Functional performance criteria for comparison of less flammable transformer oils with respect to fire and explosion risk

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Abstract:

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Transformers are traditionally filled with mineral oil, to serve as a coolant and dielectric insulator. Now globally a rising trend is observed towards the adoption of less flammable, biodegradable transformer liquids at ever increasing voltages and power ratings.
The objective of this report is to discuss past, current and future attempts to quantify the fire and explosion risk in less flammable liquid filled high voltage transformers.
Testing procedure standards that give a reliable assessment of the fire behavior of electro technical insulating liquid based on relevant physical characteristics of the fluids are currently under development, such as IEC 60695-8-3. However more effort is required in order to provide meaningful information concerning the relation between small-scale tests and large-scale tests and that between the tests and failure scenarios in real life applications.
The experimental focus of this report, small-scale comparative tests in the Cone Calorimeter and other settings, is limited to pool fires. Spray and vapour/gas cloud fires and explosions, even though of great importance, are not considered. In total 5 liquids were tested: mineral oil, silicone liquid, synthetic ester and 2 natural esters.
The comparative tests display a wide range of fire properties for the respective liquids. The higher the fire point the longer it takes for a liquid to ignite. Polluting the samples with 3% mineral oil decreased the time to ignition, especially for the natural esters. The heat release rate calculated from the cone experiments show analogies with the heat of combustion values tabled, except for the silicone liquid where a crust formation on the liquid’s surface impeded combustion.
Heat losses from the burning surface to cooler liquid below or boundaries greatly also affect the burning behaviour.
These complexities result in the fact that great care should be taken when scaling this small scale burning behaviour to use in fire safety applications.

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Disclaimer

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To my loving mother, who passed away during the writing of this report.

If roses grow in heaven,

Lord please pick a bunch for me,

Place them in my Mother's arms

and tell her they're from me.

Tell her I love her and miss her,

and when she turns to smile,

place a kiss upon her cheek

and hold her for awhile.

Because remembering her is easy,

I do it every day,

but there's an ache within my heart

that will never go away.

Anonymous

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Abstract

Power grids worldwide are expanding not only driven by ambitious clean energy, but also because of the rising need for reliable energy. Key components of these power grids are transformers.
Transformers are traditionally filled with mineral oil, to serve as a coolant and dielectric insulator. Now globally a rising trend is observed towards the adoption of less flammable, biodegradable transformer liquids at ever increasing voltages and power ratings.

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These complexities result in the fact that great care should be taken when scaling this small scale burning behaviour to use in fire safety applications.

1. Definition

1.1 General context

It is clear that power grids worldwide are expanding not only driven by ambitious clean energy projects such as the European Supergrid[1], DESERTEC[2], but also because of the rising hunger for reliable energy. Key components of these power grids are transformers.

For the majority of transformer applications highly refined mineral oil continues to be the most widely used insulating and cooling liquid. However increasing frequency of fire accidents [3]in mineral oil based transformers and its non-biodegradable nature has led to an increasing consumption of less combustible, less toxic transformer oils.

The use of alternative fluids in transformers is not new technology. For more than 100 years, insulating liquids based on mineral oil have been used for electrotechnical equipment. During the last 70 years, synthetic insulating liquids have been developed and used in specific electrotechnical applications for which their properties are particularly suitable.

1.2 Scope

The objective of this report is to discuss and quantify the fire and explosion risk in liquid filled high voltage transformers with a specific interest in alternative dielectric coolant liquids.

It consists of a discussion on scope definition, products definition with respect to functional performance parameters, relevance of the European context and initiatives at this level, identification of key parameters in relation to the actual failure scenarios and a review of existing legislations and testing procedures.

Development of testing procedures that give a reliable assessment of the fire behavior of electrotechnical insulating liquid based on relevant physical characteristics of the fluids is necessary. A certain amount of research has already been done in this area and analogies can be made with findings in the field of less flammable hydraulic liquids, but more effort is required in order to provide meaningful information concerning the relation between small scale tests and large scale tests and that between the tests and failure scenarios in real life applications.

Because the complexity of the problem set and experimental limitations within the scope of this report the focus will be on pool fires. Spray and vapour/gas cloud fires and explosions, even though of great importance, are not considered.

Thus as an important part of this study small-scale experiments were performed with the purpose of obtaining a better understanding of the fire properties of these alternative liquids.

This report also discusses possible beneficial environmental impacts and improvement potential for these products.

1.3 European context

1.3.1 EcoTransfomer [4]

A need to define and include fire behavior of distribution transformers filled with silicon liquid or biodegradable natural esters has been established in the study for the European Commission: Ecotransformer.

In Ecotransformer this conclusion can be found:

> *The fire behaviour is only included in the standard on dry type transformers in IEC 60076-11. The behavior of silicon liquid transformer under fire had never been tested under standardization condition and pressure in the tank could lead to special results. Therefore, an update of the IEC 60076-11 standard to include oil filled transformers is needed or a new one dedicated to dry type transformers can be developed. The interest of dry type transformers is not only fire behavior but also the fact there is no possibility of cold and hot pollution. The behavior of silicon transformer during fire scenario could degenerate into spreading of liquid and extend the fire outside the transformer. This should also be studied.[4]*

The draft EC Regulation Implementing Directive 2009/125/EC with regard to Small, Medium and Large Power Transformers is a result of this study. In the draft's further development a lot of attention will be paid to alternative liquids.

1.3.2 'natech' - Natural Hazard Triggering Technological Disasters [5]

There is strong political awareness in the European Union around the need to develop and implement strong Disaster Risk Management (DRM) policies that aim to build resilience against disasters and mitigate their most severe effects both inside the Union and in its external action.

At the international level, resilience and disaster risk reduction have been featured as a key theme in international summits such as the Rio Summit on sustainable development in 2012, or the G20 initiatives on disaster risk management and the development of a methodological framework intended to help governments in developing more effective DRM strategies. The European Commission organized a Conference on prevention and insurance of natural catastrophes and conducted a study entitled "Natural Catastrophes: Risk Relevance and Insurance Coverage in the European Union.

The 'Green Paper'[5], following up on this conference, poses a number of questions concerning the adequacy and availability of appropriate disaster insurance and accompanies the Communication entitled "An EU strategy on adaptation to climate change".

The Commission invites stakeholders to comment on all the issues set out in this Green Paper and to respond to any or all of the above questions.

The relevance of Transformer Fire as a 'natech' - Natural Hazard Triggering Technological Disasters in this context is clear as substations are economic assets vulnerable to all the natural disasters listed: flooding, excessive heat, earthquake and storm surges.

The EU questions applicable to this research are mentioned throughout the report.

1.4 Methodology

In this research the methodology described in the SFPE Engineering Guide to Performance-Based Fire Protection[6] was adopted.
This guide delineates the information gathered and employed during each step of the process as a means of establishing conclusions and recommendations incorporated in the written documents.

In accordance with this methodology the different steps in this research are reported like this: a definition of the scope, identification of the goals and objectives, interpretation of the failure scenarios, an experimental part and a discussion about the results and future research.

1.5 Transformers

1.5.1 Basic concept of a transformer [4]

A transformer is defined as a static piece of apparatus with two or more windings, which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.

The construction of a transformer comprises two active components: the ferromagnetic core and the windings. The passive part of a transformer is the cooling system, e.g. consisting of a tank and the cooling liquid.

A transformer uses the core's magnetic properties and current in the primary winding (connected to the source of electricity) to induce a current in the secondary winding (connected to the output or load). Alternating current in the primary winding induces a magnetic flux in the core, which in turn induces a voltage in the secondary winding. A voltage step-down results from the exchange of voltage for current, and its magnitude is determined by the ratio of turns in the primary and secondary windings.

Transformer bushing is an insulating liner in an opening through which conductors pass that allow connection to the electrical grid.

In general transformers operate at a working temperature in the order of 100 to 110 ° C. This temperature restriction comes forth from the thermal behavior of other insulation components (cellulose in particular) used in transformers.

1.5.2 Electrical transmission and distribution

Transformers convert electrical energy from one voltage level to another.

They are an essential part of the electricity network. After generation in power stations or at renewable sources such as windmills and solar panels, electrical energy needs find its way to the consumer. This transport is more efficient at higher voltage, which is why power industrially generated at 10 - 30 kV is converted by transformers into typical voltages of 220 kV up to 400 kV, or even higher. 33 - 150 kV is often the level at which power is supplied to major industrial customers. Distribution companies both transform power further down to the consumer and transform up excessive residential renewable energy.

In this way, industrially produced electrical energy passes through an average of four transformation stages before being consumed. A large number of transformers of different classes and sizes are needed in the transmission and distribution network, with a wide range of operating voltages. Large transformers for high voltages are called power transformers. The last transformation step into the consumer mains voltage (in Europe 400/230 V) is done by the distribution transformer.

The current application of alternative fluids is shown in table 1 [4].

	Mineral oil	Silicone fluid	Synthetic ester	Natural ester
Power transformers	A	X	B	B
Traction transformers	A	A	A	X
Distribution transformers	A	A	A	A
Instrument transformers	A	X	X	X

(key: A=Largely used, B=Used, but less common, X=Currently not used)

Table 1: Current application of alternative fluids (reproduced from[4])

1.5.3 Economic

For the total figure of industry and power annual sales, in the EU market, are above 200 000 units resulting in an estimated expenditure of 7 453 million euros. Distribution transformers represent the largest share of both the stock and sales. However half of this annual expenditure is due to power transformers, which are much more expensive than the other types of transformers. More details about the market size are given in the table below. Further, transformer prices strongly depend on commodity prices.

Transformer type	Rated Power	Total Sales		
		1990	2005	2020
	in kVA	units p.a.	units p.a.	units p.a.
Smaller Industrial Transformers	16	75000	75000	75000
Distribution transformers	250	119438	140400	173891
DER transformers	2000	94	2900	12967
Industry oil transformer	630	35590	43200	53505
Industry dry transformer	800	6708	8047	9966
Power Transformer	100000	2539	3046	3772
Phase	10000	26	31	38

Table 2: Market size of transformers, reproduced from EcoTransformer[4]

1.5.4 Stakeholders

On the manufacturing side the main European industry players for the distribution and power transformers are big international groups (ABB, Siemens, Areva, Schneider Electric), and some large/medium size companies (Cotradis, Efacec, Pauwels, SGB/Smit and Transfix). Transformer manufacturers from outside the EU include GE, Hitachi (Japan) and Vijai (India). T&D Europe is the representative of the European Transformer Manufacturers, regrouping several national associations.

In this study material was used from and the stakeholders listed below were contacted:

- ABB
- M&I
- The European Commission
- VITO
- FIKE
- COWI
- CIGRE
- NORCONSULT
- European Spallation Source
- Vattenfall
- Areva
- IEEE
- IEEJapan
- CG Pauwels
- SERGI
- Gexcon
- FM Global
- Hydroquebec
- Emani

1.6 Other uses of alternative liquids

Insulating liquids are also used in some designs of:

- capacitors
- cables
- bushings
- switchgear
- miscellaneous power electronics (and in some other electrotechnical applications in which the liquid serves partly as an insulant, but primarily as a coolant)

This report will focus on transformers, but the results can be applied in the other uses listed above.

