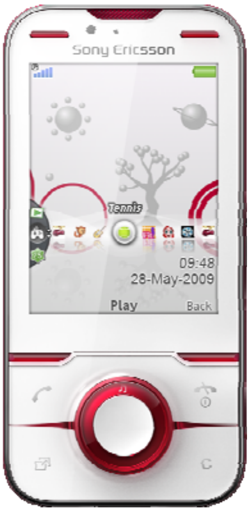
4. Empirical Studies

The following chapter presents the development of the 3D-glass keypad samples. It describes the full realization process, from selecting a model keypad and performing alterations to choosing production methods and design feature combinations.

4.1 Choice of a model keypad

One of the first decisions to be made was which keypad (and thereby which mobile phone) to choose as a base for the project. The risk factor level of the study (regarding design aspects, e. g shape and size of the keys, critical edges and minimum thickness) was deliberately set high, but not unrealistically high. When deciding what keypad to use as a starting point for the study, the choice stood between three different models – C902, Yari and C903. These three models were all considered by CDC to be suitable for having a keypad made of glass.

The C902 keypad has complex shapes, key sets with up to three keys and partially very thin cross-sections. This would be a great challenge when using glass material, but even if possible to manufacture, a C902 3D-glass keypad would most likely not stand the tests.



The Yari keypad consists of only a few larger keys with not so varying cross-sections, many flat surfaces and fairly simple shapes. This could probably result in a rather well functioning 3D-glass keypad. However, from a technical challenge point of view, the outcome of the study would presumably not provide SEMC with sufficient increased knowledge within the area.

The C903 keypad is somewhat a crossing of the two other options. Like the Yari keypad it too only has a few keys, but of varying size and shape. The keypad offers flat surfaces, arched surfaces, single keys, dual keys and different chamfers. The outcome here is not so easily predicted, but the level of complexity is high enough to expect instructive study results.

After taking these factors into consideration, together with input from CDC, the C903 keypad was the final choice for the study.

4.2 Alterations of the keypad design

The next step of the development process was to decide what alterations of the keys that had to and could be made, to make the design more suitable for glass keys. A big challenge when designing with glass is to stay within the minimum thickness range of the material. Therefore, every tenth of a millimeter gained is important. After talking to mechanical engineers from the C903 team, it was clear that the overall C903 design did not allow the keys to be placed any lower into the mobile phone. This meant that any expansion in key thickness would result in keys standing out more from the front panel. Such a change in the design of the phone would probably be rejected from both CDC's and UI's point of view. The original keys were not considered to be impossibly thin and therefore their thickness was not alternated within this study.

The original C903 keypad design is shown in figure 4.1 below.

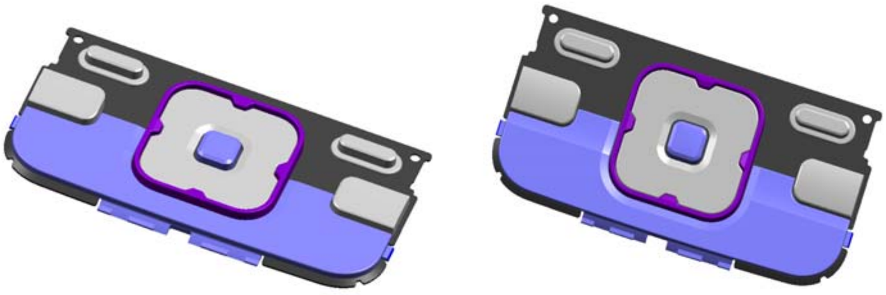


Figure 4.1. The C903 plastic navigation keypad

Since the shape of the two soft keys is entirely dependent on cavities in the surrounding front panel it was decided to let these keep their original design. The yes key, the no key and the rocker key are partially dependent on the same front panel, and therefore it was considered reasonable to let these keep their outer shape as well.

The plastic rocker key consists of two individual parts, which allow a combination of two different color coatings. However, this design would not be possible for a glass rocker key, since the individual parts would be far too thin and fragile. Therefore, the rocker key was re-designed into a uniform key. It now has an integrated frame with the same outer shape as the plastic rocker key and an inner 45 degree chamfer. The cavity chamfer surrounding the center selection key was also given a 45 degree angle, as oppose to the slightly more flat chamfer seen on the plastic rocker key. This gives the rocker key a uniform look and it also adds to the 3D-feel of the keypad. Naturally, for the rocker key alteration, as well as for all other key alterations, the recommendations found in the keyboard guideline were taken in consideration.

The yes key and the no key originally have a rather soft and round shape. This type of shape is ideal when working with glass, since it adds less tension to the material than a sharper design (Falk et al. 2005). The keys also have a slightly convex surface, which could give interesting effects when made of glass. Therefore, it was decided that there was no need to change the design of these two keys.

The large U-key is probably the most challenging one. It is not only quite long with a thin cross-section, but it is also subjected to force in two opposite points, like a seesaw. These are two typically critical factors for a glass key and it would of course have been possible to avoid them by re-designing the key and making it into two separate keys. However, right from the start of the study, this key has been considered as the worst-case-scenario-key, but also a source of valuable information regarding 3D-glass design. The main purpose of the project is to test the limits for designing with glass and this key does just that. Therefore, it was decided to keep the U-key's original design also for the glass keypad.

Regarding the U-key chamfers, these were also kept as they are. Both the chamfer surrounding the rocker key and the long, flat chamfer towards the yes- and the no key and the front panel were considered quite distinct when looking at the CAD-model, but when the plastic keys are primed with a top coat the chamfers become less visible. Since the glass keys will have all artwork applied on the backside and therefore not need any top coating the chamfers on these will hopefully be more distinct. The chamfers could of course also have been given a steeper angle to attain a bigger 3D-effect, but this would mean further reduction in an already critically thin material, which might cause unnecessary failure of the keys during the tests.

So far, not many major changes have been made to the original design of the keypad. However, a feature that had to be removed was the flanges on the sides and the front edge of the U-key (see figure 4.2 below). If the molding process was to be used, one of the main design requirements was that the keys need to have a flat bottom surface.[8] Adding to that, the flanges would also be far too thin to manufacture using glass material and it was obvious that they would not stand the tests. Since the remaining design of the keyboard and front cover did not allow any increase in material thickness, the flanges was excluded in the new design

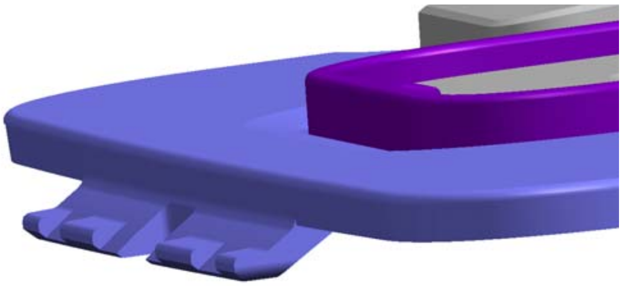


Figure 4.2. Plastic flange

The flanges on the plastic U-key keeps the keypad in place and prevents it from popping out of the front cover if the phone is dropped or subjected to impact in other ways. Therefore, the removal of the flanges requires that the keypad is attached to the keyboard in some other way. This attachment is evaluated further in chapter 4.7.

After all keys have been evaluated and some alternated, the keypad now has a somewhat different design. The C903 glass navigation keypad is seen in figure 4.3 below.

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[8] Mail conversation with Manager, Glass molding company 2009-02-12

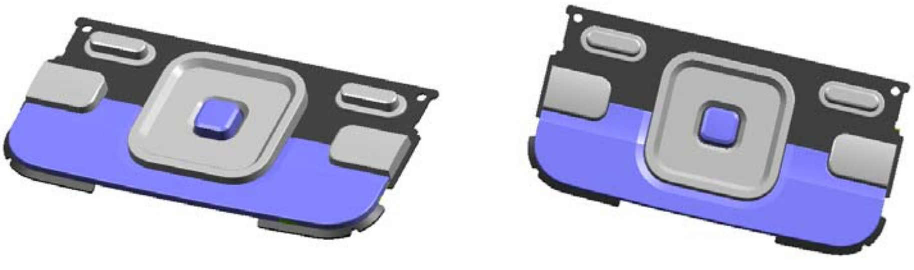

Figure 4.3. The C903 glass navigation keypad

4.3 Simulations in HyperWorks

After the alternations of the keypad design were made, the new version of the keypad was imported into HyperWorks (a FEM analysis software) and structural simulations of two drop orientations were performed. The results of the simulations are presented in figures 4.4 to 4.7 below. The same drops will be made during the test phase and the results from the tests will then be compared to the simulations. However, the simulation drops are made onto a flat surface, while the DUTs will be dropped onto concrete. This is likely to affect the results significantly, since a rough surface might cause crack formation due to local force concentrations.

Based on earlier glass studies, a soda-lime glass called B 270 might be suitable to use for the glass keys if the molding process is chosen as manufacturing method. Since this was considered a probable choice at this stage, the simulations below were made based on the material properties specification for the B 270. According to the specification, the glass' breaking strength is approximately 30 MPa for bending strain. When the glass is subjected to a rapidly applied load, like when dropped onto the ground, the breaking strength is likely to be lower. However, this level applies for non-hardened glass. Since the glass keys will be chemically hardened, the breaking strength increases. Generally, the strength of the material can be increased about ten times during optimal conditions. For the glass keys, it was realistic to believe that the strength would increase approximately five times, i. e. to a level of 150 MPa, after being chemically hardened.[9]

For the complete B 270 specification, see appendix B.

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[9] Mail conversation with Sales Manager, Schott Scandinavia AB 2009-06-23

4.3.1 Simulated front corner drop

The first simulated drop orientation was a front corner drop, shown in figure 4.4 below.

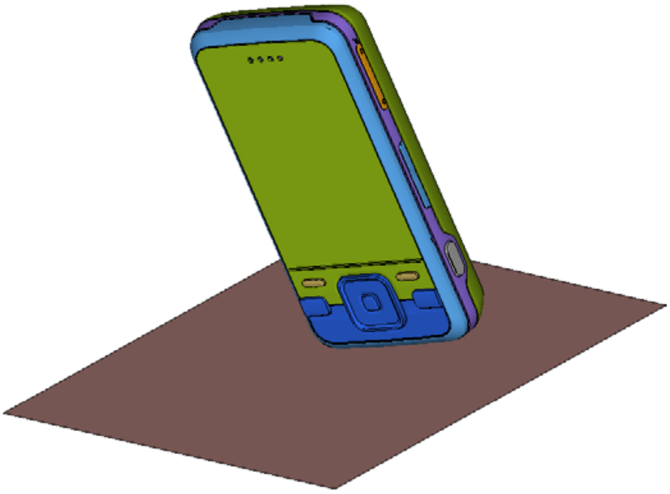


Figure 4.4. Drop orientation 1

The stress distribution plot in figure 4.5 shows that no large stress gradients occur and that the stress distribution thereby is uniform. Judging by the same plot, the maximum stresses from the front corner drop are approximately 58 MPa. However, these high stresses only occur in limited areas, while the stress level in the majority of the glass material is somewhere between 0 and 15 MPa. Therefore, there is a possibility that the glass keys could withstand the front corner drop. The maximum stress arises in the U-key; hence this is the key most likely to crack.

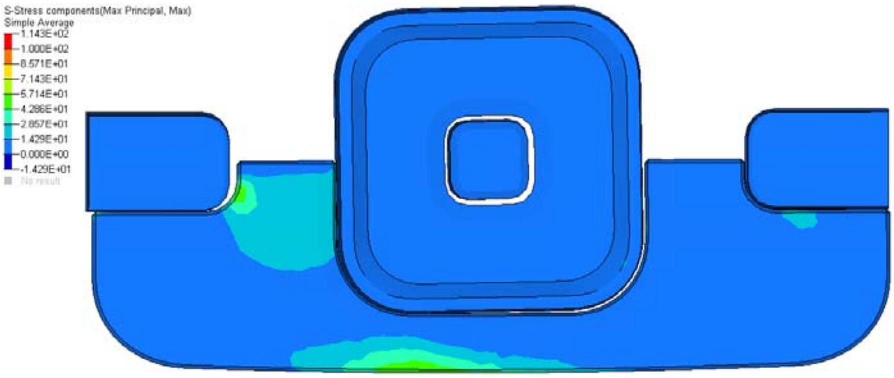


Figure 4.5. Stress distribution plot - orientation 1

The stress distribution plot also shows a certain displacement of the keys. Since the stresses in the keypad are relatively low it seems like the surrounding plastic frame carries most of the stress from the impact and distributes it away from the keys. The front frame will however deform to some extent and it is important that the design allows the keys to move without interfering each other.

