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CHARACTERISTICS OF FIRE EXPOSURE AND CONSEQUENCES ON MECHANICAL BEHAVIOR OF CONCRETE

av

Sven Thelandersson, civ ing, Sm

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CHARACTERISTICS OF FIRE EXPOSURE AND CONSEQUENCES ON MECHANICAL BEHAVIOR OF CONCRETE

Sven Thelandersson

LUND NOVEMBER 1974

This thesis comprises the following reports under the general heading: "Characteristics of Fire Exposure and Consequences on Mechanical Behaviour of Concrete".

A.	Sven Erik Magnusson Sven Thelandersson	Temperature-Time Curves of Complete Process of Fire Development. Theoretical Study of Wood Fuel Fires in Enclosed Spaces. Acta Polytechnica Scandinavica, Ci 65, Stockholm 1970
B.	Sven Erik Magnusson Sven Thelandersson	Comments on Rate of Gas Flow and Rate of Burning for Fires in Enclosures, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 19, Lund 1971
C.	Sven Erik Magnusson Sven Thelandersson	A Discussion of Compartment Fires. Fire Technology, Vol. 10, No. 3, August 1974
D.	Yngve Anderberg Sven Thelandersson	Stress and Deformation Characteristics of Concrete at High Temperatures. 1. General Discussion and Critical Review of Literature. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 34, Lund 1973
E.	Sven Thelandersson	Mechanical Behaviour of Concrete under Torsional Loading at Transient, High-Temperature Conditions, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 46, Lund 1974

1. Introduction

When a fire starts and develops in a building the performance of the load-bearing structure will soon be affected in one way or another and structural collapse may occur. This must be taken into account in the design of the load-bearing system in such a way that a reasonable safety is obtained in case of fire. Generally, the problem falls into two parts, the one is to specify the fire exposure (e.g. in the form of a temperature/time curve) and the other is to evaluate the structural consequences.

In the classical approach the fire exposure is characterized with a standardized time-temperature curve and the fire resistance of a certain building element is defined as the length of time during which the element can maintain its prescribed function (defined through certain criteria), when exposed to temperatures in accordance with the standardized curve. The fire resistance defined in this way is most oftenly determined in laboratory tests. The required fire resistance times under various conditions are then specified in building codes.

This classical approach is mainly based on work made by Ingberg /1/, who attempted to relate the severity of fire endurance tests to the conditions occurring during actual building fires. He showed that the major factor affecting the fire severity was the fire load, given as the equivalent weight of wood per unit floor area, and formulated explicitly a relation between the fire load and the fire duration. He also recognized the importance of ventilation in controlling fire behaviour but did not specify it as a separate variable.

This early work by Ingberg was for a long time the only systematic investigation of the behaviour of fully developed fires. In the years following the second world war, however, fundamental work was made in Japan by Fujita and others (reported in English in e.g. /2/ and /3/). The influence of ventilation on the fire behaviour was emphasized and it was suggested /2/ that the rate of burning for fires in enclosures should be proportional to the factor $A \cdot H^{1/2}$, where A = window area, and H = window height. A theoretical model for the behaviour of compartment fires was developed in terms of a heat balance equation /3/, where the amount of heat produced by combustion was assumed to be proportional to the ventilation factor $A \cdot H^{1/2}$. In Sweden a similar model was developed simultaneously by Ödeen /4/.

Perhaps the most important work in the field during the last ten years has been made in U.K. at the Fire Research Station, see for instance /5/ and /6/. Thomas, Heselden & Law /6/ specified two main regimes for the behaviour of compartment fires, ventilation control and fuel bed control respectively. In the ventilation controlled regime the rate of burning is roughly proportional to the factor $A \cdot H^{1/2}$, while in the fuel bed controlled regime the rate of burning depends on various factors, the most important of which is the exposed area of the fuel. The distinction between the two regimes is not quite clear, since the rate of burning depends somewhat on the fuel bed arrangement also in the ventilation controlled regime and vice versa. Thomas & Nilsson /7/ have suggested a third regime, named crib control, which gives an improved description of the behaviour of wooden crib fires.