1.7 Fire safety requirements

Less stringent requirements are globally being implemented in standards and adopted by insurance companies:

- IEC:
    - Outdoor, reduced separation requirements for K-class fluids
    - Indoor, reduced fire wall and separation requirements
- Factory Mutual
    - Reduced separation as per IEC
    - Reduced containment for approved fluid
- NFPA
    - Vault required for indoor mineral oil transformers
    - No vault requirement for approved fluids up to 35kV

On one side insurance helps to reduce the economic impact and facilitates recovery after large failures. But well-designed insurance policies can also work as a market based instrument to discourage risky behaviour and promote risk awareness and mainstream failure proofing in economic and financial decisions.

2. Dielectric liquids

Since the 1980's impregnating porous paper and other solid insulating materials used in electrical industry applications was necessary in order to raise working voltages by eliminating air and moisture, while also providing convective cooling where needed. Ever since transformer oil has a dual role acting as a dielectric insulator and a coolant.

From the early 1930s askarels, synthetic liquids based on polychlorobiphenyls (PCBs), have been used comply with restrictions on the use of relatively easily combustible transformer oil. PCB mixtures have no measurable fire point and for this reason were regarded as non-flammable. However, it was later found that the spray of such liquids and their decomposition gases could still ignite and burn briefly if a transformer ruptured following an uncontrolled high energy internal arc failure.

Due to the non biodegradable nature of PCBs and its combustion products, which cause them to remain in the environment and ultimately to enter the food chain, plus their close association with a more hazardous material, dioxin, production of these liquids has now ceased in many countries and their use is being phased out.

To replace transformer PCBs, less flammable insulating liquids (including silicones, esters and high molecular weight hydrocarbons) with fire points above 300 °C came into use in the 1970s and are increasing a lot in popularity in the last decade.

Furthermore SF6, an incombustible heavy gas also used as an electrical insulator in high voltage equipment has been widely used since the 1950's in circuit breakers, gas-insulated substations and is increasingly popular in offshore substations

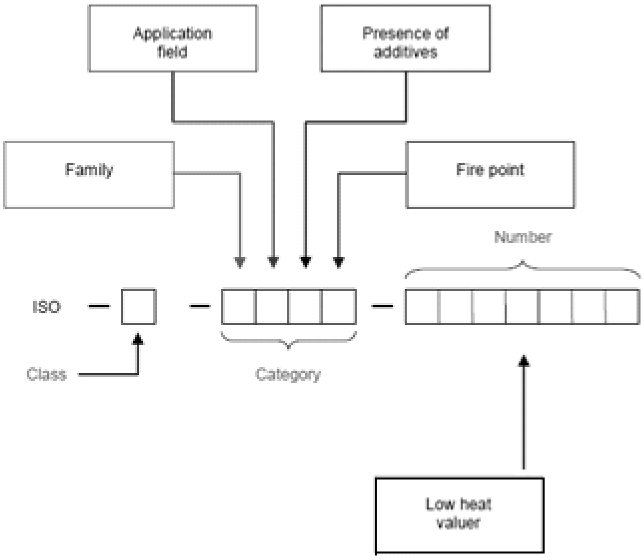
2.1 Classification

2.1.1 International Standard IEC 61039[7]

The International Standard IEC 61039 establishes the detailed classification of the N family (insulating liquids) that belongs to class L (lubricants, industrial oils and related products) affecting product categories that include products derived from petroleum processing, synthetic chemical products and synthetic and natural esters.

The classification system indicates the products with a nomination that includes (figure 1):

- the abbreviation “ISO”,
- the class of the petroleum products or related products is indicated by a letter
- the category is indicated by four letters
- a seven-figure number that makes up the identification code



[8]

Figure 1: detailed classification of the N family, reproduced from IEC 61039[7]

Of importance here is the classification according to fire point and net heat of combustion:

The fourth letter identifies the fire point as follows:

- if the fire point is < 300 °C
- K if the fire point is > 300 °C
- L if the fire point of the liquid is not detectable

The fifth figure identifies the heat of combustion as follows:

- 1 if the low heat value is ≥ 42 MJ/kg;
- 2 if the low heat value is < 42 MJ/kg;
- 3 if the low heat value is < 32 MJ/kg

2.1.2 Factory Mutual

FM Global has set up a range of performance criteria for Industrial fluids in order to be eligible for FM Approval or as a FM Specification Tested Product under this standard [9]:

- *Determination of the Fire Point by Cleveland Open Cup*
- *Determination of the chemical heat release rate of a highly atomized spray of the industrial fluid*
- *Determination of the industrial fluid density per ASTM D1480 or ASTM 4052*
- *Calculation of the critical heat flux for ignition of the industrial fluid*
- *Calculation of the Spray Flammability Parameter Equation (SFP) of the industrial fluid*

Compliance to this standard results in a reduction of the fire protection measures required by FM Global such as safety distances and fire ratings.

2.1.3 **UL Standard 340** [10]

UL Standard 340 provides a method, based on the results of specified flammability tests, for the classification of liquids as nonflammable, or as flammable with the degree of fire hazard rated both in general terms and on a numerical scale.

However the assigned classifications do not apply when the liquid is dispersed in the atmosphere in the form of finely divided spray, mist, or fog.

Nor is the scope of this method of classification applicable to liquids susceptible to dangerous decomposition reactions during phase change or when exposed to heat or mechanical shock.

Hence this rating system can be applied to pool fire failure scenarios, but leaves out the other important failure systems, such as spray fires and vapour/gas cloud explosions.

2.2 Mineral oil

All types of mineral oils are obtained from crude petroleum. A naturally occurring mixture, consisting predominantly of hydrocarbons, which is removed from the.

There are three main groups of hydrocarbon molecules: paraffins, naphthenes and aromatics. In the UK for at least 60 years, insulating oils have been manufactured almost exclusively from naphthenic or intermediate crudes. Paraffininc oils are also used but show a lower life expectancy and not as good viscosity characteristics.

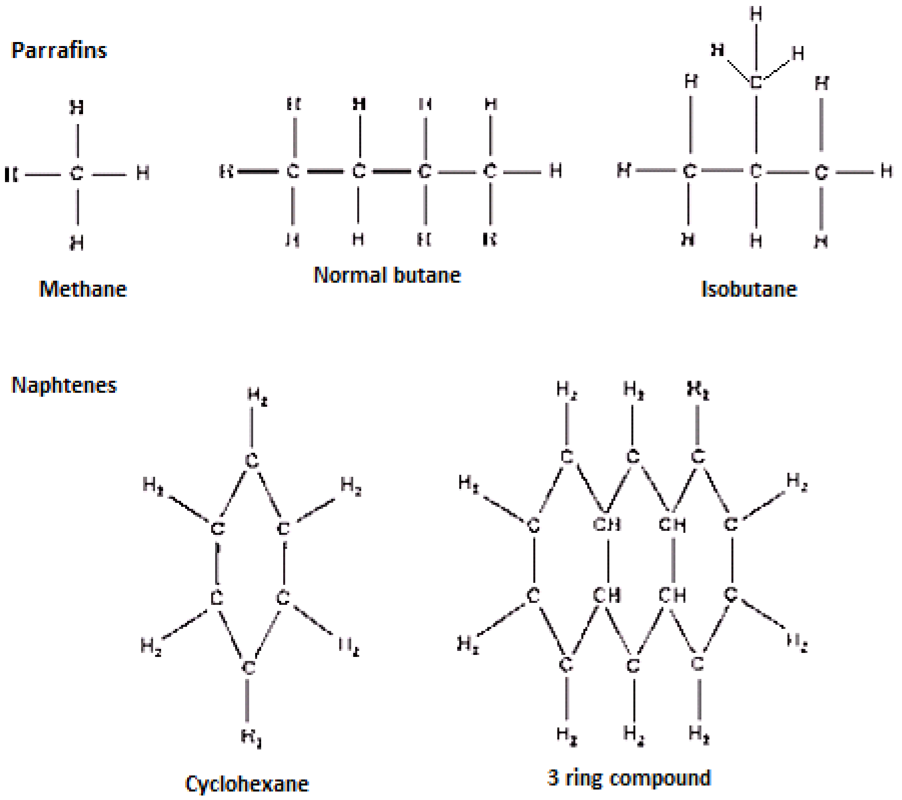
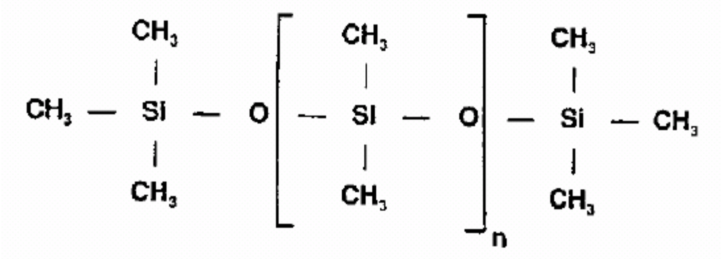


Figure 2: Hydrocarbon molecules

Since mineral oil has been used for such a long time, a large database of information is available to enable interpretation of changes to its characteristics and thus predict the possible malfunction of a transformer[11][12][13][14].

2.3 **Silicon oil**

Silicones (more accurately called polymerized siloxanes or polysiloxanes) are mixed inorganic-organic polymers. These materials consist of an inorganic silicon-oxygen backbone with organic side groups attached to the silicon atoms.



$$CH_3-Si(CH_3)_2-O-\left[Si(CH_3)_2-O\right]_n-Si(CH_3)_2-CH_3$$

Figure 3: silicon transformer liquid

The raw materials for the manufacture of this type of silicone are sand and methanol.

Silicon liquids are happily marketed with their exceptional fire profile:

- Relatively difficult to ignite
- Formation of a silica crust inhibiting the combustion process.
- Low emission of fumes

2.4 Synthetic ester

Synthetic esters are liquids made in a lab. They are already widely accepted in the fields of high-temperature lubrication and hydraulics, because they have proved more stable and less toxic.

They are usually formed by synthetic or natural carboxylic acids bonded to a central polyol structure. The acids used are usually saturated in the chain, giving the synthetic esters a very stable chemical structure.