4.3.2 Simulated front drop

The second simulated drop orientation was a front drop, shown in figure 4.6 below.

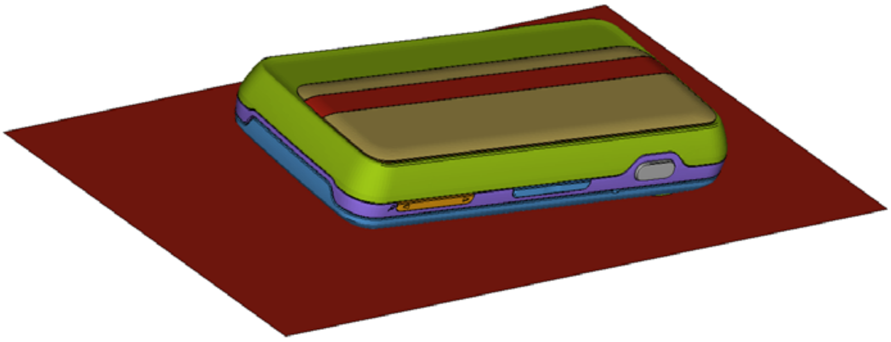


Figure 4.6. Drop orientation 2

The stress distribution plot in figure 4.7 shows that large stress gradients occur over the entire set of keys, with maximum stress in the U-key, by the Rocker key and the No-key. Judging by the same plot, the maximum stresses from the front drop are approximately 440 MPa. This means that the glass material fails, since the breaking strength is exceeded by far. Therefore, the glass keys will not likely withstand a front drop.

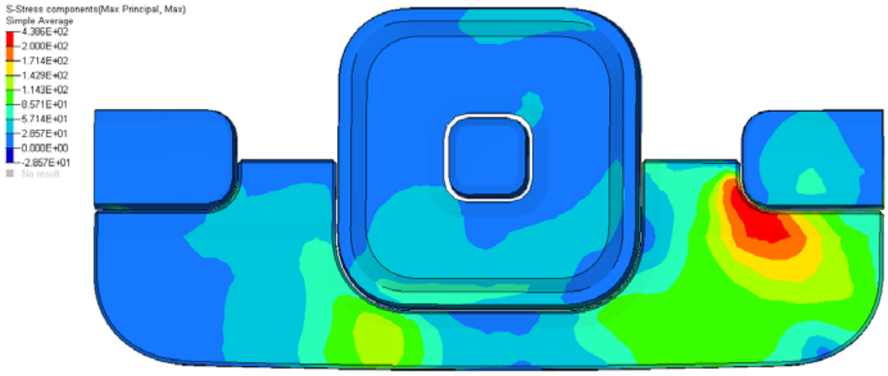


Figure 4.7. Stress distribution plot - orientation 2

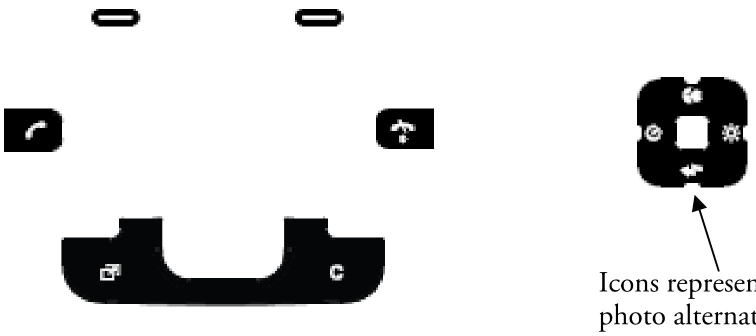
Despite these results, no further changes of the keypad design were made. Such extensive changes would be far too expensive and time consuming for this small scale project. Hopefully the project will still lead to important insights regarding 3D-glass design.

An important aspect to consider when using FEM analysis is that it is an approximate method. The results should therefore be revised critically and if possible verified through testing. For results from the free fall test, see chapter 5.4.4.

4.4 Artwork

Naturally, since using a principally pre-defined keypad as a base for the study, a related artwork design for the navigation keys exists too. This existing design was evaluated and combined with the alternated shape of the keypad. Any reason to not use the same artwork for the glass keypad as for the plastic one was not found and therefore it was decided to proceed with the original design. However, for transparent glass keys, the artwork will be applied onto the backside of the keys, as oppose to on top of the key surface. This will leave the top surface of the glass keys clean and smooth, and the advantage of working with a transparent material will be even more emphasized.

As figure 4.8 below shows, the artwork consists of a thin line icon for each of the two soft-keys, a receiver icon for the yes-key, a crossed out receiver icon and a small power switch icon for the no-key, an envelope icon for the shortcut-key and a C icon for the clear-key. These are all visible whether the transmitting light is turned on or not, but once the camera function is activated, four additional icons representing different photo alternatives appears on the rocker key. This effect was not considered as an important factor for the glass keys. Therefore, it was decided to leave the rocker key blank and only apply the artwork to the other keys. This means that the rocker key, as well as the center selection key, will not have any artwork and is therefore to be completely color coated, metalized or sand blasted.



Icons representing different photo alternatives – not used for glass keypad

Figure 4.8. Artwork

4.5 Choice of suppliers and production methods

As mentioned in chapter 1.6.3, glass is a relatively new design material for SEMC and the mobile phone industry. To start with, three potential keypad suppliers were contacted and interviewed regarding the possibility to produce 3D-glass keypads. Although they all showed an interest in the 3D-glass area and gave the impression of wanting to explore the area further, they did not have sufficient experience or knowledge of 3D-glass forming to produce the glass keypad samples for the study. Therefore, as expected, cooperation between a SEMC existing keypad supplier and an external supplier from the glass forming industry will most likely be the best alternative possible for this study.

When choosing what production method to use for the glass keys, one of the most critical issues to consider was whether or not the method would be suitable for mass production. During the pre-study within glass material, pressure (or blank) molding appeared to be a good production method for this small scale project, but it also showed potential to suite the manufacturing of larger quantities of glass keys. A major advantage

with the blank molding method is that all the 3D-glass keys for each keypad can be made as a set, instead of having to manufacture them individually, one by one.
Another important factor to consider was the appearance of the keys. All plastic keys need to have a top coat to protect the key and the artwork from wear and tear. As mentioned in chapter 3.1.5, the artwork for glass keys will be applied on the backside surface and thereby not top coat is needed. Hopefully the shape of the keys and the chamfers will then be more distinct than that of injection-molded plastic keys. However, to mill the glass keys would probably result in even more distinct shaped keys than keys made using the molding process. Therefore, even if not so suitable for mass production, the milling process was also an interesting option.

Both the molding- and the milling process were considered as interesting methods, with similar potential of giving satisfactory results. Since 3D-glass keypads is a not yet explored area for SEMC, all newfound knowledge will be valuable for further studies and for a possible implementation of glass keys in future development projects. Hence, to collect as much information and gain as wide 3D-glass experience as possible, it was decided to proceed with both the molding- and the milling process. This will not only give SEMC essential knowledge within both processes individually, but it will also present an opportunity to compare the two. Pros and cons regarding the two different manufacturing methods can be evaluated and hopefully lead to a conclusion about which method is to prefer.

As mentioned previously in this report, due to earlier general studies within the 3D-glass area performed at SEMC, the company has already established some contact with a supplier from the glass molding industry. The supplier is a medium-sized German company which specializes in pressure/blank molding technology, producing a wide range of high-precision components of optical glass [11]. Existing SEMC keypad suppliers were also questioned about the molding process, but none of these could offer state of the art technology within molding. Therefore, after renewing the contact with the German company and discussing the project with the manager, they were chosen to be the supplier of the molded glass keys. This meant that the keys were to be molded in Germany and then shipped to a keypad supplier for artwork application and keypad assemblage.

For the milled keys and the keypad assemblage, three of SEMC's most frequently used keypad suppliers were contacted and questioned about their glass experience and their ability to produce milled glass keys with the specific C903 navigation keypad design. They all showed great interest in the project and appeared to be able to offer keypads with milled glass keys as well as assembly of the keypads with molded keys. From these three, the keypad supplier that showed the least potential was discarded in a first selection phase. Of the two remaining suppliers, one was the supplier that produces the C903 plastic navigation keypad. At first, this supplier was considered to be the best choice for the study, since they already have the equipment for the manufacturing of the rubber mats and all the fixtures for the assembly. However, when compared to the other potential keypad supplier, the existing C903 supplier was substantially more expensive and had longer lead times. Therefore, the other keypad supplier was chosen to be the supplier of the keypads with milled keys and to assemble the keypads with molded keys.

4.6 Design concept – combination of features

An important part of the project was to study the effect that different combinations of artwork application, surface treatments and backside coatings have on the appearance and durability of the glass keys. To do this, the glass keypad samples were produced in a number of different versions, where manufacturing process, type of glass, artwork application and backside surface treatment were features differentiating the various versions from each other.

Manufacturing process
As mentioned in chapter 4.5, the glass keypad samples were produced using two different production methods; 3D-milling and blank molding. This most likely affects the appearance of the glass keys, but the manufacturing process might also be decisive for the outcome of some of the tests. For example, the glass material for a milled key is subjected to more machining than that for a molded key, which increases the risk of micro cracks within the material. In combination with the milled keys probably having sharper edges than the molded ones, this could mean that the fracture toughness is lower for the milled keys than for the molded.

Type of glass
The transparent molded keys were made from B 270, a high quality soda-lime glass with good molding qualities.[10] For the milled keys, the keypad supplier had several options of glass to offer. One of the suggested types of glass was IG3, which is a soda-lime glass that has similar material properties to those of the B 270, but the keypad supplier considered the IG3 to be a more suitable glass for the milling process than the B 270. The IG3 is also a glass that is widely used in production and would not cause any lead time or inventory issues.

The molded keys were also made in a tinted version, using a soda-lime glass with coloring substances. These were mainly produced for the sake of appearance, but it can also be interesting to see if the effect from solar radiation and abrasion will be different for a tinted glass material.

Sapphire glass was also considered when choosing what glass material to use for the keys. This single crystal version of aluminum oxide (Al_2O_3) is often used for watches, because of its high impact toughness and scratch resistant surface.[11] However, when consulting the glass molding company, the answer was that sapphire glass is not suitable for the blank molding process. Therefore, sapphire glass was discarded as a potential design material for this study.

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[10] Mail conversation with Manager, Glass molding comapny 2009-05-11

[11] Mail conversation with Sales Manager, Optical Products, Roditi International 2009-06-10

Artwork

As described in chapter 3.1.5, the artwork was applied using two different methods; laser etching and laser engraving. When using laser etching, the artwork appears by etching away the backside coating, but the glass keys themselves are not subjected to any machining. To try to get an even deeper feel to the artwork, it is possible to use laser engraving. This means that the laser not only removes the backside coating but also engraves the artwork into the actual glass material. However, the glass processing might affect the material properties negatively, and therefore it was considered interesting to test both versions.

Backside surface treatment

Three different backside surface treatments will be evaluated; color coating, metallization and sand blasting. The difference between a color coated surface and a vacuum metalized surface is purely aesthetical, but sand blasting might affect the material properties negatively.

Table 4.1 below shows all versions of samples developed and produced, which resulted in a number of different combinations of features.

Table 4.1. Variants of samples with different combination of features
(the grey areas mark that the feature exists on the sample)

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metalliza-tion	Sand blasting
1	■		■		■		■		
2	■		■		■			■	
3	■		■		■				■
4	■		■			■	■		
5	■		■			■		■	
6	■		■			■			■
7	■			■	■			■	
8	■			■	■				■
9	■			■		■		■	
10	■			■		■			■
11		■	■		■		■		
12		■	■		■			■	
13		■	■		■				■
14		■	■			■	■		
15		■	■			■		■	
16		■	■			■			■

All the versions in the table are versions produced for appearance evaluation only. Eight of these (no. 1, 3, 4, 7, 9, 11, 13 and 14) were considered to have unique characteristics that might affect the outcome of some of the tests. Therefore, these versions were produced in a larger number of samples to be used for the test phase.

4.7 Keypad attachment to keyboard

Since the new design of the C903 navigation keypad does not have any flanges on the large, U-shaped shortcut/clear key, it was necessary to attach the bottom part of the rubber mat to the keyboard. The surface that was to be fixated is shown in figure 4.9 below. This extra attachment is to prevent the keypad from popping out through the front panel during a drop test, i. e. avoid any unsnapping that would be considered as a failure of the test.