In spite of the progress made in fire research the design procedure based on the standardized temperature-time curve is still used in most countries. At the time being, however, an international development towards a more functionally based structural fire engineering design can be seen. The most important contribution to this development has been made by Pettersson, who proposed a design model based on the natural fire behaviour and the actual response of structural materials and structural components to fire exposure /8/. The principles of this design model are illustrated in Figure 1 in form of a flow chart. A general application of these design principles requires an advanced knowledge of the physical characteristics of the fire process and its influence on building structures. In order to incite research and development in the area, the design system was included in the Swedish Building code of 1967 as an alter-

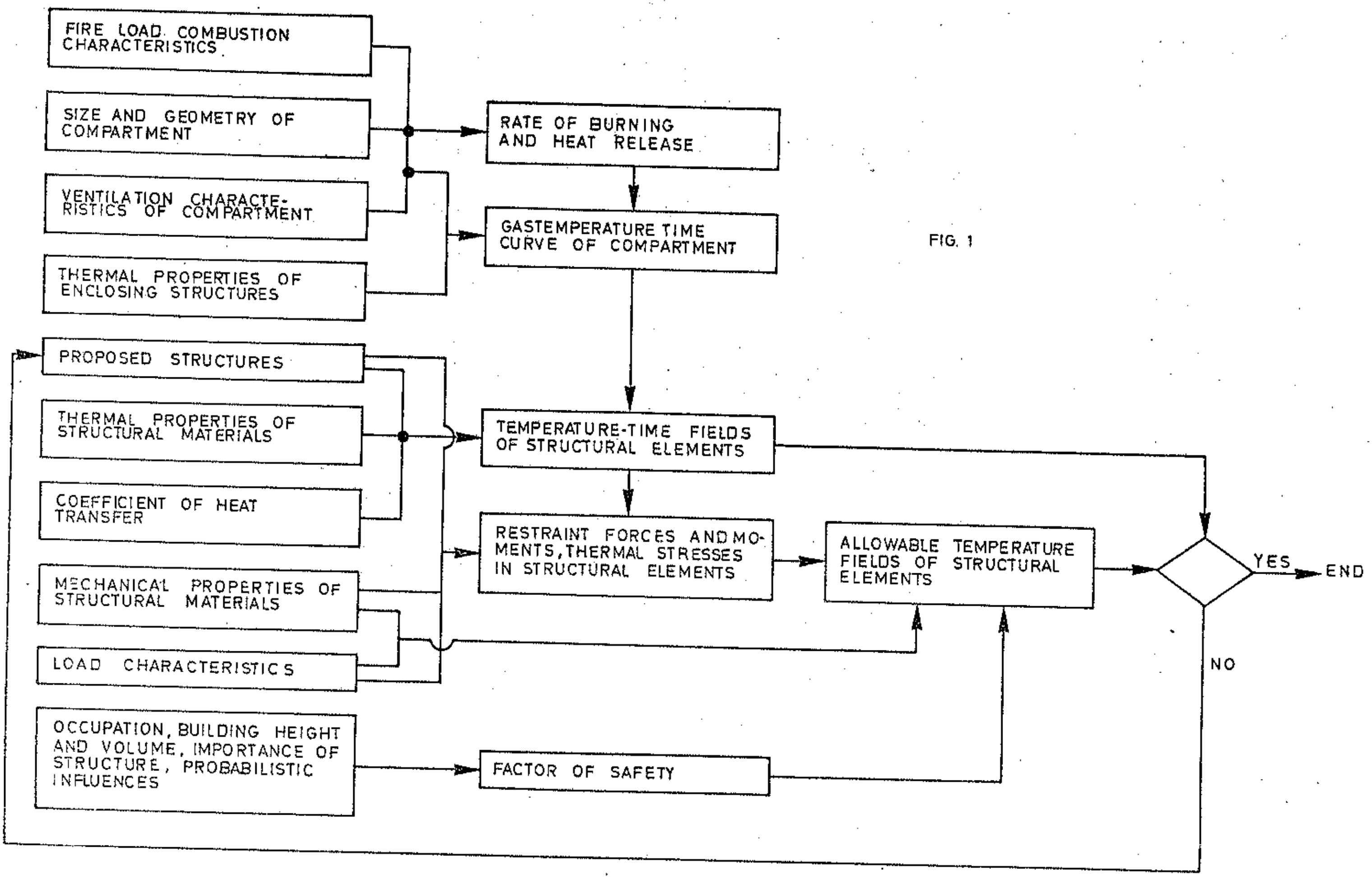
FIRE LOAD. COMBUSTION CHARACTERISTICS.
SIZE AND GEOMETRY OF COMPARTMENT
VENTILATION CHARACTERISTICS OF COMPARTMENT
THERMAL PROPERTIES OF ENCLOSING STRUCTURES
PROPOSED STRUCTURES
THERMAL PROPERTIES OF STRUCTURAL MATERIALS
COEFFICIENT OF HEAT TRANSFER
MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS
LOAD CHARACTERISTICS
OCCUPATION, BUILDING HEIGHT AND VOLUME, IMPORTANCE OF STRUCTURE, PROBABILISTIC INFLUENCES
RATE OF BURNING AND HEAT RELEASE
GASTEMPERATURE TIME CURVE OF COMPARTMENT
TEMPERATURE-TIME FIELDS OF STRUCTURAL ELEMENTS
RESTRAINT FORCES AND MOMENTS, THERMAL STRESSES IN STRUCTURAL ELEMENTS
FACTOR OF SAFETY
ALLOWABLE TEMPERATURE FIELDS OF STRUCTURAL ELEMENTS
YES
END
NO

FIG. 1

native to the traditional fire engineering design.