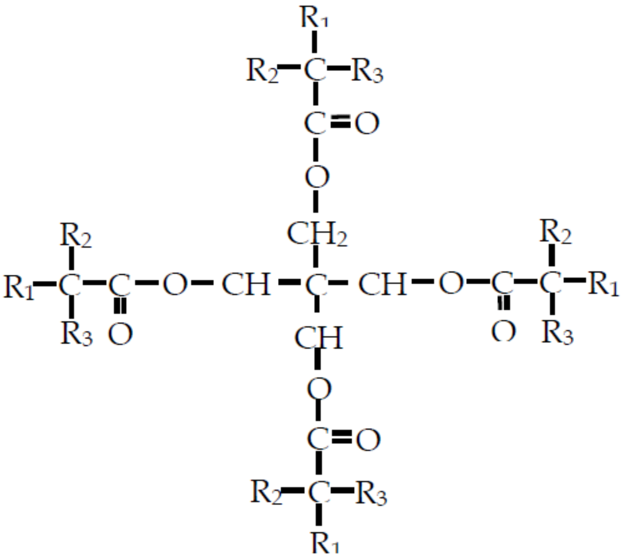


Figure 4: Synthetic ester structure

2.5 Natural ester

Natural esters are produced from vegetable oils. The structure of natural esters is based on a glycerol backbone, to which 3 naturally occurring fatty acid groups are bonded.

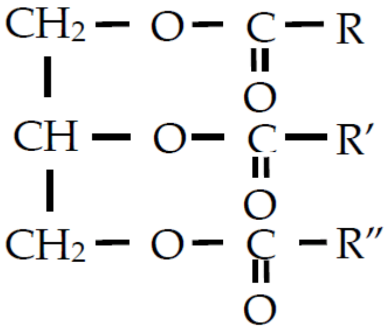


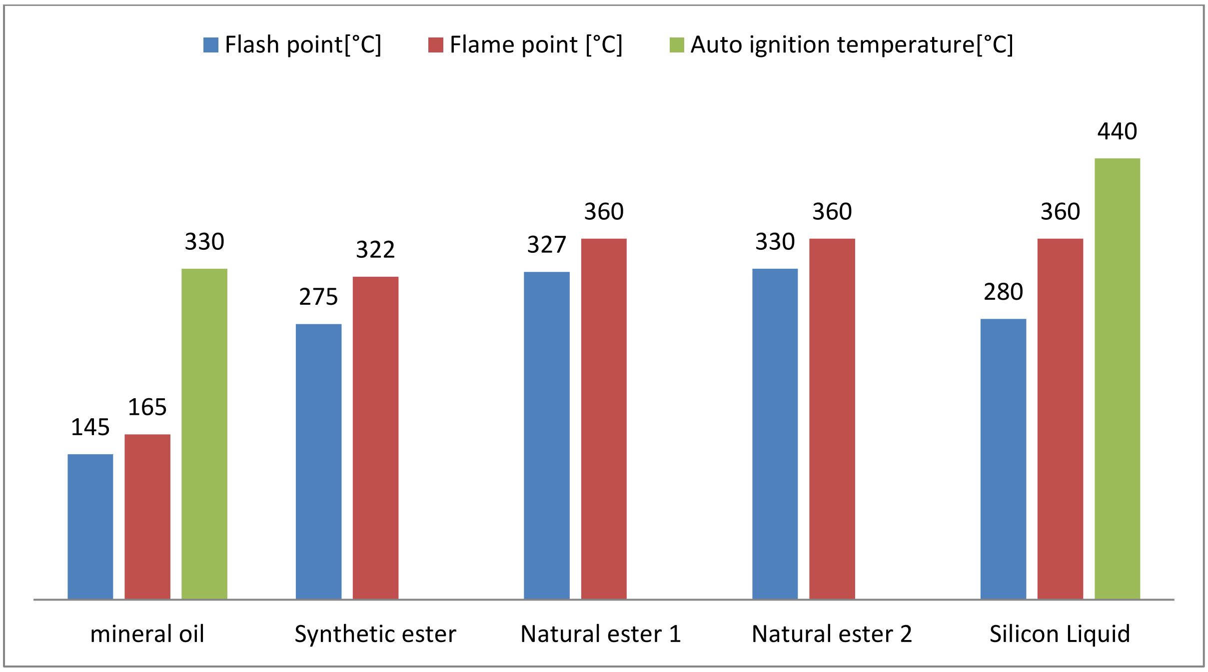
Figure 5: Natural ester structure

2.6 Characteristics and comparisons

Table 3 and graph 1 show the primary comparison properties of transformer liquids relative to fire risk. See further 5.2 for the definitions of the characteristics [8][15][16]

	mineral oil	Synthetic ester	Natural Ester 1	Natural Ester 2	Silicon Liquid
Flash point [°C]	145	275	327	330	280
Flame point [°C]	165	322	360	360	360
Auto ignition temperature[°C]	330	-	-	-	440
Heat of combustion[J/g]	46050	31600	37500	-	32100
Fire Classification	O	K3	K2	K	K2

Table 3: Properties of transformer liquids



Graph 1: Flash point, flame point and auto ignition temperature of transformer liquids

3. Protection goals and objectives

3.1 Goals

Fire safety is a key concern of users of insulating liquids. The protection goals listed in IEC 6095[17] standard are:

Minimization of fire hazard arising from the use of electrical insulating liquids, with respect to:

- electrotechnical equipment and systems,
- people, building structures and their contents.
- environment

As insulating liquids are always part of an insulating system, the fire hazard of the complete system must also be assessed in a risk analysis. Risk of transformer fires is discussed in detail in the next chapter.

3.2 Objectives

The practical objective shall be to prevent ignition, but if ignition occurs, to control the fire with respect to heat, toxic smoke and soot, preferably within the enclosure of the electrotechnical equipment. How this objective is to be accomplished will differ from case to case with different strategies according to the desired level of risk acceptance.

For instance it is obvious that measures will be different transformers aboard ships, in subway tunnels, in populated areas, etc.

Three aspects are important in the decision making process: The economical aspect, the safety aspect and the environmental aspect

Economical: When a mineral oil filled transformer failure results in a fire the transformer will often be damaged to a degree where repair is not economic. Traditionally the aim is therefore not to save the transformer if a transformer fire occurs but rather to minimize:

The replacement cost of the substation
Damage to neighbouring installations
    Through heat and radiation
    Through (corrosive) smoke deposits
The cost of outage time

However this reasoning might be up for reviewing as tests suggest that the severity of K class liquid fires is far less both in size and duration.

Life safety is less an issue in substation fires as public access is generally restricted.

Environmental considerations are a driving engine of the use of alternative liquids. Esters and silicon liquid are both biodegradable[18] in case of an oil spill. Smoke produced during the combustion of these liquids is less toxic in nature.

4. Transformer failures

4.1 Risk approach of transformer fires

Rational decision making requires a clear and quantitative way of expressing risk so that it can be properly weighed, along with all other costs and benefits, in the decision process.

Risk is often looked at as ‘probability times consequence’. Given the fact that mineral oil fires are in general rather severe this assumption holds up. However in the case of alternative liquids the experimental data suggests that the range of severity of consequence might be a lot wider. Therefore Kaplan and Garrick’s[19] model based on ‘risk is probability and consequence’ is better suited here.

Kaplan and Garrick argue that in the case of a single scenario the probability times consequence viewpoint would equate a low-probability low-damage scenario with a high probability low damage scenario – clearly not the same thing at all. In the case of multiple scenarios the probability times consequence view would correspond to saying that the risk is the expected value of damage, ie., the mean of the risk curve

It is not the mean of the curve, but the curve itself, which is the risk. A single number is not a big enough concept to communicate the idea of risk. It takes a whole curve

4.2 Statistical data

There is a fair amount of information to be found on the probability of transformer failures, however up to date data is not freely available. How large a percentage of transformer failures causes transformer fires and also information on correlation between transformer failure modes and transformer fires is harder to get.

Failure rate surveys in various reports[20][21][22][23] generally show that the probability of major transformer failure, which requires major repairs or scrapping of the transformer varies from around 1% per transformer service year.

The percentage of transformer failures resulting in a transformer fire is typically in the order of 5 to 15 % of serious transformer failures, with an average probability of approximately 10 % of all serious failures.

The European commission has taken initiative in this domain acknowledging that insurers can provide market-based incentives for risk prevention and that data should be readily available. It has also posed a public question that could be the starting point for a European transformer failure monitoring platform:

> *“How could better sharing of data, risk analysis and risk modeling methods be encouraged? Should the available data be made public? Should the EU take action in this area? How can further dialogue between insurance industry and policy-makers be encouraged in this area?”*[5]

4.3 Natural Hazard Triggering Technological Disasters

Natural hazards and disasters, for example, lightning, low temperature or earthquakes, may trigger man-made (‘natech’ - Natural Hazard Triggering Technological Disasters) disasters such as atmospheric releases, liquid spills or fires (i.e., the 2011 Fukushima nuclear disaster, Japan).

There are many recent examples of ‘natech’ transformer fire and explosions [24].

Here also the EU is following up on this with a public question on one of the main techniques to enable insurance to handle correlated risks, bundling together several types of uncorrelated perils into a single insurance policy, e.g., fire and flood, storm or earthquake.[5]

4.4 Fire scenarios

Origin fire scenario

A whole range of possible failure scenarios can result in a fire. In IEC 60695[17]the causes of fire in origin fire scenarios are listed.

All these scenarios can be broken down into 3 base cases: pool fire, spray fire, vapour/gas cloud explosion or any combination.

Therefore it is important to establish appropriate test methods that reflect the behavior of insulating liquids in these cases.

Victim fire scenario

Transformers containing insulating liquid can be exposed to an external fire. Comparative (small scale) fire tests determining whether the liquid is going to stay fully contained within the electrotechnical equipment or if it is going to be released after a period of time are beyond the scope of this research, but certainly advisable.

4.4.1 Pool

Pool fires experience with mineral oil-filled transformers has shown that, if the transformer tank is ruptured by a catastrophic failure caused by a high energy internal arc, the insulating liquid can be ejected as a spray. This spray burns intensely for a short time and can itself cause damage, but, in most recorded accidents, a considerable contribution to total fire damage was caused by the high heat release rate from the resulting burning pool of oil. For this reason, the possibility of a pool fire must be a matter for particular consideration.

4.4.2 Spray

Spray may burn intensely for only a short period of time. Pressure is limited by comparison with e.g. hydraulic applications, because the container in most electrotechnical equipment has only a limited pressure withstand capability.

The fire behaviour of a pool fire is generally much less efficient than that of a spray. Thus a pool fire would be expected to produce larger amounts of smoke than a spray fire, while a spray fire would be expected to have a larger instantaneous heat release rate than a pool fire.

4.4.3 Gas/vapour cloud explosion

Under the influence of an arc and/or heat during the failure transformer liquid diffracts in combustible gases. These gases come out, mixed with the liquid under high pressure in case of a burst resulting in an explosive cloud.

This scenario is not included in the scope of this report.

5. Performance criteria

5.1 Link laboratory scale experiments – failure scenarios

In order to obtain generally applicable information it is necessary to test some inherent fire characteristic of the fluid. However knowing what the properties being tested are and how these results can be related back to the actual failure scenarios requires a great deal of fire science.