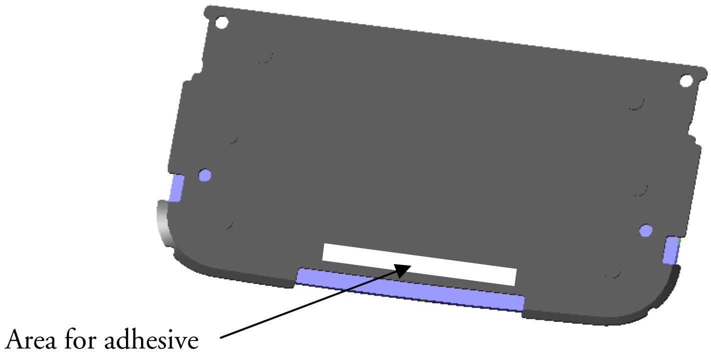

Figure 4.9. Adhesive area

The choice of what adhesive to use stood between a thin coat of glue and a double-coated adhesive tape. After discussions with the keypad supplier and engineers from the test and verification department at SEMC it was decided that a double-coated adhesive tape would be the best choice. This way, the tape will be applied on the back of the rubber mat by the keypad supplier and the finished keypad samples are ready to be attached to the test phone keyboards directly at arrival. If a thin coat of glue was to be used, this would have to involve an application procedure after the arrival of the samples, which probably would be less precise and more time consuming.

When choosing adhesive and the size of the surface to be fixated, the results from previous studies within the 3D-glass area were also taken in consideration. An important issue was to allow the glass pieces to move relative to adjacent parts, which then will reduce the risk of propagating tension that might emerge during a free fall, from e. g. the front cover. Using only a small strip of double-coated adhesive tape at the bottom of the rubber mat will hopefully result in good enough fixation without causing any excessive damage on the glass keys.

4.8 Project costs

Since this is a small scale study, the material- and manufacturing costs per keypad were naturally higher than what they would have been if they were to be mass produced. In order to make a trustworthy comparison of costs between glass keys and plastic keys, the two involved suppliers were asked to do an estimation of what the costs would be for a larger series of 3D-glass keypads.

The estimation showed that keypads with molded keys would cost approximately five times more to produce than the equivalent plastic keypad. For milled keys, the cost would be approximately ten times more than for plastic keys. Even though these are just estimated figures, they give a good indication of the large difference in cost between glass and plastic. They also show the difference in cost between the two chosen manufacturing processes, which is likely to be a decisive factor when evaluating the various concepts.

For the evaluation of concepts, see chapter 6.

5. Test and Verification

The following chapter presents the test and verification of the 3D-glass keypad samples. All test procedures and results are individually described and analyzed. A comparing study between the results and results from tests performed on the C903 plastic keypad is also carried out.

5.1 The test phase

The third and final phase of the study was the testing and verification of the glass keypads. Within this step the quality of the glass keys were explored. The material properties were evaluated as well as how suitable the shapes of the keys are. Numerous samples with different combinations of features were tested, with the purpose to identify which applied features have a negative (or positive) affect on the glass material. The versions that fulfill the requirements of the SEMC test specification were thereby singled out and the gained knowledge of limitations will be guidance on how the design and the applied features can be modified to improve the strength and durability of the glass keys.

As mentioned in chapter 4.6, some of the combinations of features are mainly interesting from an appearance point of view. Therefore, only versions expected to have unique characteristics that might affect the results were put to the test. Factors considered most crucial were the manufacturing process and if the backside surface is sand blasted or not. Since color coating and metallization does not affect the material properties, these features were not applied to the samples produced only for testing. Naturally, these samples therefore neither have the laser etched artwork.

5.2 SEMC test specification

The SEMC test specification is a generic reliability- and environmental resistibility requirements specification, containing a large number of tests within different fields of testing. All the tests performed on the 3D-glass keypads followed this standard test procedure and were carried out at the Department for Testing and Verification at SEMC in Lund. The tests and requirements in the specification are to be used as a base when evaluating design requirements for a phone project, with the main focus to identify potential product failures before the product reaches the customer [15].

5.3 The testing procedure

According to the test specification, the tests should be applied to complete products. Therefore, all 3D-glass keypads were fitted in C903 mobile phones when performing the tests. After discussions with test engineers at the test and verification department, the tests from the specification that were considered critical for a glass keypad were chosen. As mentioned earlier, a total of eight versions of samples were involved in the testing procedure. From these eight versions, the most relevant versions of samples were chosen for each test, based on whether a certain feature was expected to have an effect on the outcome of the specific test or not.

The result for each tested sample was evaluated separately, but also analyzed in comparison with the other versions and their test results. This approach presents a good overall picture of the performance of the glass material and the effects caused by different design features. All tests were performed on a minimum of three DUTs per version, which hopefully gives more accurate results than if only one DUT per version were to be tested.

5.4 Performed tests

A total of six different tests were performed on the 3D-glass keypads. Below follow individual descriptions of each test. Since the project only concerns keypads, some of the testing procedures were modified and adapted to fit this specific application. Due to company secrecy, further detailed information regarding the testing procedure will not be presented.

5.4.1 Thermal shock test

Purpose of the test
The purpose of this test is to induce mechanical stress by the use of rapid temperature cycling to induce electrical, acoustical and mechanical performance failures, cosmetic failures, adhesive failures and solder joint damages.

Test description
The DUTs are exposed to + 85°C and -40°C temperature extremes during approximately six days. The DUTs functionality, performance, cosmetics and solder joints will then be evaluated. Any loss in functionality, together with special attention on damage to adhesives, is considered as a failure.

Tested samples
Table 5.1 shows the versions of samples used for the thermal shock test. The grey areas with white stripes (in the color coating and metallization columns) mark that the feature does not exist on the test samples, but it exists on the equivalent original version.

Table 5.1. Samples used for the thermal shock test

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metallization	Sand blasting
1	■		■		■		▨		
3	■		■		■				■
4	■		■			■	▨		
7	■			■	■			▨	
9	■			■		■		▨	
11		■	■		■		▨		
13		■	■		■				■
14		■	■			■	▨		

When exposed to quick temperature changes, any crack formations and weaknesses within the material might lead to a breakage. The aspects considered most critical during this test were the manufacturing process and the sand blasting. The milled keys have been subjected to far more mechanical processing than the molded glass keys and are therefore more likely to have internal micro cracks. Micro cracks might also occur when engraving the artwork into the glass material. The sand blasting procedure could also affect the thermal shock resistance negatively.

Outcome of test
The test did not result in any failure or defects on the glass keypad samples.

Analysis
The outcome of the test showed that the glass keys withstand rapid cyclic temperature changes within the applied temperature scale. Since the samples have gone through a hardening process, which has brought extra strength to the material, it was not unexpected that the glass keys would pass the thermal chock test.

5.4.2 Solar radiation test

Purpose of the test
The purpose of this test is to simulate exposure to sunlight to determine if any material changes (color, strength etc.) occur.

Test description
The DUTs are exposed to artificial sunlight containing UV-radiation for ten days. For color and surface delta evaluation, a section of the tested surface is taped to prevent exposure, for comparison purposes. Any color shifts outside decided limits, stickiness or haze of external surface, cracks, blistering and deformation is considered as a failure.

Tested samples
Table 5.2 shows the versions of samples used for the solar radiation test.

Table 5.2. Samples used for the solar radiation test

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metallization	Sand blasting
3	▨		▨		▨				▨
11		▨	▨		▨		▨		
12		▨	▨		▨			▨	

When exposed to intense sunlight, parts of the glass might work as a lens, which could lead to defects on the coated backside surfaces. Since transparent glass is considered as worst case scenario, no samples with tinted glass were tested. Both molded keys and milled keys were tested, since the shapes (and thereby the light refraction) are somewhat different.

Outcome of test
The test did not result in any defects on the glass or on the backside surface treatments of the keys.

Analysis
The outcome of the solar radiation test showed that the glass keys can withstand normal sunlight without resulting in any undesired changes to the material or the backside coatings. Since the tested keypads consists of several different keys, with varying shape, thickness and edge sharpness, solar radiation is not considered as a glass design limitation factor. All types of backside surface treatment also appears to be unaffected by the sunlight.

5.4.3 Operational durability test - normally used keys

Purpose of the test
The purpose of this test is to ensure that the normally used keys performance and functionality is maintained throughout the product lifetime. The definition of normally used keys is dedicated keys for example dialing, navigation and game control.

Test description
The normally used keys should withstand a level of activation corresponding to normal usage and a lifespan of three years, without fatigue or functionality loss. After testing, the result is subjectively evaluated and any loss in key functionality, cracks or degraded fitting is considered as a failure.

Tested samples
Table 5.3 shows the versions of samples used for the operational durability test for normally used keys. The grey areas with white stripes (in the color coating and metallization columns) mark that the feature does not exist on the test samples, but it exists on the equivalent original version.

Table 5.3. Samples used for the operational durability test for normally used keys

No	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metalliza-tion	Sand blasting
1	■		■		■		▨		
3	■		■		■				■
4	■		■			■	▨		
7	■			■	■			▨	
9	■			■		■		▨	
11		■	■		■		▨		
13		■	■		■				■
14		■	■			■	▨		

The tests were performed on the U-key, with alternating activation on the Shortcut key and the Clear key, since this key was the one considered as most likely to fail. Just as for the thermal shock test, the aspects considered most critical were the manufacturing process, the sand blasting and the laser engraving. All these factors might affect the mechanical properties of the glass.

Outcome of test
The test did not result in any cracks or other defects on the glass keys.

Analysis
The outcome of the operational durability test showed that the glass keys can withstand repeated activation during a normal product lifetime. This was not totally unexpected, since glass materials in general can withstand pressure very well, about ten times better than tensile stress (Falk et al. 2005).

5.4.4 Free fall test –front corner and front

Purpose of the test
The purpose of this test is to confirm that the DUT can withstand the end user dropping it accidentally during intended use or during transport, respectively.

Test description
The DUT is dropped according to a predefined drop scenario at ambient temperature. The free fall scenario for these specific DUTs includes corner and face drops from

1,5 meters onto concrete. Since closed position is considered to be the worst case scenario for the navigation keypad on a slider phone, the DUTs should be dropped with the slide closed. Applicable functionality and performance is evaluated following testing and any cracks or unsnapping of non-user replaceable parts is considered as a failure.

Tested samples

Table 5.4 shows the versions of samples used for the free fall test. The grey areas with white stripes (in the color coating and metallization columns) mark that the feature does not exist on the test samples, but it exists on the equivalent original version.

Table 5.4. Samples used for the free fall test

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metallization	Sand blasting
1	■		■		■		▨		
3	■		■		■				■
4	■		■			■	▨		
7	■			■	■			▨	
9	■			■		■		▨	
11		■	■		■		▨		
13		■	■		■				■
14		■	■			■	▨		

The HyperWorks simulations indicate that the front drop will be the most critical drop. Even though the simulations give a good hint of what might happen, there is a big difference between simulation and reality; the simulation drop surface is entirely flat, but the drop surface for the tests is made of concrete. The rough concrete surface will be a much bigger challenge for the glass keys. Therefore, to see if the drop surface is such a critical aspect, a sheet of office paper was placed on the concrete slab for a first series of tests.

Regarding the choice of versions, the aspects considered most critical were again the manufacturing process, the sand blasting and the laser engraving, which might affect the mechanical properties of the glass.

Outcome of test

The results of the free fall test are presented in table 5.5 below.

Table 5.5. Outcome of free fall test
(the light grey areas mark when failure occurred)

No.	Corner drop (with paper)	Front drop (with paper)	Corner drop	Front drop
1 - 1	OK	Cracks in U-key	---	---
1 - 2	OK	Cracks in U-key	---	---
1 - 3	OK	Cracks in U-key	---	---
3 - 1	Pops out of front cover	Pops out of front cover, cracks in Rocker key and U-key	---	---
3 - 2	OK	Cracks in Rocker key and U-key	---	---
3 - 3	Pops out of front cover, cracks in U-key when adjusted	---	---	---
4 - 1	Pops out of front cover	Pops out of front cover, cracks in U-key	---	---
4 - 2	OK	Pops out of front cover, cracks in U-key	---	---
4 - 3	Pops out of front cover	OK	OK	Cracks in Rocker key
7 - 1	Pops out of front cover, Yes- and No-key slightly out of position	Pops out of front cover, cracks in Rocker key and U-key	---	---
7 - 2	Pops out of front cover	Pops out of front cover, cracks in U-key	---	---
7 - 3	OK (slide opens)	Cracks in U-key	---	---
9 - 1	OK	Cracks in U-key	---	---
9 - 2	Pops out of front cover	Pops out of front cover, cracks in U-key	---	---
9 - 3	Pops out of front cover	Pops out of front cover, cracks in Rocker key and U-key	---	---
11 - 1	OK	Cracks in U-key	---	---
11 - 2	OK	Cracks in Rocker key	---	---
11 - 3	OK	OK	OK	Cracks in Rocker key and U-key
13 - 1	Pops out of front cover, Yes-key slightly out of position	Cracks in Rocker key	---	---
13 - 2	Pops out of front cover, No-key slightly out of position	Pops out of front cover, No-key slightly out of position	Pops out of front cover, No-key slightly out of position	Cracks in Rocker key
13 - 3	OK	Cracks in Rocker key	---	---
14 - 1	Pops out of front cover	Cracks in U-key	---	---
14 - 2	Yes-key slightly out of position	OK	Cracks in U-key	---
14 - 3	Pops out of front	Cracks in Rocker key	---	---

As the table shows, none of the samples passed the free fall test. 20 of 24 samples did not even make it to the real drop scenario defined by the test specification, as they failed already when dropped onto the paper covered surface.

Analysis
The outcome of the free fall test shows that the glass keypads would not withstand the end user dropping it onto the ground. None of the aspects separating the different versions seem to make much of a difference, but it is obvious that the most critical drop is the front drop, just as the simulations indicated. When dropped with the front down, the 3D-glass keys are the ones to hit the ground first, since they stand out from the front panel. This explains the cracks and the main conclusion is that glass keys probably need to be more protected if they are to pass the free fall test.

To see if the glass keys could withstand the drop impact if being more protected, extra front drops were made using two versions; one with molded keys and one with milled keys. This time, an extra front frame was taped onto the front cover, see figure 5.1 below.

Figure 5.1. DUT with extra front frame

When dropped with the front down, the extra front frame was now the first thing to hit the ground. Drops were made both with and without paper, and this time all the samples stayed intact. Thereby, the glass keys now passed the test.

Further drop tests from 1 meter were also made, to see if the non-protected glass keys can withstand a free fall from a lower level. This time, only the worst case scenario samples (no. 3 and no. 13) and the best case scenario samples (no. 4 and no. 14) for both molded and milled keys were put to the test. The result from this test series is presented in table 5.6 below.

Table 5.6. Outcome of free fall test – 1 meter
(the light grey areas mark when failure occurred)

No.	Corner drop (with paper)	Front drop (with paper)	Corner drop	Front drop
3 - 1	OK	OK	OK	Small crack in Rocker key
3 - 2	OK	OK	OK	Pops out of front cover
3 - 3	OK	OK	OK	Small crack in Rocker key
4 - 1	OK	OK	OK	OK
4 - 2	Pops out of front cover	OK	OK	Small cracks in Rocker key
4 - 3	OK	OK	OK	OK
13 - 1	OK	OK	OK	OK
13 - 2	OK	OK	OK	Small cracks in Rocker key and U-key
13 - 3	OK	OK	OK	OK
14 - 1	OK	OK	OK	OK
14 - 2	OK	OK	OK	OK
14 - 3	OK	OK	OK	OK

As the table shows, the majority of the keypads passed the test when dropped from only 1 meter. The failures that did occur were mainly on the worst case scenario samples (no. 3 and no. 4), while the best case scenario samples seemed to be able to withstand the impact of a 1 meter free fall.

5.4.5 Tumble test

Purpose of the test
The purpose of this test is to determine the robustness and reliability of the keys when subjected to a combination of shock and vibration. Cosmetic durability is not the objective of this test and is therefore not of concern.

Test description
The DUTs are placed into a tumbler and tumbled for 60 hours at ambient conditions. The functionality of the units is evaluated following 20, 40 and 60 hours of testing with the performance being re-evaluated following 60 hours of tumbling. Any damage to the keypad, e. g. cracks is considered as a failure.

Tested samples

Table 5.7 shows the versions of samples used for the tumble test. The grey areas with white stripes (in the color coating and metallization columns) mark that the feature does not exist on the test samples, but it exists on the equivalent original version.

Table 5.7. Samples used for the tumble test

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metallization	Sand blasting
1	■		■		■		▨		
3	■		■		■				■
4	■		■			■	▨		
7	■			■	■			▨	
9	■			■		■		▨	
11		■	■		■		▨		
13		■	■		■				■
14		■	■			■	▨		

Once again, the aspects considered most critical were the manufacturing process, the laser engraving and the sand blasting, which all could affect the mechanical properties of the glass.

Outcome of test

The tumble tests resulted in cracks on all the DUTs after only tumbled for 20 hours. Hence, none of the samples passed the test.

Analysis

The outcome of the tumble test shows that the glass keypads are not robust and reliable enough to withstand the combination of shock and vibration.

To see if the samples could perform better if better protected, an additional test was performed with extra front frames tapes onto the front covers of the DUTs (like the DUT in figure 5.1). Unfortunately, the extra front frames could not be attached securely enough to the DUTs and fell off sometime during the test, resulting in failure for all the glass keypads again. Therefore, the result was hard to interpret, but it is possible that the keypads would have passed the test if they had been protected during the whole test time.

5.4.6 Abrasion tumbling test

Purpose of the test
The purpose of this test is to verify that the DUT has good enough resistibility for dust penetration and abrasion resistibility. The target area for this test is mainly key functionality and cosmetics.

Test description
The DUTs are exposed to dust and fibers by tumbling them during six hours together with various items usually found in pockets and bags. The functionality of the units is evaluated following 20 minutes, two hours, four hours and six hours of testing, with the performance being re-evaluated following six hours of tumbling. For tumbling up to 20 minutes, minor scratches are allowed. Scratches are allowed after two hours but after this, there are no further cosmetics subjective requirements. Regarding functionality of keys, no degradation in click feeling is allowed for test times up to two hours. After that, only functionality loss is considered a failure.

Tested samples
Table 5.8 shows the versions of samples used for the abrasion tumbling test. The grey areas with white stripes (in the color coating and metallization columns) mark that the feature does not exist on the test samples, but it exists on the equivalent original version.

Table 5.8. Samples used for the abrasion tumbling test

No.	Man. process		Type of glass		Artwork		Backside surface treatment		
	Molded keys	Milled keys	Transparent glass	Tinted transparent glass	Laser engraved	Laser etched	Color coating	Metallization	Sand blasting
1	■		■		■		▨		
7	■			■	■			▨	
11		■	■		■		▨		

Since all cosmetics are applied on the backside of the keys it will not be subjected to any tear and wear during the tumbling. The aspects considered most critical for this test were the manufacturing process and the type of glass. The molded keys and the milled keys have somewhat different shapes and it was also unclear if the tinted glass would be more affected by the abrasion tumbling than the transparent glass.

Outcome of test
The results of the abrasion tumbling test are presented in table 5.9 below.

Table 5.9. Outcome of abrasion tumbling test
(the light grey areas mark definite failure)

No.	20 min	2 h	4 h	6 h
1 - 1	Some wear and tear, mainly to the Yes- and No keys	Wear and tear, all keys	More wear and tear, all keys	Same as after 4 h
1 - 2	Some wear and tear, mainly to the Yes- and No keys	Wear and tear, all keys	More wear and tear, all keys	Same as after 4 h. Cracks in U-key
1 - 3	Some wear and tear, mainly to the Yes- and No keys	Wear and tear, all keys	More wear and tear, all keys	Same as after 4 h
7 - 1	Wear and tear to the Yes- and No keys	More wear and tear, mainly to the Yes key, No key and Soft keys	Even more wear and tear, now also Rocker key	Same as after 4 h
7 - 2	Wear and tear to the Yes- and No keys	More wear and tear, mainly to the Yes key, No key and Soft keys	Even more wear and tear, now also Rocker key	Same as after 4 h
7 - 3	Wear and tear to the Yes- and No keys	More wear and tear, mainly to the Yes key, No key and Soft keys. Cracks in Rocker key	Even more wear and tear, now also Rocker key	Same as after 4 h
11 - 1	Some wear and tear	Wear and tear	More wear and tear. Shreds missing from Soft key and No key	Same as after 4 h
11 - 2	Some wear and tear	Wear and tear	More wear and tear	Same as after 4 h
11 - 3	Some wear and tear	Wear and tear	More wear and tear	Same as after 4 h

None of the keys had any loss in functionality. Hence, from that point of view they all passed the test. But as the table shows, one sample of each version had cracked keys or missing shreds when the test was finished. These are all considered as definite failures.

The test showed that the tinted glass appeared to be less scratch resistant. Scratches are also generally more visible on tinted glass than on transparent glass.

The cosmetic evaluation is highly subjective, but overall, the glass keys were considered to be a little too sensitive to scratches. The Yes key, the No key and the Soft keys in particular lose their shiny surface after less than two hours, but since the artwork is applied on the backside it is not affected as much by the wear and tear as it would be if applied on the top surface. This is an advantage when working with glass keys.

Analysis

The abrasion tumbling test showed that the glass keypads can withstand some wear and tear, but a more scratch resistant surface would be desired. As a result, further studies within material hardening and surface treatments will be recommended. The cracked keys could be coincidental, but it is still considered a serious failure. Therefore, it would be interesting to perform additional tests, with extra front frames protecting the glass keys (like the extra front drops that were made in chapter 5.4.4). However, due to the time limit, such further tests will not be performed within this Master Thesis.

5.5 Comparison with the C903 plastic keypad test results

All tests performed on the glass keypads have also been performed on the C903 original plastic keypad. The plastic keys are made of a polymer using the injection-molding process. Although the design of the keypad has been somewhat alternated for the glass keys, it is still considered significant to make a comparison between the glass- and the plastic test results.

When performing the six tests presented in this chapter on the plastic keypad, no failures occurred. The plastic keypad passed all the tests and no particular problems with the design or the material had to be solved. As shown in chapter 5.4, the glass keypad caused a bit more trouble. However, this does not mean that glass is a bad choice for mobile phone applications. SEMC engineers have much more knowledge and experience from working with plastic material than they have from working with glass. The C903 navigation keypad obviously has a good design that works for plastic keys, but even though the keypad design has been alternated for this project, simulations and tests have shown that it is not optimized for glass keys. Therefore, glass as a design material for mobile phone keypads should not be discarded only because these particular glass keypads do not stand all the tests.

5.6 Conclusions of the test phase

By going through the tests described in this chapter, the 3D-glass keypad samples have all been exposed to different kinds of stress. The outcomes of the tests were varied and not always satisfactory. Breakage of the glass is the main reason for failure and it is possible that this is a consequence of defects in the material, e. g. micro crack formations, which are not visible to the eye. Another reason for test failure is that the C903 and its keypad design simply are not optimal for glass keys. For pictures of tested samples, see appendix C.

Although some test results were disappointing, the study has resulted in gained knowledge within the 3D-glass area and a number of valuable conclusions have been made. These conclusions are presented below.

5.6.1 Conclusions - critical aspects

Based on the outcome of the tests, the following aspects are considered critical for the glass keypads:

Figure 5.2. Cracked key

- *Poor impact resistance*
  The glass keypad samples fail both the free fall tests and the tumble tests, due to inadequate impact resistance. When better protected and tested again, the keys pass the tests.

- *Abrasion of tinted glass keys*
  The tinted glass is less scratch resistant than the transparent glass.

- *Design limitations*
  The key most likely to fail when dropped is the Rocker key, which is a result of the key being highly exposed and having a bold design. Since its thin cross-sectioned outer frame is the first to hit the ground when dropped with the front down, large stress concentrations occurs in the key and cause crack formation.

5.6.2 Conclusions – positive aspects

Based on the outcome of the tests, the following aspects are considered positive for the glass keypads:

- *No top coat needed*
  The glass surface does not need a top coat and thereby, the risk of the surface going yellow due to solar radiation is eliminated. Also, since the artwork is applied on the backside, it does not gradually wear off.

- *Withstand thermal chock*
  The glass keypad samples withstand the thermal chock test, which is a sign that the glass does not contain high inner tensions.

- *Withstand activation*
  The U-key, which is the largest and thinnest key, can withstand a quite high activation force during the entire simulated product lifetime without any failure.

6. Evaluation of concepts

The following chapter presents the evaluation of the different design concepts with varying combinations of features. All versions produced and tested are analyzed using a weighted sum of rated criteria to determine concept ranking.