Similar to performance criteria for hydraulic fluids[25] the most important things that need to be considered are:

- Which fire characteristics should be measured to give a realistic indication of the fire behavior of the fluid?
- What measurement procedure can be relied upon the give best repeatability and reproducibility?
- Can all fluids be compared on an equal basis or is the method unsuitable for the comparison of for example silicone based liquids?
- What ignition source should be employed to best illuminate the chosen fire characteristics?

In IEC 60695[17] it is concluded that by measuring the fire point and heat release rate of insulating liquids, and the corrosion damage, smoke opacity and toxic hazard effects of fire effluent from burning insulation liquids, the hazards associated with insulating liquids used in electrotechnical equipment can be assessed, based on the principles that:

- the higher the fire point, the more difficult is ignition, and
- if ignition occurs, the lower the heat release rate and production of fire effluent, the lower is the expected hazard and difficulty of fire fighting.

Bear in mind though that the fire behaviour of an insulating liquid depends on its properties as well as the size and geometry of its container, the presence of other combustible material and heat sources.

All of the above will be addressed more in detail in this report.

5.2 Combustion characteristics

5.2.1 Heat of combustion

The heat of combustion can be obtained by dividing the heat release rate, calculated with the oxygen depletion technique, by the mass loss rate.

5.2.2 Flash point

The closed flash point of oil is measured by means of the Pensky-Martens apparatus [26]. It gives a guide to the temperature of the oil at which the combustible vapour in a confined space above it accumulates sufficiently to ‘flash’ upon exposure to a flame or other equivalent source of ignition.

5.2.3 Flame point [26]

The flame point is the temperature at which the vapor continues to burn for at least 5 seconds after ignition by an open flame. Several standards describe how to measure this value.

5.2.4 Flame spread

Drysdale[27] describes experiments performed by McKinven et al(1970) on hydrocarbon fuels contained in trays or channels(1-3m). In these experiments, preheating of the fuel – which occurs with wick ignition – was avoided by partitioning a short section at one end of the channel with a removable barrier and igniting only the enclosed liquid surface. The barrier was then taken away and flame allowed to spread over liquid whose surface was still at ambient temperature.

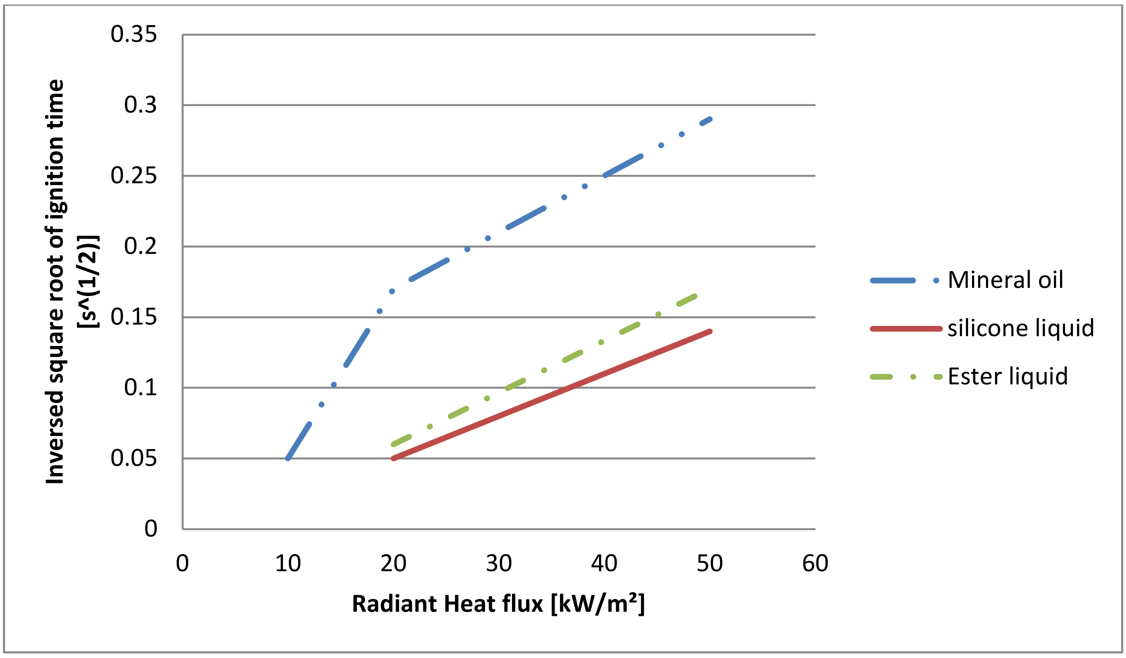
From this research as well as Miller and Ross(1992) it was found that if the temperature of the liquid is below its flashpoint, then for shallow pools, the flame spread rate will decrease as the depth is reduced. This is due mainly to restriction of the internal convection.

If the liquid is above its firepoint, then the rate of flame spread is determined by propagation through the flammable vapour/air mixture above the surface.

5.2.5 Time to ignition when exposed to radiation

Yamagishi[28][29][30] andSuzuki[30] did extensive Cone testing at Tokyo University of Science, Suwa. They came up with a few correlations for time to ignition assuming semi infinite heat transfer:

Plotting the inverse of t_{ig}^(0.5) against heat flux yields a straight line across most of the range of fluxes (the linearity breaks down as the heat flux tends towards the critical heat flux for ignition.



Graph 2: Simulated correlation between inverse square root of ignition time and radiant heat flux to the samples (redrawn from [30])

However Simonson[25] emphasises that the burning behavior is often more relevant in terms of fluid classification than its specific ignition behavior.

Also Carvel[31] raised some issues regarding the interpretation of ignitability tests carried out in the standard cone calorimeter test:

The principal assumption in the standard flammability test is the ‘inert substance’ assumption. That is, it is assumed that the liquid under test remains physically unchanged and chemically unreactive until the moment of ignition. Of course, this is never the case, as the pyrolysis process must have been ongoing for some time before ignition, such that a flammable gas/air mixture could be generated at the pilot spark location.
The most obvious example here is silicon liquid

Another standard assumption, which may be valid for some, but certainly not all materials is that there is no in-depth absorption of radiation; all of the heat flux is assumed to be absorbed at the surface. This assumption considerably simplifies the analysis, but Bal and Rein [32] showed with experiments on PMMA the necessity of a multi-band radiation model to calculate accurately the heat transfer to the free surface of a translucent fuel. Because radiation absorption is directly dependent of the sample-heater interaction.

Furthermore, as the assessment of t_{ig} requires the generation of a flammable gas/air mixture at the pilot location, it is also dependent on the flow conditions around the sample, thus the properties predicted in this manner are dependent on the setup of the apparatus, not merely the material itself.

6. Test methods

6.1 General

Combustion characteristics should be considered in terms of the contribution to the fire load, the potential fire growth, and the fire hazards caused by fire effluent.

As a part of this project experiments were performed to obtain and better understand the combustion characteristics of transformer liquids. In total 5 liquids were compared: mineral oil, 2 natural esters, synthetic ester and silicon liquid.

Reviewing the IEC 60695-8-3 draft standard[33] cone experiments were performed as well as more intuitive pool fire experiments.

6.2 Cone Calorimeter

The most common standard flammability apparatus is the cone calorimeter, which is used to assess combustion characteristics. The main part of the apparatus is shown in Fig. 7.

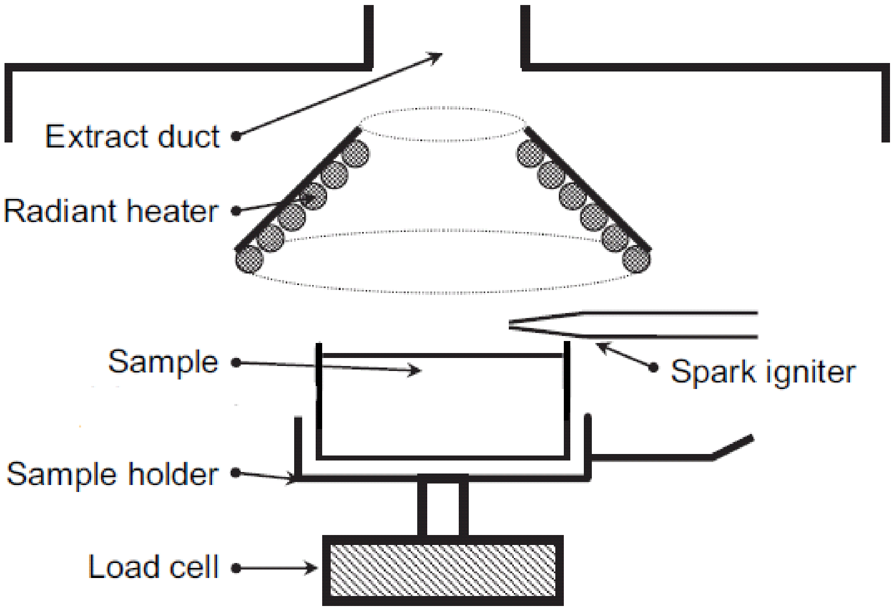


Fig. 1. Schematic of cone calorimeter.

Figure 6: Cone Calorimeter set up, reproduced from[32]

As a starting point IEC 60695-8-3 Heat release – Heat release of insulating liquids used in electrotechnical products[33] was used. This paragraph serves as a review of this standard and to generate practical data.

6.2.1 Test apparatus

For the purpose of the test, the test apparatus specified in this standard and additional equipment was used.

Test specimen tray

The test specimen tray shall be located so that the surface of the liquid test specimen is 25 mm ± 1 mm below the lower edge of the conical heater.

Figure 7: Test specimen recipients

For the actual experiments a shallow square tray, dimensions 10x10x2cm) and a deeper round cup, diameter 10cm, depth 5cm, were used. Both, as seen in picture 8 are made of stainless steel.

6.2.2 Procedure

The Sample liquid is placed in a sample holder on a load-cell, a short distance beneath a conical radiant heater. This heater subjects the exposed face of the sample to a nominally constant (in time) and uniform (across the surface) heat flux.

Provided the external flux is large enough, the sample will eventually begin to pyrolyse and release flammable gases. Once sufficient gases have been released to produce a flammable gas/air mixture in the volume above the surface, the gas is ignited by means of an electrical spark, positioned slightly above the sample surface.

The time between the initial exposure of the sample to the external heat flux and the establishment of a persistent flame at the surface is taken to be the 'ignition delay time' or 'time to ignition', (tig).

Air, pyrolysis and combustion gases are drawn away from the cone through a hood and duct positioned above it. Various sensors in the duct record temperature, pressure, velocity, opacity and gas concentrations (oxygen, carbon monoxide and carbon dioxide). From these, the heat release rate (HRR; Q_) can be calculated.

The test procedure used was based on standard IEC 60695-8-3[33] and consists of the following steps cited below:

- place the liquid in the test specimen holder(1cm for the shallow square tray, 4,5 cm for the deep round cup)
- place the test specimen screen in position
- place the test specimen holder under the cone heater set at zero irradiance

- start logging and remove the screen after 1 minute. Simultaneously activate the spark igniter.
- When the liquid ignites shut off the Cone heating element.

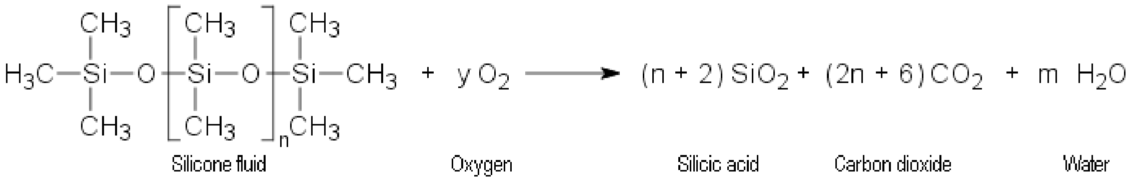
Alterations were made to the procedure in the IEC standard.
More liquid was put in the sample holders to diminish the influences from the boundaries of the cup. This was investigated even more by using a deeper cup.
The radiation element was shut off after ignition. However it took a while for this element to cool down, especially when big flames kept on heating it.

6.2.3 Calibration

The rate of heat release in full-scale fire tests was determined based on the O_2 consumption principle described in Janssens' paper[34].

Janssens discusses the fact that a more or less constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. This is found to be also true for organic substances and an average value is obtained for this constant of 13.1 MJ/kg of O_2.

This method was used for all 5 liquids however it should be noted that this is incorrect for silicon liquid as it is not mainly based on the reaction of carbon with oxygen.



$$H_3C-Si(CH_3)_2-O-[Si(CH_3)_2-O]_n-Si(CH_3)_2-CH_3 + y\,O_2 \longrightarrow (n+2)\,SiO_2 + (2n+6)\,CO_2 + m\,H_2O$$

For n=1

1 mole of $Si_3O_2C_8H_{24}$ weighing 3*28+2*16+8*12+24*1=236 g/mole

reacts with 16 mole O_2 weighing 32 g/mole

So 1 g of oxygen reacts with $\frac{236}{16*32} = 0.460\ g\ Si_3O_2C_8H_{24}$

The silicone liquid used has a heat of combustion 32100 J/g, so for every gramme of oxygen consumed 32100*0.460=14796 J is released.

This value is higher than the value of for carbohydrates of 13kJ/g but transformer liquid is generally more viscous and longer chain silicon molecules are present. Longer chain molecules are heavier and this results in a lower heat release rate.

In the further calculations the value of 13kJ/g was used for all liquids, including the silicone liquid.

6.2.4 Results

Time to ignition

Results seemed to follow the existing data set made in Japan. However because of the reasons discussed earlier this experimental data was not processed further.

Extinction of flame

In the square shallow cup all samples burnt out except for the silicone oil where the formation of a white crust on the surface impeded the combustion process.

In the deep cup the liquid bulk acting as a heat sink resulted in the extinguishment of both natural esters. The other liquids were manually put out after 30-40minutes burning.

Analogies can be made to Carvel's technique[31] to quantify the boundary condition on the back of a PMMA sample in the cone by adding a heat sink. If the heat conductivity of the heat sink (aluminium block) is much larger than that of the insulation and sample, then by embedding thermocouples into this block, the temperature changes of the block and, hence, the heat transfer to the block during a test could be estimated.

$$q_{loss} = \frac{\dot{1}}{A}\frac{dT}{dt}mc_p$$

Heat release rate – mass loss rate

The mineral oil clearly shows the highest heat release rate. The peak just before burn out in the square shallow pan is to be explained by increased pyrolysis due to various changing boundary conditions, such as re radiation from the bottom of the tray. The other liquids do not display this behaviour.

Apart from this peak the heat release rates displayed in graph 3 are correlated to the heat of combustion of the respective liquids. However for the silicon liquid the combustion process was impeded by the formation of a white crust on the surface resulting in very low values.

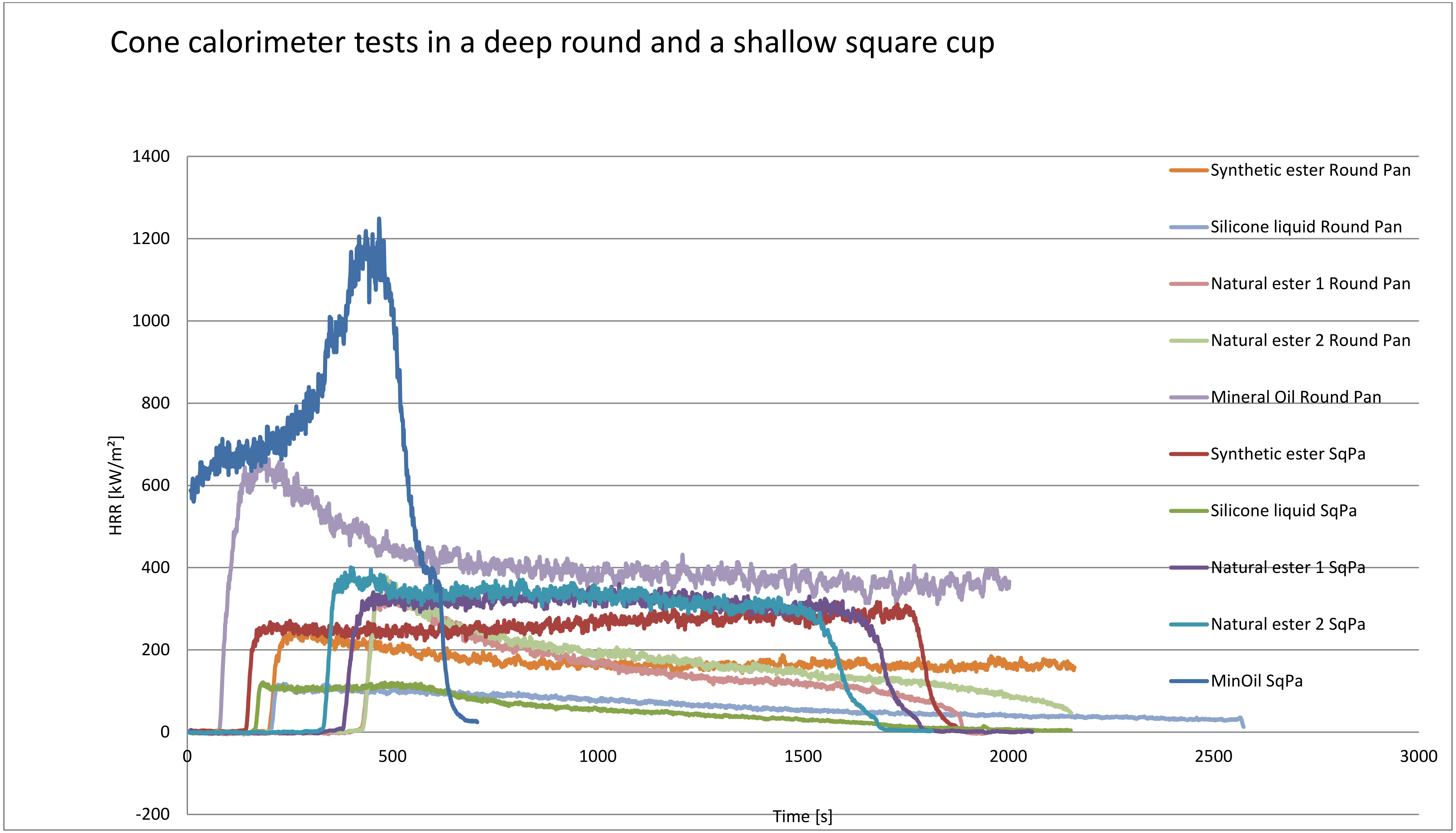
	mineral oil	Synthetic ester	Natural ester 1	Natural ester 2	Silicon Liquid
Heat of combustion[J/g]	46050	31600	37500	-	32100

Table 4: Heat of combustion for dielectric liquids

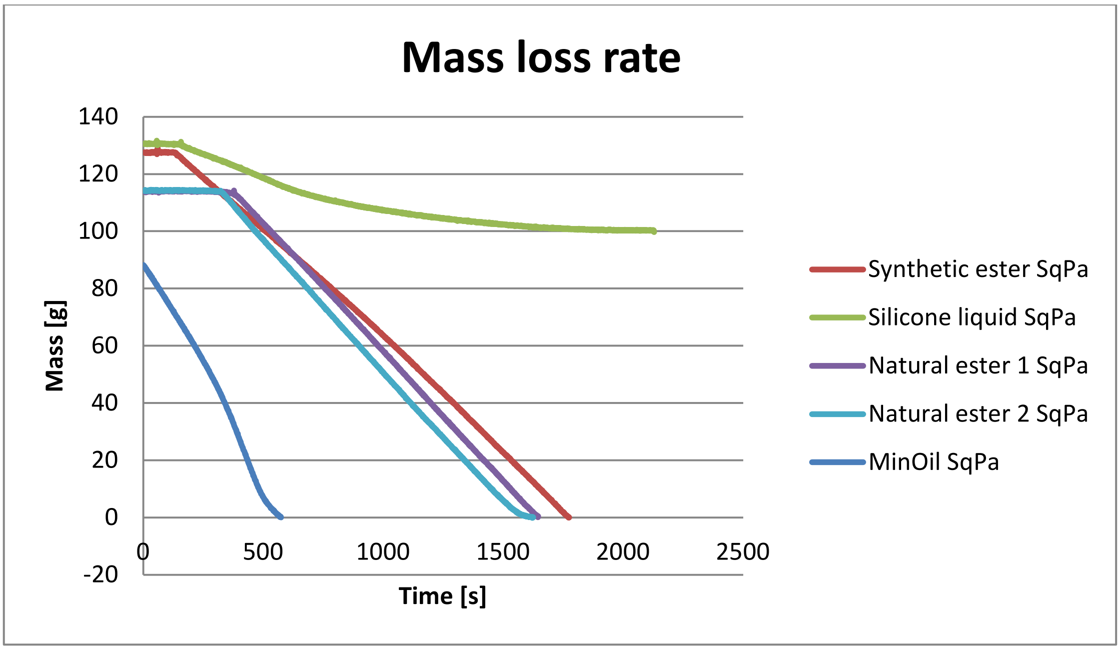
A steady state regime was reached after a while, in particular in the shallow square pan. Heat losses to the cold bulk liquid in the deep cup resulted in the fire extinguishing after a while for the natural esters.

Times to ignition were not processed as discussed in 5.2.5. However for different experiments the same ranking was observed: Mineral oil ignited almost right away, next to ignite were the synthetic esters and the silicone liquids. The natural esters took a long time to ignite.

As prescribed in the IEC standard [33] the applied heat flux was chosen to 30kW/m² so that the times to ignition were below 10 minutes. Thermal losses to the sample holder boundaries become too large after that.