As mentioned in chapter 4.6, an important part of the project was to study the effect that different combinations of artwork application, surface treatments and backside coatings have on the performance of the glass keys. Therefore, the glass keypads were produced in 16 different versions (see table 4.1 in chapter 4.6). After going through various testing, some conclusions regarding the glass keys' durability were made. Although this is a very essential part, factors like appearance, cost, lead times and suitability for mass production were also necessary to take into consideration.

6.1 Concept scoring

To further evaluate the different design concepts, a variant of concept scoring was carried out. Concept scoring is a method used to better differentiate competing concepts. Selection criteria are established and the relative importance of these is weighted to give a more refined comparison between the different concepts (Ulrich & Eppinger 2008). For every selection criterion, each concept is rated on a scale from 1 to 5, where 1 is the lowest score and 5 is the highest. The total concept scores are then determined by the weighted sum of the ratings.

For the concept scoring, the following six criteria were chosen:

- *Cost*
  Cost and lead times for manufacturing are always important factors to consider when working on a development project. However, a 3D-glass keypad will probably be an exclusive feature, only used on perhaps special edition mobile phones. Therefore, cost is not weighted as a high importance criterion for this application. Regarding the variation in cost for the different concepts, milling is rated lower than molding due to need of much more machine time.

- *Design possibilities*
  When designing with glass material, there are some clear limitations, but these are not considered as determining criteria for the evaluation. The molding process will always leave glass keys with a radius of at least 0,2 mm and it is preferable to have one flat side, but other than that there are numerous design possibilities.[12] The

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[12] Mail conversation with Manager, Glass molding company 2009-06-17

milling process evaluated in this study is only 2,5 dimensional and does not allow mass production of keys with concave shapes[13].

- *Glass appearance*
  If the glass keys do not look as though they are made of glass, there is no point in using such a challenging material. To get a good glass look, backside metallization is to prefer. Milled keys will also have more distinct shapes that emphasize the optical glass qualities.

- *Production suitability*
  Since mobile phones are produced in fairly large series (even when being special editions), the production suitability is an important factor to consider. The molding process allows manufacturing of several keys at once, while milled keys will have to be made one by one. For the artwork, to engrave will mean more machine time and thereby it is a less suitable production method than laser etching.

- *Quality*
  The quality of a product is of highest importance to get satisfied customers. In general, the glass keypads did not perform as well as hoped and some versions meant more difficulties than others. The tinted glass turned out to be more sensitive to abrasion than the transparent glass and the sand blasting caused problems during the production, as the small and thin glass keys tended to break due to the impact from the sand blasting process.

- *User friendliness*
  Another part of satisfying the customer is to make the product user friendly. Naturally, having to return a mobile phone due to cracked glass keys is not acceptable, and therefore the ratings for these somewhat unreliable keys are relatively low. The molded keys are considered more user friendly than the milled keys, since the more rounded shape of the molded keys makes it easier to put in and pull out of a pocket. The milled keys may have a more distinct shape, but they have sharper edges which are not regarded as very user friendly. Also, if a tinted glass is to be used, it is important that the tint is not too dark, since the illuminated artwork then will be difficult to see.

6.2 The concept scoring matrix

Based on the criteria presented above, the 16 versions produced were evaluated and rated, resulting in the concept scoring matrix shown in table 6.1 below.

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[13] Mail conversation with Manager, Keypad supplier 2009-06-22

Table 6.1. Concept scoring matrix

Concepts	Selection Criteria And Weight	Cost	Design possibilities	Glass appearance	Production suitability	Quality	User friendliness	Total Score	Rank
		12%	6%	17%	22%	26%	17%		
1 Mo-Tr-En-Cc	Rating	5	4	2	4	3	2	3,18	5
	Weighted Score	0,6	0,24	0,34	0,88	0,78	0,34		
2 Mo-Tr-En-Mz	Rating	5	4	4	4	3	2	3,52	3
	Weighted Score	0,6	0,24	0,68	0,88	0,78	0,34		
3 Mo-Tr-En-Sb	Rating	5	4	1	4	1	1	2,32	9
	Weighted Score	0,6	0,24	0,17	0,88	0,26	0,17		
4 Mo-Tr-Et-Cc	Rating	5	4	2	5	3	3	3,57	2
	Weighted Score	0,6	0,24	0,34	1,1	0,78	0,51		
5 Mo-Tr-Et-Mz	Rating	5	4	4	5	3	3	3,91	1
	Weighted Score	0,6	0,24	0,68	1,1	0,78	0,51		
6 Mo-Tr-Et-Sb	Rating	5	4	1	4	1	1	2,32	9
	Weighted Score	0,6	0,24	0,17	0,88	0,26	0,17		
7 Mo-Ti-En-Mz	Rating	5	4	3	4	2	2	3,09	6
	Weighted Score	0,6	0,24	0,51	0,88	0,52	0,34		
8 Mo-Ti-En-Sb	Rating	5	4	1	4	1	1	2,32	9
	Weighted Score	0,6	0,24	0,17	0,88	0,26	0,17		
9 Mo-Ti-Et-Mz	Rating	5	4	3	5	2	2	3,31	4
	Weighted Score	0,6	0,24	0,51	1,1	0,52	0,34		
10 Mo-Ti-Et-Sb	Rating	5	4	1	4	1	1	2,32	9
	Weighted Score	0,6	0,24	0,17	0,88	0,26	0,17		
11 Mi-Tr-En-Cc	Rating	1	3	3	1	3	1	1,98	14
	Weighted Score	0,12	0,18	0,51	0,22	0,78	0,17		
12 Mi-Tr-En-Mz	Rating	1	3	5	1	3	2	2,49	8
	Weighted Score	0,12	0,18	0,85	0,22	0,78	0,34		
13 Mi-Tr-En-Sb	Rating	1	3	2	1	1	1	1,29	16
	Weighted Score	0,12	0,18	0,34	0,22	0,26	0,17		
14 Mi-Tr-Et-Cc	Rating	1	3	3	2	3	1	2,20	13
	Weighted Score	0,12	0,18	0,51	0,44	0,78	0,17		
15 Mi-Tr-Et-Mz	Rating	1	3	5	2	3	2	2,71	7
	Weighted Score	0,12	0,18	0,85	0,44	0,78	0,34		
16 Mi-Tr-Et-Sb	Rating	1	3	2	2	1	1	1,51	15
	Weighted Score	0,12	0,18	0,34	0,44	0,26	0,17		

The concept scoring matrix shows that version no. 5 is the highest ranked concept – a keypad with molded, transparent keys with a metallization backside application and a laser etched artwork (see figure 6.1). It is also clear that the advantages of the molding process are immense, since the six highest ranked concepts are molded keys. The lowest ranked version is a keypad with milled, transparent keys, with a sand blasted backside and a laser engraved artwork. Both the sand blasting and the laser engraving are considered as unnecessary applications, since they could affect the glass properties negatively without really adding any appearance value.

Figure 6.1. The highest ranked concept

7. Analysis and Conclusions

The following chapter includes the final analysis and conclusions of the Master Thesis, evaluating and answering the problem statement and the supplementary research questions. Pictures of some of the glass sample versions produced are also presented.

The main issue of this Master Thesis has been whether or not it would be realistic to implement 3D-glass keypads on future mobile phones. After thoroughly evaluating possibilities as well as limitations, it is obvious that glass is an interesting but complex design material. Material composition, manufacturing methods and applied design features have been some of the main focus areas for this project, within which both research and testing have been performed. The results and the knowledge gained from this emphasize the significance of creating a design optimal for glass and to carefully evaluate the importance of each aspect taken into consideration.

7.1 Answers to the research questions

Regarding the manufacturing process, the study has shown that both molding and milling could be suitable choices. The blank molding process has the advantage of allowing production of large series with relatively short lead times and designs with vast variation of possible shapes. However, molded glass keys will always have a defined radius, so sharp edges and clear facets are difficult to obtain. The requirement to have a minimum of one flat side is also a limitation of the molding process. The milling process used for this project is really a 2D-process applied as a 3D-process, resulting in 2,5D-glass keypads. Concave shapes are not possible for mass production and since every key has to be milled one by one it is both a time consuming and expensive method. On the other hand, the result is glass keys with sharp and distinct edges, which emphasize the glass' optical qualities.

The B 270 soda-lime glass used for the molded keys is highly suitable for the blank molding process, but it would be preferable to find a more impact- and scratch resistant glass material if possible. The IG3 used for the milled keys appeared to have about the same mechanical qualities as the B 270, and maybe here it is also possible to find a glass that suites a keypad application better.

If a tinted glass is to be used, a light tint is to prefer over a darker tint. The darker the tint is the more visible will the wear and tear be. The effect of a backside coating will also be lost if the glass is to dark, and the illumination of the artwork will not shine though properly. Another difficulty with using tinted glass could be to get an exact color match with other details made of different materials. It is also harder to get a high surface fineness on tinted glass keys than on transparent glass keys.

Three types of backside coating were tested and the tests and evaluation shows that they are all possible to use on glass keys. However, a simple color coating does not enhance the glass appearance nearly as well as the metallization. When using a color coating or sand blasted surface it is also important to choose a proper adhesive that does not leave marks that shine through. The sand blasting is not suitable for small and thin keys, but it could be interesting to use on the sides of a thicker, molded key. This way, a molded key could get the same deepening effect that a milled key gets due to the matt machined surface on the edges.

Since the glass keys are relatively thin, to laser engrave the artwork does not result in a big enough deepening effect to give ground for such a time consuming process.

Regarding after treatments, it is obvious that glass keys need to be hardened, preferably through a chemical hardening process. An anti-splinter coating could be applied, but it is not suitable for smaller details and it would also mean that the glass keys would get even rounder shapes. Since glass is a relatively hard material and no artwork is applied on the top surface, a hard coat is not considered meaningful.

7.2 Reflections on the glass key concept

Throughout the study, the general opinion has been that sharp and distinct shapes are practically necessary to enhance the glass' appearance enough. Why this is the case is hard to say. A vase is almost always made of glass and it usually has rather round and soft shapes, but it is not likely that someone would question whether or not it is made out of real glass. A crystal bowl has more defined diamond cut surfaces, but when comparing it to a squat mouth blown bowl they are still both equally much considered as glass items.

When implementing glass keys, a mobile phone provider enters a field of application that is fairly unknown for the consumer. If purchasing a new mobile phone one probably expects the keys to be made of plastic or metal, but not glass. Keys are not a mobile phone feature that the consumer would normally associate with glass materials. Therefore, in order for him or her to embrace and value such an application, it probably must be crystal clear that the keys are actually made of glass and not just a glass-looking type of plastic. The effects must be so distinct that they can not be achieved from any other material than glass, even though the same person gladly assumes that any random organically shaped vase is made of glass. So until mobile phone glass keys are a well-recognized feature, a sharp and distinct look might be necessary to overcome the skepticism of the average end user.

7.3 Glass samples

8. Recommendations

The following chapter presents the final guideline for the utilization of 3D-glass when designing keypads.

8.1 3D-glass keypad design guideline

The purpose of a design guideline is two-fold. One purpose is to institutionalize knowledge by converting lessons learned into recommendations for further work. By documenting what went wrong and how it was resolved others can avoid the same problem. The second purpose is to help engineers find relevant design information that is pertinent to their particular assignment; i. e. reduce the amount of time spent doing detective work when starting a new design [13].

The results of this study show that glass is a complex design material. If 3D-glass keypads are to be implemented on future mobile phones, every keypad design needs to be individually evaluated, However, based on this Master Thesis, some general recommendations for the design and the development can be made;

- When choosing what manufacturing method to use, be sure to carefully evaluate what aspects to take into consideration and the individual importance of these aspects. The molding process is suitable for larger series and designs with double curved surfaces, but the keys will have edges with a minimum radius of 0,2 mm (although a radius of 0,5 mm is recommended). Through the milling process, keys with more distinct edges and facets can be produced, but it is a time consuming and expensive process that does not allow concave shapes.

- For the molding process, the minimum possible glass thickness is approximately 0,5 mm.[14] For the milling process, glass details thinner than 0,4 mm can not be produced.

- Since glass is a very brittle material it is important to create a keypad design that protects the keys and thereby minimizes the risk of breakage if the end user would accidentally drop the mobile phone.

- Make sure that the design allows the keys to move without interfering each other.

- To minimize the risk of failure of the keys, always harden the glass material through a chemical hardening process.

- If possible, use a glass material that is highly scratch resistant.

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[14] Mail conversation with Manager, Glass molding company 2009-01-26

- To emphasize the glass' optical qualities, a vacuum metalized backside surface is recommended.