Graph 3: Cone calorimeter tests in a deep round and a shallow square cup



Graph 4: Mass loss rates for the shallow square cup

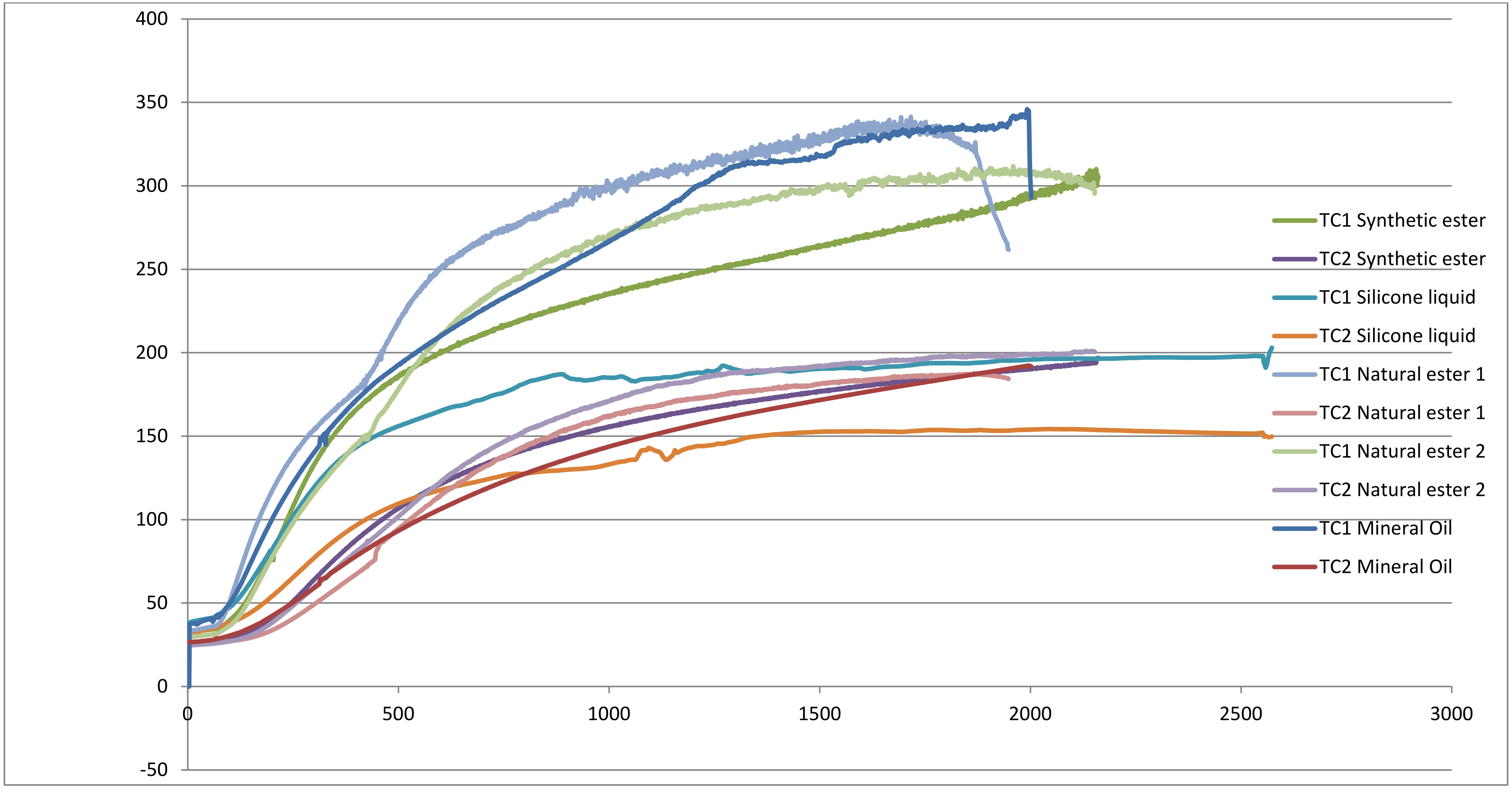
The mass loss rates displayed in graph 4 (only for the shallow square pan) show a very steep curve for mineral oil. The esters show a linear behaviour, which explains the steady state heat release rate that was reached. The silicone liquid curve is not linear because of the crust formation on the burning surface limiting pyrolysis.

Temperature distribution in the liquid

In the deep cup (figure 8) experiments 2 thermocouples were placed in the liquid. One 1 cm below the surface and one 3 cm below the surface.

Figure 8: deep round cup

The temperature profiles for the different liquids are displayed in graph 5



Graph 5: : Temperature in the liquid through 2 thermocouples

In graph 5 the temperature curves show similar behaviour except for the silicone liquid. The heating of the liquid here is obstructed by a crust after ignition.
In all the other liquids the temperature curves converge to a sort of steady state temperature distribution in the fluid explaining. This is in accordance with the constant heat release rate observed in graph 3. For the natural esters the heat conduction away from the burning surface was too high to sustain burning.

6.3 Pool fire test procedure(ad hoc)

6.3.1 Literature

A series of pool fire tests on silicon liquids and organic fuels has been performed at Nist[35][36][37]. However no similar data was found that could be related back to ester liquids.

For the silicon liquids the mass flux and the radiative fraction of the heat release were measured as a function of burner diameter and silicone fluid chain length in steady-state pool fires. The fire parameters varied markedly with chain length of the silicone fluid. Short chain silicone oligomers and aliphatic/aromatic hydrocarbons exhibited a strong dependence of the mass flux and the radiative faction on pool size. The longer chain length silicon fluids and alcohols exhibited both markedly lower mass fluxes and lower radiative components of heat release and these parameters were virtually independent of pool size.

Silica ash was observed to form in the gas phase. Typically, agglomerates of ash fell back to the surface of the liquid pool where they collected and subsequently submerged.

6.3.2 Experimental set up and procedure

Apart from cone calorimeter data a consecutive set of tests was performed on all the liquids to further compare the fire properties in another setting than the Cone.

Figure 9: Pool fires, experimental set up

About 100g of liquid in a 30cm round pan was put on a cooking stove and heated up to about 280°C(figure 9 and 10). At this point the 1.5kW cooking stove reached its maximum heating capacity.

Next the pan was placed on a piece of Rockwool and the liquid was further heated from the surface with a propane-butane mixture burner.

In the process the liquid temperature was frequently measured with a portable thermocouple.

After reaching a sustained fire in the pan the contents of the pan was poured in a large tray filled with 2mm of the respective (cold) liquid, recreating a sudden burst in the transformer container.

6.3.3 Observations

Figure 10: Simulating a burning hot liquid spill

Mineral oil

Mineral oil has a flashpoint of 145-155°C. No pre heating on the stove was necessary, after only 30 seconds burning the sample ignited.

When pouring the oil into the empty tray the fire extinguished.
However when there was a layer (>2mm) oil present in the tray the fire spread across the surface resulting in a big pool fire.

The fire produced sooty black smoke

Natural ester 1

Flashing started when the upper layer of the liquid reached 330°C and when heated to 350-360° the flashing evolved in a steady sustained fire.

When pouring the ester liquid in the tray filled with natural ester 1 at 20°C the fire extinguished.

The fire produced black smoke. A popcorn scent was constantly present.

Silicon liquid

Flashing started when the upper layer of the liquid reached 300°C and when heated more the flashing evolved in a steady sustained fire even before reaching its flame point of 330°.

A crust formation covered the liquid surface partially limiting the combustion process.

When pouring the silicon liquid in the tray filled with silicon liquid at 30°C the fire did not fully extinguish, but kept on burning around the crust areas.

The fire produced white smoke.

Natural ester 2

Similar to natural ester 1 flashing started when the upper layer of the liquid reached 330°C and when heated to 350-360° the flashing evolved in a sustained fire.

However the fire seemed more vigorous than the natural ester 1 test

When pouring the ester liquid in the tray filled with natural ester 2 at 20°C the fire extinguished.

The fire produced black smoke.

Synthetic ester

After taking the pan of the fire (280°C) and applying the gas flame briefly to the surface a sustained fire developed.

As expected the flame height was lower than in the natural ester test as the heat of combustion is lower for the synthetic ester.

When pouring the ester liquid in the tray filled with synthetic ester at 20°C the fire extinguished.

The fire produced black smoke.

Summarizing all liquids burned when enough heat was applied to them. Whenever the upper layer of the liquid reached its fire point sustained burning was reached. For mineral oil this happened very quickly, a couple of seconds with the burner was enough. The other liquids required preheating on the stove combined with reasonably long heating with the burner.

Pouring the burning liquid in a pool of cold liquid induced heat losses to the extent that except for mineral oil their temperatures went below their respective fire points resulting in the extinguishment of the fire.

7. Chapter 7 – Retrofilling

Somewhat on a sidenote a series of Cone Calorimeter experiments was performed on polluted liquids to simulate retrofilling.
Retrofilling is the process of removing the insulating liquid of an existing working transformer and replacing it with a new liquid.

There is a list of reasons why this is done[38] and what new liquid is chosen for what purpose. Fire safety is again a driving factor behind this, however still controversial as there is a lack of experimental data.

A properly retrofilled transformer will contain maximum 2-3% of (original) oil.

Eperiments were performed on all 4 alternative liquids with a 3% concentration of mineral oil in 100ml liquid in the square shallow pan in the Cone Calorimeter following the same procedure as the tests discussed earlier.

Results (graph 12) show that heat release rate is not affected. Time to ignition is slightly less for both the silicon liquid and the synthetic ester. However the natural esters show a relatively large decline of time to ignition.