- Sand blasting is not recommended on keys with thin cross sections, due to the risk of breakage during manufacturing and thereby causing yield problems. However, sand blasting could be an interesting feature if used as a side- and edge application on thicker molded keys, enhancing the depth effect of the glass.

- Using transparent glass will result in keys with a finer surface finish than on keys made from tinted glass. If a tinted glass is desired, always choose a light tint and make sure it is possible to color match with other details made from different materials.

- Laser etching of the artwork is a preferred method rather than laser engraving. For the engraving to give an increased depth effect it would have to be at least 0,1-0,3 mm deep, which is not a realistic feature for glass keys.

8.2 Suggestions on further studies

If a 3D-glass keypad is to be a realistic feature on future mobile phones, further studies need to be performed before including the application in a development project. Below follows a list of suggestions on what areas to further explore.

- *Verify the process with suitable suppliers*
  In order to take 3D-glass keypads from the study phase to being a validated mobile phone feature it is necessary to study the whole chain; including finding suitable suppliers, producing larger volumes, using proper tools and getting an acceptable yield (finding and working with top three yield loss drivers).

- *Perform an extended study on glass materials*
  Try to find even more suitable glass qualities for mobile phone keys and for the chosen manufacturing processes.

- *Develop an optimal 3D-glas keypad design*
  Explore the possibilities to design a keypad where the keys are protected enough to pass all the tests.

- *Improve the molding tool*
  Work on developing a molding tool that can produce keys with high surface fineness, minimal radiuses and as distinct shapes as possible.

- *Perform a study together with Customer Service*
  Try to estimate what the return rate would be on a mobile phone with glass keys and investigate what types of defects (cracks or scratches) that would cause this.

Naturally, these are only a few suggestions on areas that could be meaningful to perform further studies within. 3D-glass keypads is a yet fairly unexplored area, but it is an exciting one that could give future products of SEMC an added value on the mobile phone market.

9. References

9.1 Literature

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9.2 Electronic sources

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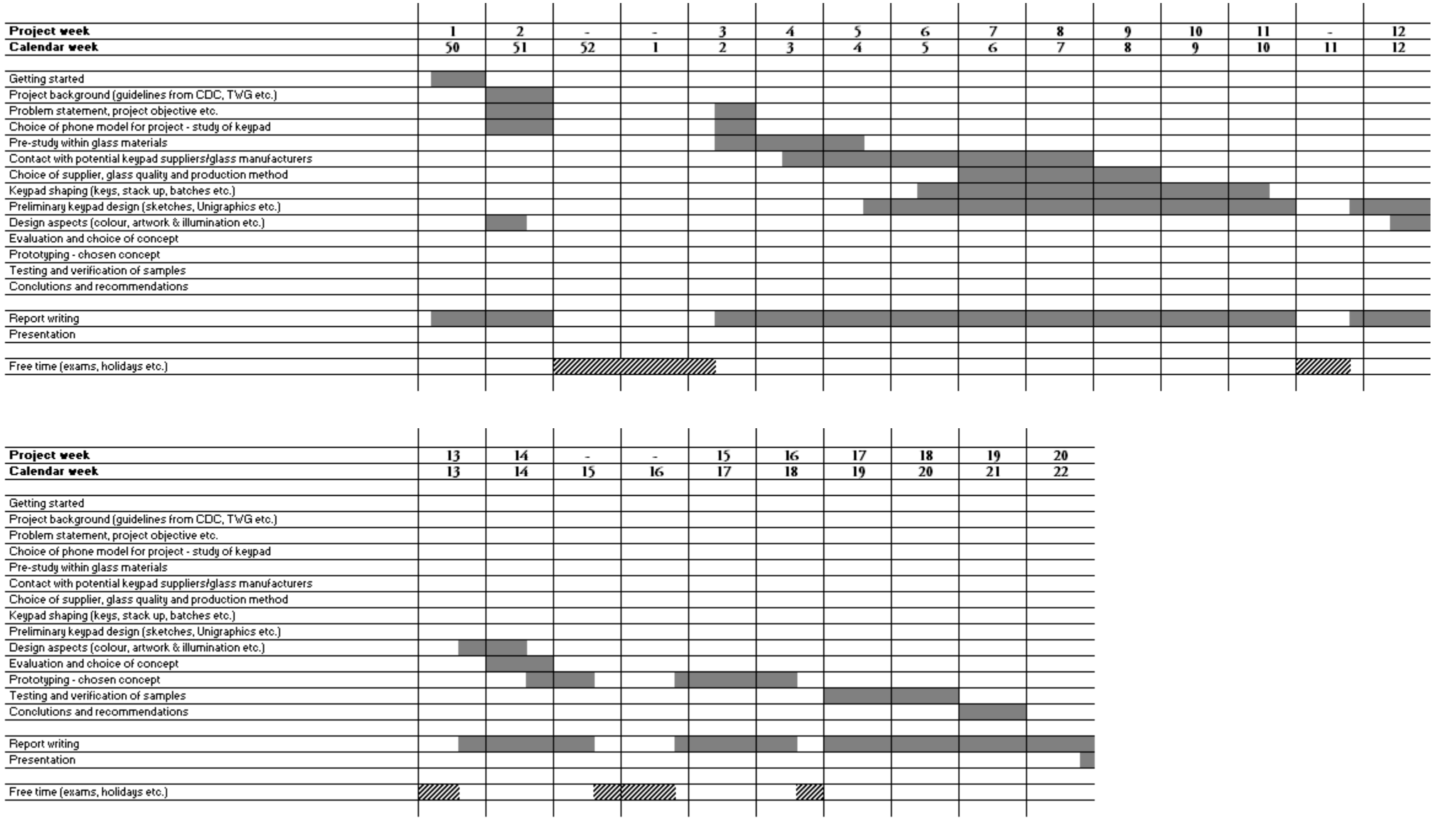
9.3 Internal documents

[13] SEMC Keyboard Design Guideline

[14] SEMC Thin Keypad Design Guide

[15] SEMC Test Specification

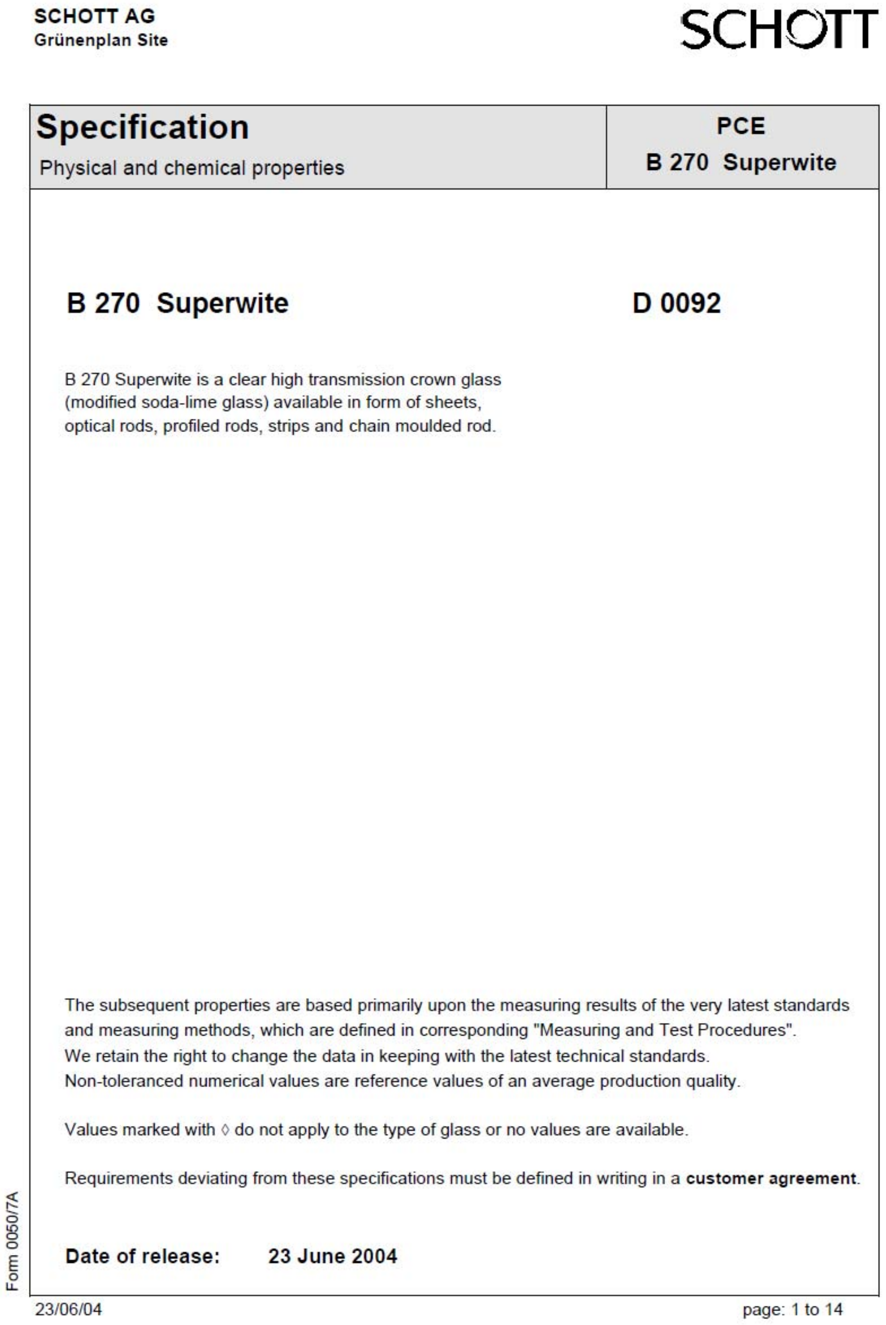
Appendix A – Early time plan



Project week	1	2	-	-	3	4	5	6	7	8	9	10	11	-	12
Calendar week	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12
Getting started	■														
Project background (guidelines from CDC, TWG etc.)		■													
Problem statement, project objective etc.		■			■										
Choice of phone model for project - study of keypad		■			■										
Pre-study within glass materials					■	■	■								
Contact with potential keypad suppliers/glass manufacturers						■	■	■	■	■					
Choice of supplier, glass quality and production method									■	■	■				
Keypad shaping (keys, stack up, batches etc.)								■	■	■	■	■	■		
Preliminary keypad design (sketches, Unigraphics etc.)							■	■	■	■	■	■	■	■	■
Design aspects (colour, artwork & illumination etc.)		■													■
Evaluation and choice of concept															
Prototyping - chosen concept															
Testing and verification of samples															
Conclutions and recommendations															
Report writing	■	■			■	■	■	■	■	■	■	■	■	■	■
Presentation															
Free time (exams, holidays etc.)			▨	▨	▨									▨	

Project week	13	14	-	-	15	16	17	18	19	20
Calendar week	13	14	15	16	17	18	19	20	21	22
Getting started										
Project background (guidelines from CDC, TWG etc.)										
Problem statement, project objective etc.										
Choice of phone model for project - study of keypad										
Pre-study within glass materials										
Contact with potential keypad suppliers/glass manufacturers										
Choice of supplier, glass quality and production method										
Keypad shaping (keys, stack up, batches etc.)										
Preliminary keypad design (sketches, Unigraphics etc.)										
Design aspects (colour, artwork & illumination etc.)	■	■								
Evaluation and choice of concept		■								
Prototyping - chosen concept		■	■	■	■	■				
Testing and verification of samples							■	■		
Conclutions and recommendations									■	
Report writing	■	■	■	■	■	■	■	■	■	■
Presentation										■
Free time (exams, holidays etc.)	▨		▨	▨		▨				

Appendix B – Material specification B 270



SCHOTT AG
Grünenplan Site

SCHOTT

Specification

Physical and chemical properties

PCE

B 270 Superwite

B 270 Superwite

D 0092

B 270 Superwite is a clear high transmission crown glass (modified soda-lime glass) available in form of sheets, optical rods, profiled rods, strips and chain moulded rod.

The subsequent properties are based primarily upon the measuring results of the very latest standards and measuring methods, which are defined in corresponding "Measuring and Test Procedures".
We retain the right to change the data in keeping with the latest technical standards.
Non-toleranced numerical values are reference values of an average production quality.

Values marked with ◊ do not apply to the type of glass or no values are available.

Requirements deviating from these specifications must be defined in writing in a **customer agreement**.

Form 0050/7A

Date of release: 23 June 2004

23/06/04

page: 1 to 14

Specification

Physical and chemical properties

PCE

B 270 Superwite

1. Optical properties

1.1 Refractive indices (20 °C)

Pretreatment of samples	n_g	1.5341
annealed at 40 °C/h	$n_{F'}$	1.5297
	n_F	1.5292
	n_e	1.5251 ± 0.001*
	n_d	1.5230
	n_D	1.5229
* ± 0.0003 upon request	$n_{C'}$	1.5207
	n_C	1.5203
Further refractive indices in UV and IR (reference values)		see annex

1.1.1 Abbe value

ν_e	58.3 ± 0.6
ν_d	58.5

1.2 Transmittance data

1.2.1 Spectral transmittance τ (λ)

1.2.1.1 τ (λ) - curve

Plot of spectral transmittance $\tau(\lambda)$ for	
d = 2.0 mm and d = 15 mm (λ = 280 nm to 650 nm)	see annex
d = 2.0 mm and d = 15 mm (λ = 280 nm to 2000 nm)	see annex

1.2.1.2 τ (λ) - individual values in %

see annex

1.2.1.3 Edge wavelength (d = 2.0 mm)

Edge wavelength	$\lambda_c(\tau = 0.46)$ in nm	312
Solarization refer to 6.2		
Additional data	$\lambda_S(\tau = 0.05)$ in nm	294
	$\lambda_P(\tau = 0.85)$ in nm	340

1.2.2 Luminous transmittance τ_v

1.2.2.1 Luminous transmittance as a function of thickness

thickness in mm	τ_{vD65} in %	τ_{vA} in %
2.0	91.7	91.7
4.0	91.6	91.6
15.0	91.0	91.0

1.2.3	**Special transmittance values in % (d = 2.0 mm)**		
1.2.3.1	**UV - transmittance**	τ_{UVA}	84
		τ_{UVB}	19
1.2.3.2	**IR - transmittance**	τ_{A}	92.5
1.2.3.3	**Solar direct transmittance**	τ_{e}	91.4
1.3	**Colour**		
1.3.1	**Visual evaluation**		disregard
1.3.2	**Colorimetry (d = 2.0 mm)**		
	Chromaticity coordinates (colour locus) are referred to the namend Standard Illuminant according to CIE 2°-observer	D_{65} x	0.314
		y	0.332
		A x	0.448
		y	0.408
1.3.3			disregard
1.3.4	**General colour rendering index R_a (d = 2.0 mm)**		100

Specification Physical and chemical properties	**PCE** **B 270 Superwite**

2. Thermal properties

2.1 Viscosities and corresponding temperatures

Designation	Viscosity log η in dPas	Temperature ϑ in °C
Strain point	14.5	**511** (~952 °F)
Annealing point	13.0	**541** (~1006 °F)
Softening point	7.6	**724** (~1335 °F)
Forming temperature	6.0	**827** (~1521 °F)
Forming temperature	5.0	**915** (~1679 °F)
Forming temperature	4.0	**1033** (~1891 °F)

2.2 Transformation temperature *Tg* in °C

533 (~991 °F)

2.3 Coefficient of thermal expansion α

2.3.1 Coefficient of mean linear thermal expansion α in 10^{-6} K^{-1} for the indicated temperature range (static measurement)

α (20 °C;300 °C)	9.4
α (20 °C;200 °C)	9.0
α (20 °C;100 °C)	8.2

2.3.2 Coefficient of mean linear thermal expansion α in 10^{-6} K^{-1} for the indicated temperature range (dynamic measurement)

α (20 °C;100 °C)	7.8
α (20 °C;150 °C)	8.4
α (20 °C;200 °C)	8.8
α (20 °C;250 °C)	9.1
α (20 °C;300 °C)	9.4
α (20 °C;350 °C)	9.6
α (20 °C;400 °C)	9.8
α (20 °C;450 °C)	10.0
α (20 °C;500 °C)	10.3

Specification

Physical and chemical properties

PCE

B 270 Superwite

2.3.3	**Coefficient of mean linear thermal expansion** **α in 10^{-6} K^{-1} for the mentioned temperature intervals** **(dynamic measurement)**	see annex
2.4	**Fuseability**	
	Stress-free fusion with suitable lower segments out of our product range is possible.	
2.5	**Mean specific heat capacity c_p (20 °C to 100 °C) in J/ (g·K)**	0.86
2.6	**Thermal conductivity λ in W/ (m·K) for the indicated temperatures**	
	ϑ = 24.5 °C	0.92
	ϑ = 89 °C	1.01
	ϑ = 127 °C	1.08
	ϑ = 167 °C	1.15
2.7	**Specific thermal stress φ in N/ (mm²·K)**	0.86

Specification Physical and chemical properties		**PCE** **B 270 Superwite**
3.	**Mechanical properties**	
3.1	**Density ρ in g/cm³**	2.55
3.2	**Stress optical coefficient C in $1.02 \cdot 10^{-12}$ m²/N**	2.7
3.3	**Breaking strength**	
	Admissible value for the bending strength σ_{zul} of technically annealed glasses as calculation basis (air) in N/mm²	30
	A higher mechanical strength can be realized by chemical toughening according to the ion exchange procedure (refer to annex 3.3.1) or by thermal toughening.	
3.3.1	**Chemical toughening**	
	Processing temperature ϑ in °C	420
	Processing time t in h	16
	Compressive stress Ds as birefringence in nm/cm	7200
	Penetration depth Nz up to neutral zone in µm	48
	Further information	see annex
3.3.2	**Thermal toughening**	
	Recommended minimum thickness d in mm for toughened safety glass for building purposes according to DIN 1249 T10 - 1990	4.0
3.4	**Young´s modulus E in kN/mm²**	71.5
3.5	**Poisson´s ratio μ**	0.219
3.6	**Torsion modulus G in kN/mm²**	29.3
3.7	**Knoop hardness HK_{100}**	542

Form 0050/7B

Specification

Physical and chemical properties

PCE
B 270 Superwite

4.	**Chemical properties**	
4.1	**Hydrolytic resistance acc. to DIN ISO 719**	
	Hydrolytic class	HGB 3
	Equivalent of alkali (Na_2O) per gram of glass grains in µg/g	170
4.2	**Acid resistance acc. to DIN 12 116**	
	Acid class	S 2
	Half surface weight loss after 6 hours in mg/dm²	1.4
4.3	**Alkali resistance acc. to DIN ISO 695**	
	Class	A 2
	Surface weight loss after 3 hours in mg/dm²	140
5.	**Electrical properties**	
5.1	**Dielectric constant (Permittivity) ε_r at 1 MHz**	7.0
5.2	**Dissipation factor tan δ bei 1 MHz**	$30 \cdot 10^{-4}$
5.3	**Electric volume resistivity ρ_D in $\Omega \cdot$ cm at the specified temperatures**	
5.3.1	**ρ_D for alternating current 50 Hz and 3 kHz**	
	ϑ = 1260 °C	10.2
	ϑ = 1386 °C	6.8
5.3.2	**ρ_D for direct current**	
	ϑ = 250 °C	10^9
	ϑ = 350 °C	$1.6 \cdot 10^7$
	ϑ = 400 °C	$2 \cdot 10^6$
5.4	**Temperature t_{k100} in °C for a specific electric volume resistivity of 10^8 $\Omega \cdot$ cm**	301

Specification

Physical and chemical properties

PCE
B 270 Superwite

6. Other properties

6.1 Lead equivalent in mm Pb at 15 mm glass thickness for X-rays

Tube voltage 50 kV/0.16 mm Cu total filtering	0.24
Tube voltage 80 kV/0.16 mm Cu total filtering	0.32
Tube voltage 110 kV/0.40 mm Cu total filtering	0.33
Tube voltage 150 kV/0.70 mm Cu total filtering	0.27

Measuring and Test Procedures

For X-radiation (constant voltage) the lead equivalent is defined by the total filtering specified in the table (refer also to DIN 6845).

The exposed area has a diameter of 50 mm. The absorption of radiation in the sample piece is compared to lead absorbers of such a thickness that the same attenuation of the dose performance is reached in both cases.

As detector, a scintillation dosimeter (scintillator 44 mm diameter, 15 mm height) is used.

The measuring inaccuracy is ± 0.03 mm.

6.2 Solarization

Shifting of the edge wavelength λ_c ($\tau = 0.46$) after UV-radiation in the direction of longer wavelength	$\Delta\lambda_c$ in nm	2

Measuring and Test Procedures

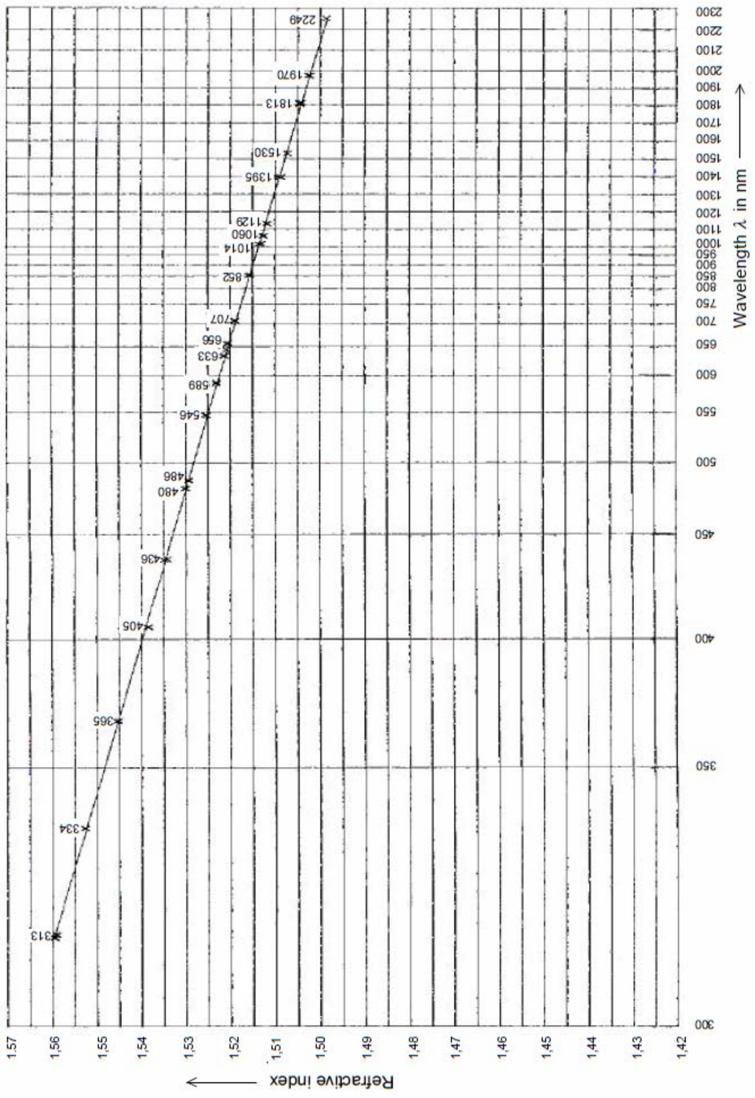
The sample will be irradiated with a UV - F 400 floodlamp.
The irradiation time amounts to 7h; the distance between floodlamp and samplefastening is 14 cm.