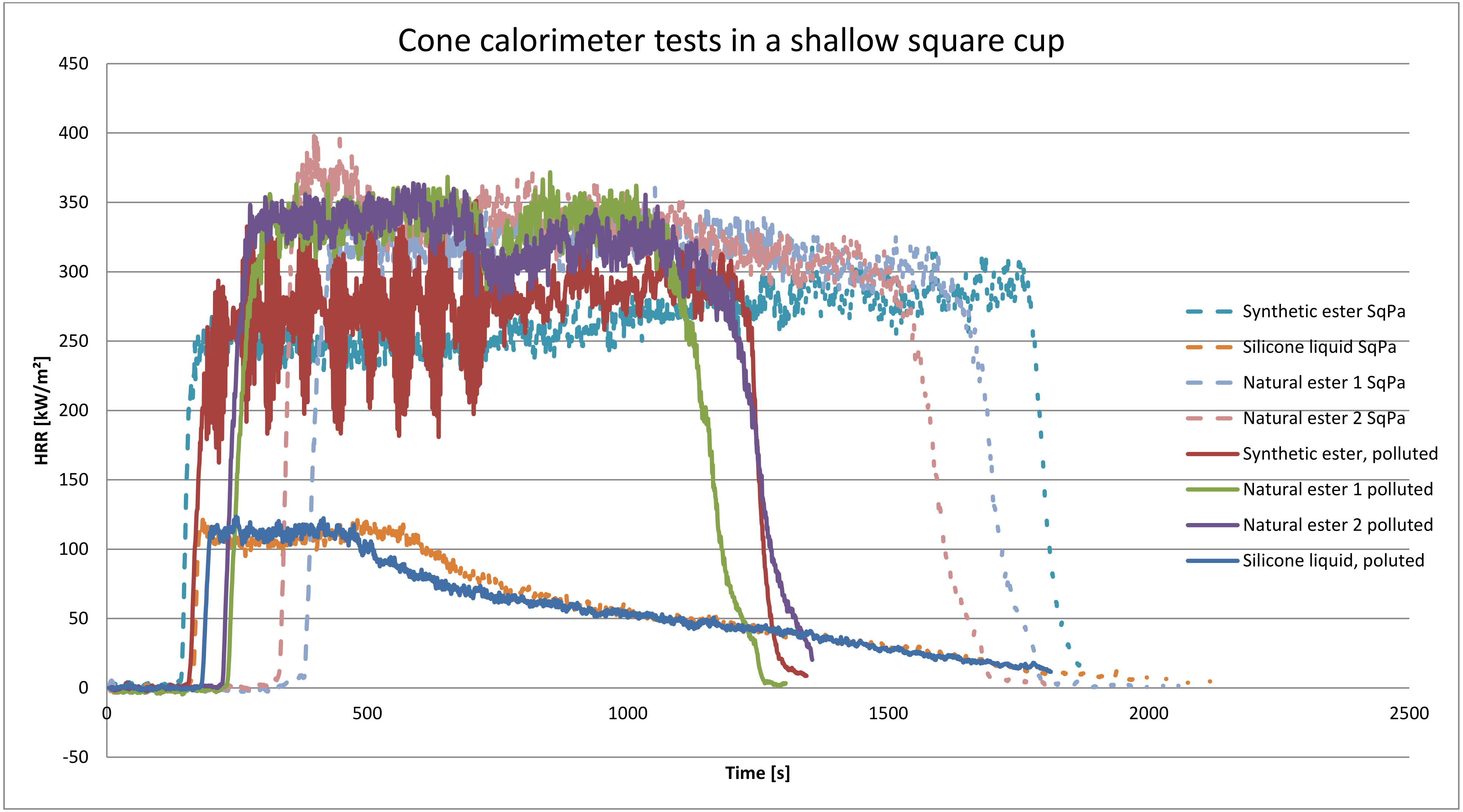


Figure 11: Retrofilling cone tests

8. Chapter 8 – Discussion and conclusions

The goal of this report was to analyse the fire and explosion risk of liquid filled transformers with a specific interest in the range of dielectric liquids available on the market.

This is a very controversial matter and there were many different opinions and approaches in between various stakeholders. However most of these stakeholders also had projects running or in the pipeline, it is a 'hot topic'. The development of European harmonization projects both with ecological goals as well as ensuring security of energy supply play a big role in the regulation and acceptance of less flammable transformer liquids.

It is clear that less flammable liquids(K class, FM approved) exhibit a fire risk far less than mineral oil. However quantifying how much less is not an easy task. The experiments in this study give an idea of how much the heat release rate is less, but bear in mind that this was for very specific laboratory conditions. Relating laboratory findings back to the actual failure conditions requires in depth knowledge of transformer failures scenarios as well as a great deal of fire science.

When a mineral oil filled transformer failure results in a fire the transformer will often be damaged to a degree where repair is not economic. Traditionally the aim is therefore not to save the transformer if a transformer fire occurs but rather to limit damage to the surrounding equipment and the environment.
However for these less flammable liquids the fire will be less fierce, less likely and shorter in duration so a revision of the 'traditional' protection goals is in place.

The experimental scope of this study was limited to pool fires due to the complex nature of the problem and the lab setting.: transformer failures resulting in fire.
The comparative tests display a wide range of fire properties for the respective liquids. The higher the fire point the longer it takes for a liquid to ignite. Polluting the samples with 3% mineral oil however affected the time to ignition especially for the natural esters. The heat release rate calculated from the cone experiments show analogies with the heat of combustion values tabelled, except for the silicone liquid where a crust formation on the liquid's surface impeded combustion. Great care should however be taken when scaling this small scale burning behaviour to use in fire safety applications.

Following IEC 61039-8-3(draft), slightly altered though, a somewhat steady state heat release rate was reached for most of these liquids. These values can be used for extrapolating to real size pool fires.
Important differences with the standardized procedure was that the external heat flux from the Cone was shut off after ignition and more liquid was put in the sample.

Heat losses from the burning surface to cooler liquid below or boundaries greatly affect the burning behaviour. Providing a large enough heat sink in the form of bulk liquid, the fires extinguished whenever the liquid surface cooled below its flame point.
There is no simple way to quantify this heat sink effect for different dielectric liquids.

This was investigated further with a deeper cup and two thermocouples in the fluid. The extra fluid acted as a heat sink clearly visible on the graphs. Heat was conducted away from the liquid surface restricting the burning.

Future research

Future research would have to include pool fire experiments over a range of pool sizes and external heat fluxes. As well as more research into heat losses from the burning liquid surface.

Equipping the Cone Calorimeter with a removable Cone would be useful to not have the effect of a slow cooling Cone element when shutting it down after ignition.

Regarding mist/gas/spray fires looking more in depth at thermal kinetics of the liquid would be more interesting than performing only a few large scale arcing tests. From these small scale experiments alone it can be seen that there are a enormous influences from the boundary conditions. In complex large scale experiments this will only be more the case. Hence an actual test like this will end up to be a unique one out of a many possible failure scenarios. Conclusions then could be made for these unique parameters, but many questions will stay unanswered.

9. Acknowledgements

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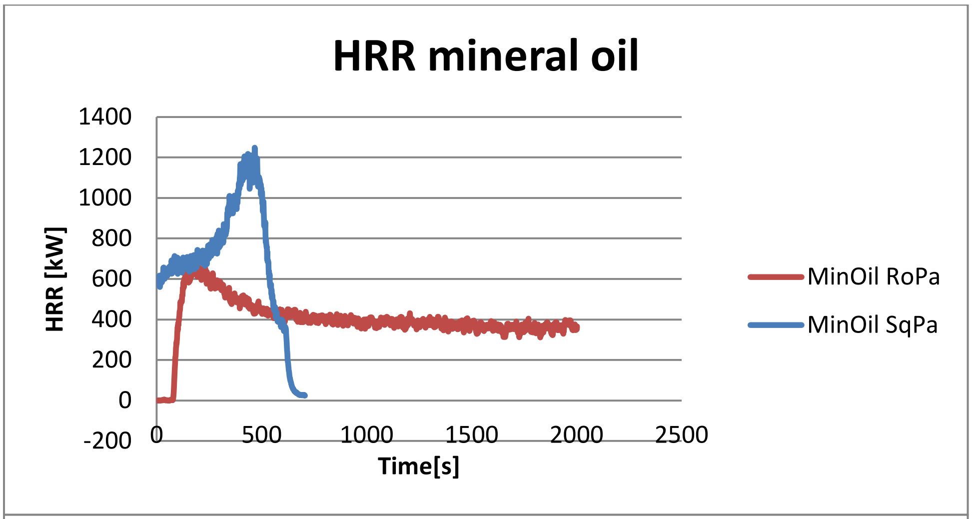
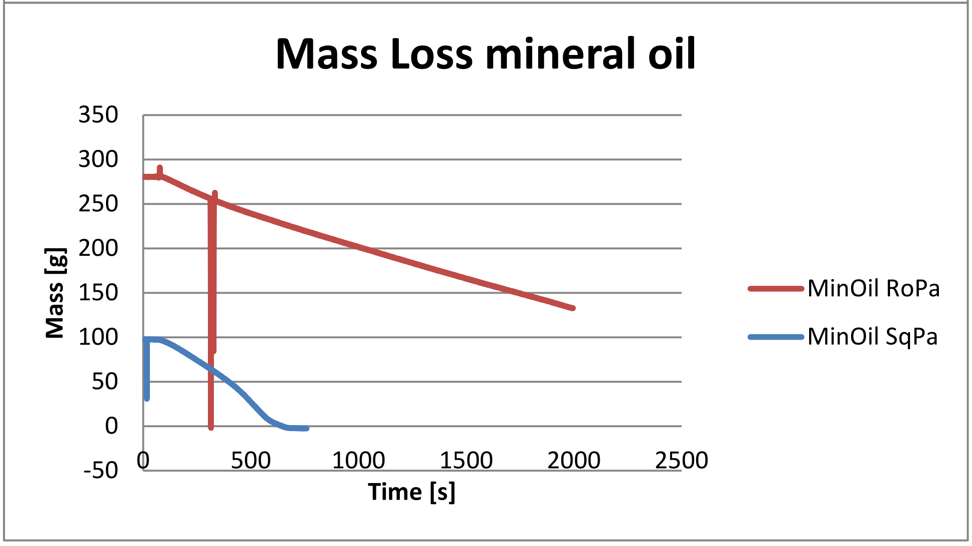
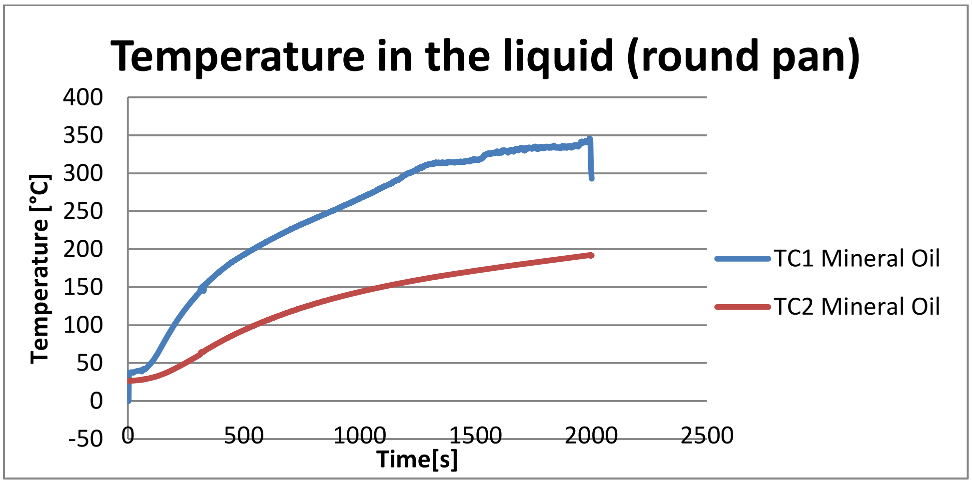
11. Appendix