7. Annex (diagrams, curves)

Annex 1.1

Specification	**PCE**
Physical and chemical properties	**B 270 Superwite**

Refractive indices of B 270 Superwite in relationship to the wavelength



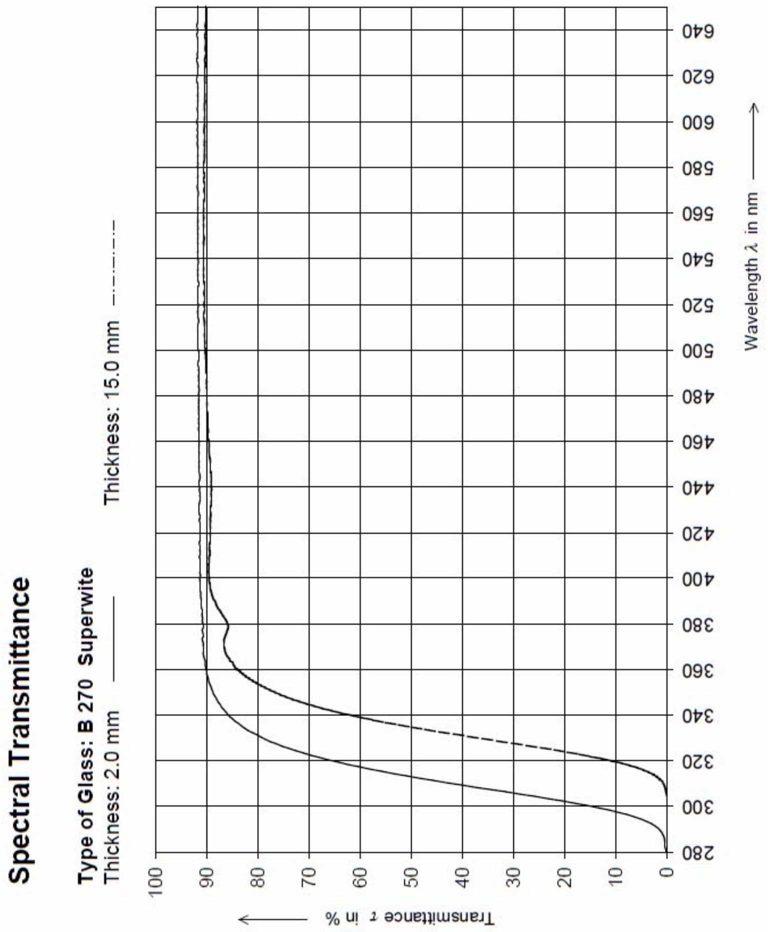
Form 0050/7B

Specification

Physical and chemical properties

PCE

B 270 Superwite



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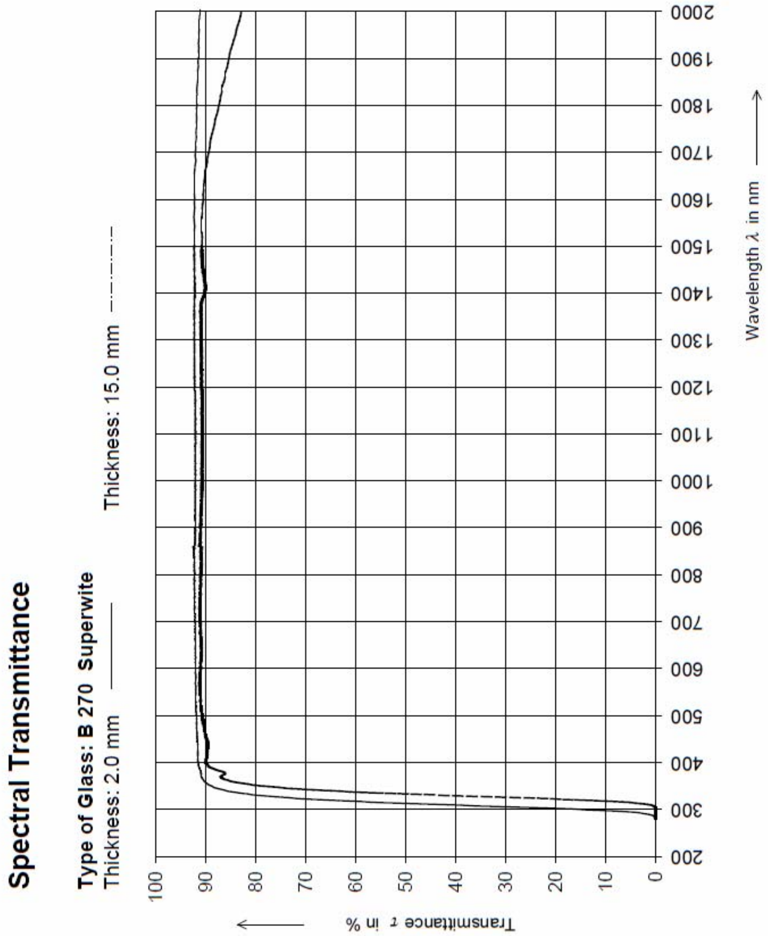
Annex 1.2.1.1

Specification

Physical and chemical properties

PCE

B 270 Superwite



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Annex 1.2.1.2

Specification

Physical and chemical properties

PCE

B 270 Superwite

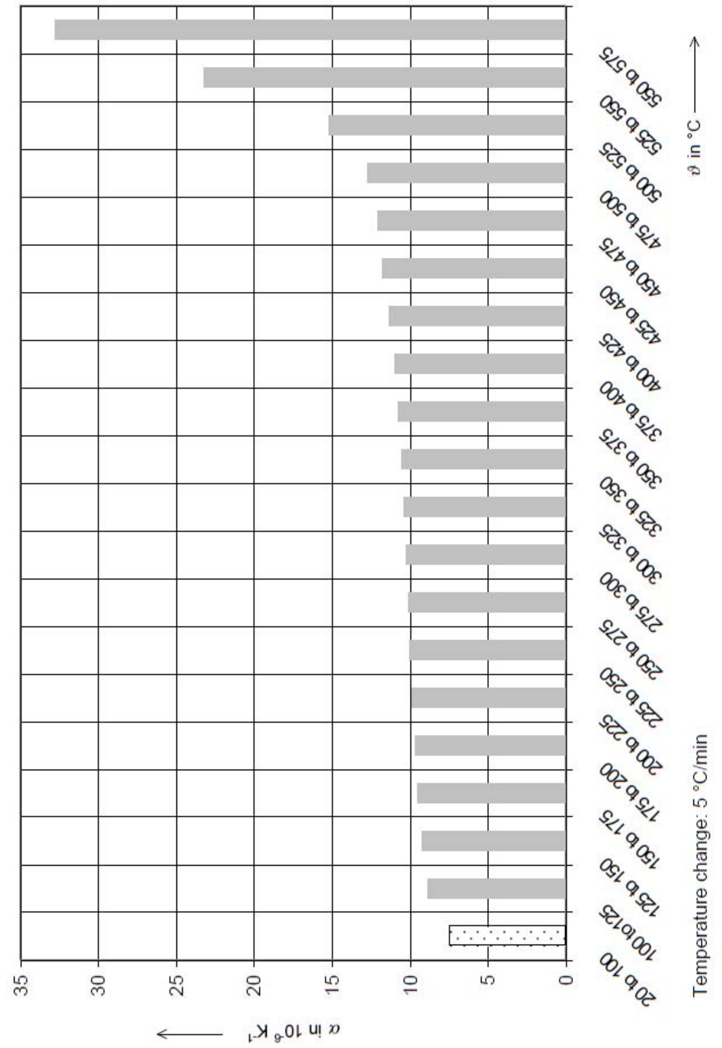
Spectral transmittance τ (λ) in % for the named thickness

	thickness in mm													
λ in nm	1	2	3	4	5	6	7	8	9	10	15	20	25	30
300	35.1	13.5	5.2	2.0	0.8	0.3	0.1	0.0	0.0	0.0				
310	60.0	39.6	26.1	17.2	11.4	7.5	4.9	3.3	2.2	1.4				
320	76.0	63.4	52.9	44.1	36.8	30.7	25.6	21.4	17.8	14.9	10.9	5.4	2.6	1.3
330	84.2	77.8	71.8	66.3	61.3	56.6	52,3	48.3	44.6	41.2	34.6	25.0	18.1	13.1
340	88.0	84.9	81.9	79.0	76.3	73.6	71.0	68.5	66.1	63.8	59.6	51.8	44.9	39.0
350	89.8	88.4	87.1	85.7	84.4	83.1	81.8	80.6	79.3	78.1	75.1	70.4	65.9	61.8
360	90.6	89.9	89.2	88.5	87.9	87.2	86.5	85.9	85.2	84.6	83.0	80.4	77.8	75.4
370	90.8	90.4	89.9	89.4	89.0	88.5	88.0	87.6	87.1	86.7	85.6	83.8	82.0	80.3
380	90.9	90.4	90.0	89.5	89.1	88.6	88.1	87.7	87.2	86.8	85.4	83.6	81.7	79.9
390	91.2	91.0	90.7	90.5	90.3	90.1	89.9	89.7	89.5	89.2	88.6	87.7	86.8	85.9
400	91.3	91.2	91.0	90.9	90.7	90.6	90.5	90.3	90.2	90.0	89.5	88.9	88.2	87.6
410	91.3	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.7	89.1	88.5	87.9
420	91.4	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.6	88.9	88.3	87.7
430	91.4	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.4	88.8	88.1	87.4
440	91.4	91.3	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.1	89.5	88.8	88.1	87.4
450	91.4	91.3	91.2	91.1	90.9	90.8	90.7	90.5	90.4	90.3	89.7	89.1	88.5	87.9
460	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.8	90.7	90.6	90.0	89.5	89.0	88.5
470	91.5	91.4	91.4	91.3	91.2	91.1	91.0	90.9	90.8	90.8	90.3	89.9	89.4	89.0
480	91.6	91.5	91.4	91.3	91.3	91.2	91.1	91.1	91.0	90.9	90.5	90.1	89.8	89.4
490	91.6	91.5	91.5	91.4	91.4	91.3	91.2	91.2	91.1	91.1	90.8	90.5	90.2	89.9
500	91.6	91.6	91.5	91.5	91.4	91.4	91.4	91.3	91.3	91.2	90.9	90.6	90.4	90.1
510	91.6	91.6	91.5	91.5	91.4	91.4	91.4	91.3	91.3	91.2	90.9	90.7	90.4	90.2
520	91.7	91.6	91.6	91.5	91.5	91.4	91.4	91.3	91.3	91.2	91.1	90.9	90.7	90.5
530	91.7	91.6	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.4	91.2	91.0	90.8	90.6
540	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.9	90.7
550	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.9	90.7
560	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.8	90.6
570	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.8	90.6
580	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.1	90.9	90.6	90.4
590	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.0	90.8	90.5	90.3
600	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	90.9	90.7	90.4	90.1
610	91.7	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.9	90.6	90.3	90.0
620	91.7	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.8	90.4	90.0	89.7
630	91.8	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.7	90.3	90.0	89.6
640	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.6	90.2	89.8	89.4
650	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.6	90.2	89.8	89.4
660	91.8	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.7	90.3	89.9	89.5
670	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.7	90.3	90.0	89.6
680	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.7	90.3	90.0	89.6
690	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
700	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
710	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
720	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
730	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
740	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
750	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
760	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
770	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.0	89.6
780	91.8	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.1	90.7	90.3	89.9	89.5
790	91.9	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.7	90.2	89.8	89.4
800	91.8	91.8	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.6	90.2	89.7	89.3

Specification

Physical and chemical properties	**PCE** **B 270 - Superwite**

Coefficient of mean thermal expansion α at continuously increasing temperature, in steps of 25°



Annex 3.3.1

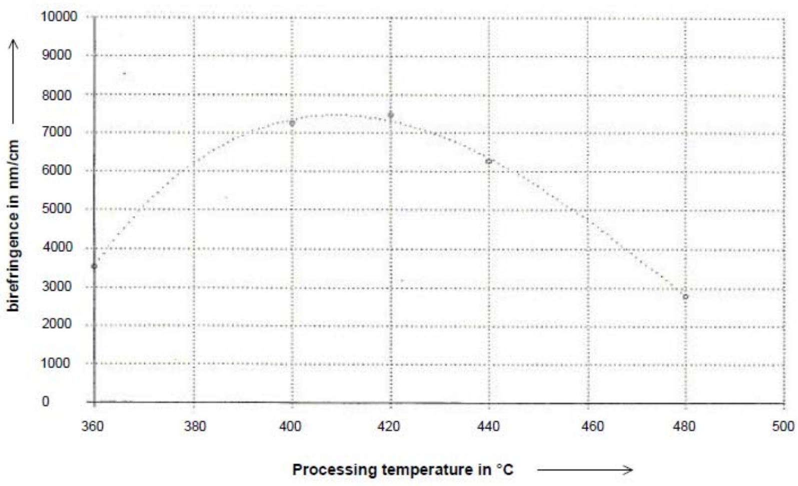
Specification

Physical and chemical properties

PCE
B 270 Superwite

Chemical toughening parameter

Glass and chemical toughening parameters		
Transformation temperature	°C	533
Glass thickness	mm	3
Processing time	h	16
Processing temperature	°C	420
Salt bath (* weight percentages)	KNO_3 in % *	99.5
	SiO_2 x H_2O in % *	0.5
Chemical toughening results *		
Penetration depth	µm	48
Birefringence	nm/cm	7200
* measured across at a sample piece ground down to 0.3 mm ± 0.05 mm		
Ball drop test acc. FDA	% failed	not carried out
Ball drop test acc. DIN	% failed	not carried out



Appendix C – Pictures of tested samples

Results of the free fall test

Results of the tumble test

Result of the abrasion tumbling test

Appendix D – 3D-glass keypad drafting