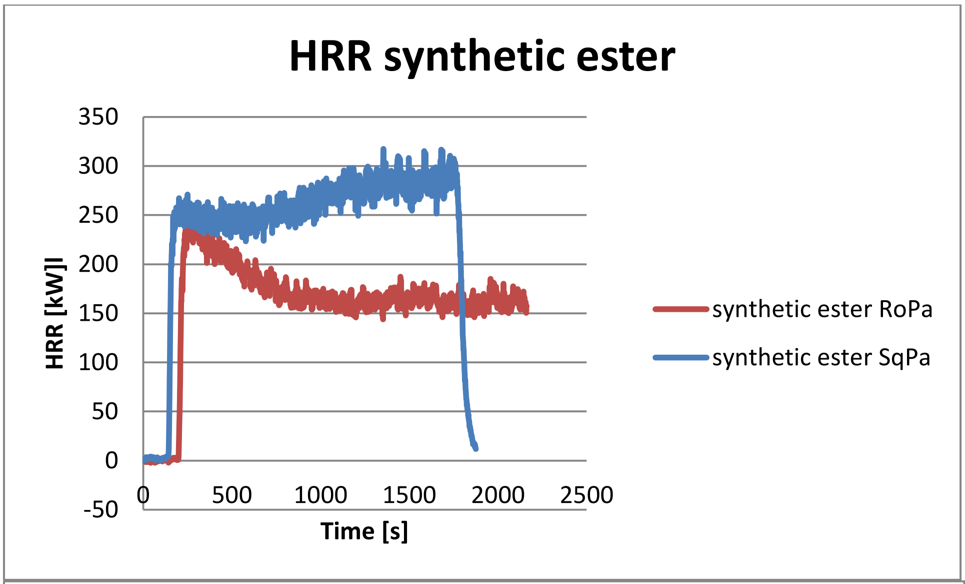
11.1 Mineral oil

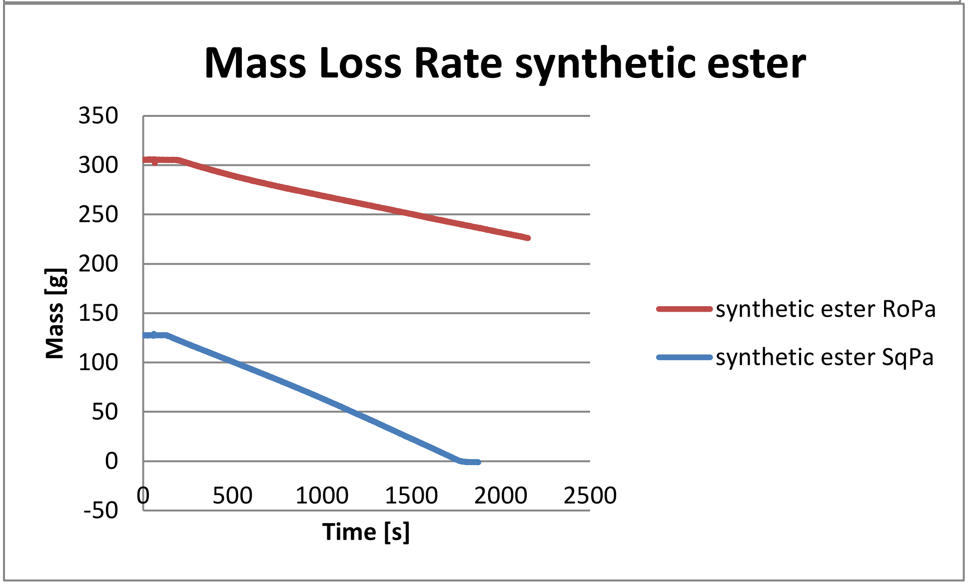


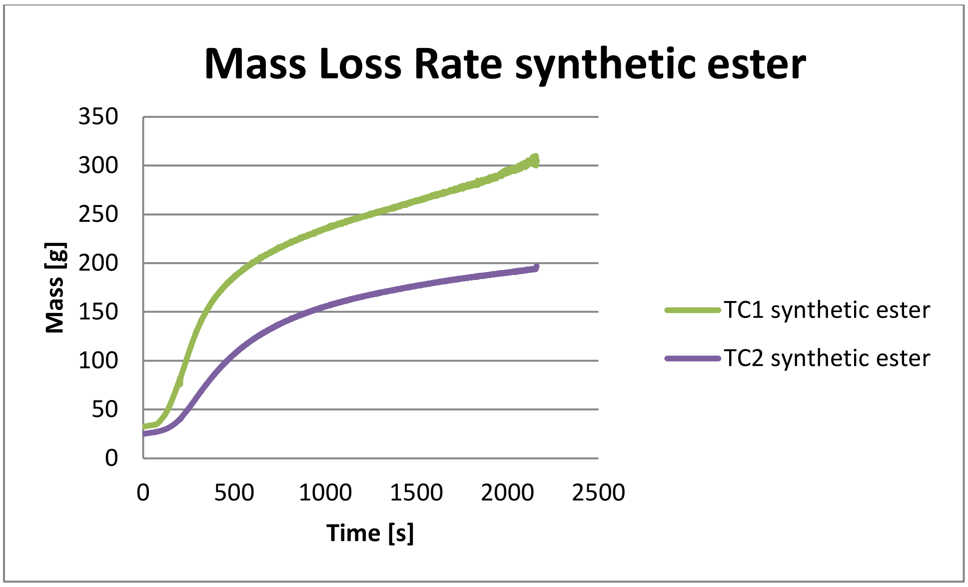




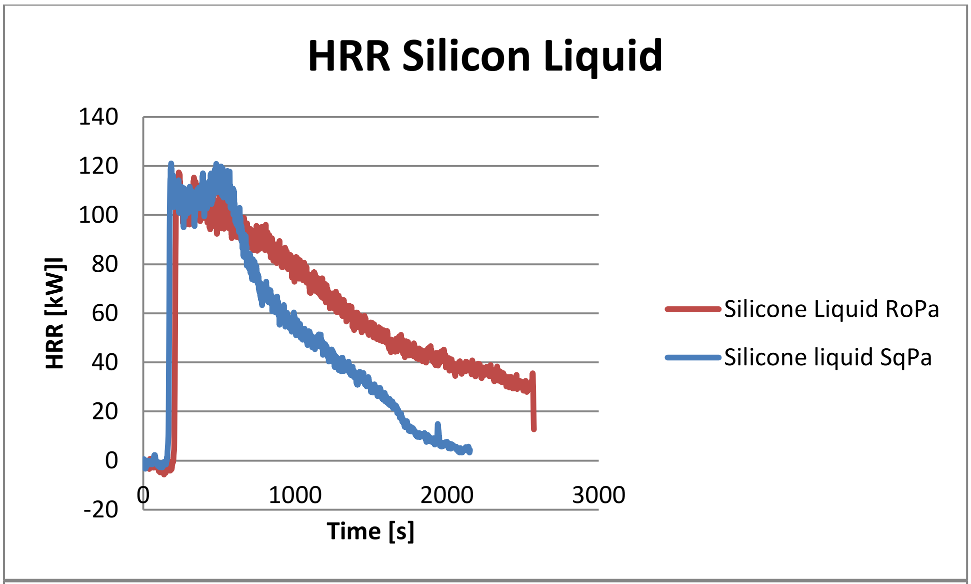
11.2 Synthetic ester

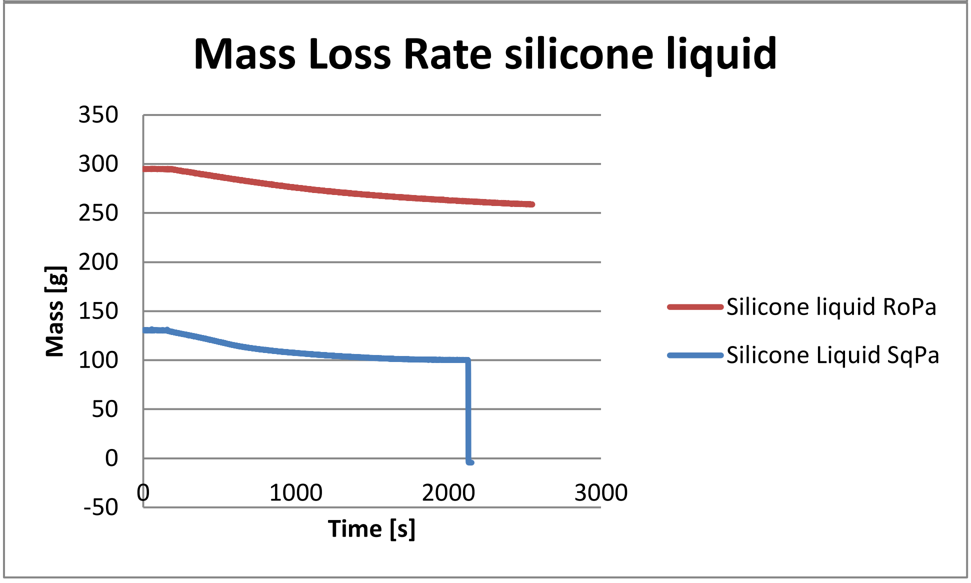


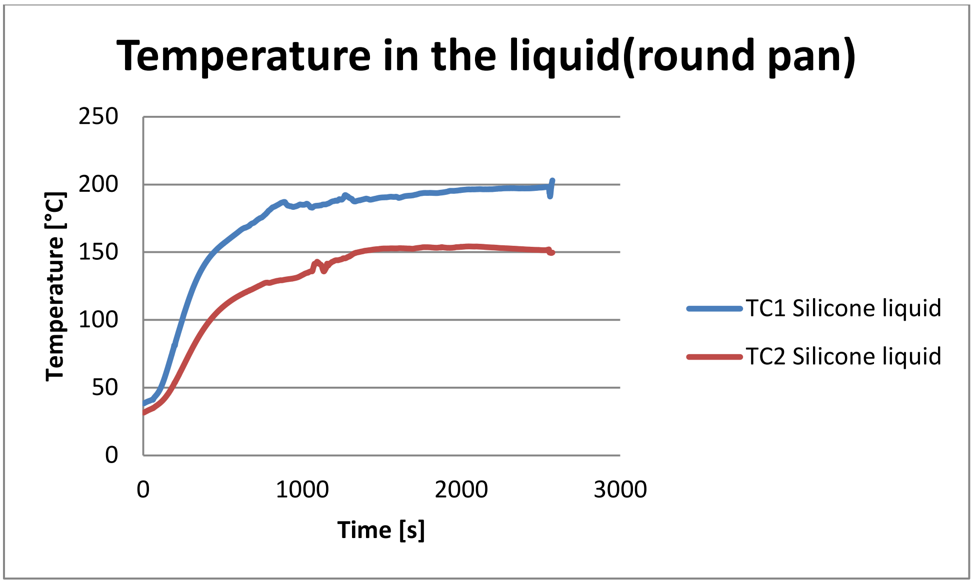




11.3 Silicone liquid







11.4 Natural esters