Under the circumstances great research efforts have been made in Sweden during the recent years, and the reports summarized in this thesis are all aimed at studying problems in connection with the application of the design model shown in Figure 1.

2. Behaviour of fully developed compartment fires, papers /A/, /B/ and /C/

As mentioned in the introduction an important problem in evaluating the effect of fire on structures is to specify the fire exposure. In papers /A/, /B/ and /C/ a theoretical model is employed with the purpose of predicting the gastemperatures attained in fully-developed compartment fires under various conditions. In /A/ the theoretical model is accounted for in detail and its reliability is checked against full scale tests from the literature. Results are presented in the form of gastemperature-time curves for different combinations of fire load density, ventilation characteristics and thermal properties of surrounding walls, floor and ceiling. In the papers /B/ and /C/ the validity of the basic assumptions and the relevancy of the model for the prediction of fire severity is further discussed, partly on the basis of new information.

The theoretical basis for the work is the heat balance model established by Kawagoe & Sekine /3/ and Ödeen /4/:

$$I_C = I_L + I_W + I_R \qquad (1)$$

where

I_C = rate of heat release by combustion

I_L = rate of heat loss by convection in the openings

I_W = rate of heat loss through bounding walls, floor and ceiling

I_R = rate of heat loss by radiation through the openings

The terms I_L, I_W and I_R express the total heat transfer from the fire compartment to the surroundings and are all functions of the average gastemperature in the compartment. Thus if the rate of heat release I_C is known for a given instant the gastemperature can be obtained from Eq. (1), which expresses the momentary heat balance. A computer program of a considerably general validity, written by Magnusson, was used for the calculations.

Of the three heat transfer terms on the right hand side of Eq. (1) I_W and I_R could rather easily be determined with sufficient accuracy, while I_L, which is directly proportional to the rate of gas flow, is more difficult to model mathematically. Under simplified assumptions, the rate of gas flow Q is shown to be proportional to the ventilation factor $A\sqrt{H}$. The validity of this relation was to some extent verified experimentally by Kawagoe /2/ in full scale fire tests and the relation was also used in the heat balance equation derived by Kawagoe & Sekine /3/. Later, Thomas et al /6/ pointed out that for large openings the abovementioned assumption may give too high values of the rate of gas flow. A considerable uncertainty in the predicted rate of gas flow is inherent in the choice of discharge coefficient μ. This factor probably depends on the size of the opening and the detailed arrangement at the boundaries, but no information is available about this.

In default of a better model, the relation $Q \sim A\sqrt{H}$ was adopted in /A/, though the influence of possible deviations from this assumption was analysed in /B/.

The term I_C in Eq. (1) is the effective rate of heat production in the burning compartment. Since the pyrolysis (production of combustible volatiles) of the fuel is a heat-consuming reaction, a certain portion of the heat produced in combustion must be fed back to the fuel to sustain the burning. This is not included in Eq. (1) and I_C is defined as the net production of heat excluding the feed back.

The combustion of fuels like wood is a combined heat- and mass transfer process of a very complex nature and our basic knowledge of this process is by no means sufficient for a direct prediction of I_C. But since we are here restricting our attention to the fully-developed fire as a structural engineering problem many details in the combustion process are of negligible importance and I_C can be treated on a more empirical level.

Empirical information about the time variation of I_C could in the following way be indirectly obtained from full scale fire tests. For tests with sufficient data for a calculation with the equation of heat balance to be possible, a time graph of I_C was chosen on trial. On the basis of this a time-temperature curve was calculated and compared with the measured temperatures. If needed, the time graph of I_C was changed and used for a new calculation. This was repeated until the calculated and measured time-temperature curves were in agreement. Such comparative calculations were in /A/ performed for some 30 full scale tests. For all trials of a certain test the following condition was fulfilled

$$\int_0^\infty I_C dt = M \cdot W \qquad (2)$$

where

t = time
M = total weight of fuel
W = effective heat value of the fuel.

By neglecting the combustion taking place outside the compartment and taking the value of W equal to the calorific heat value, corrected with respect to the moisture content, it was possible to determine a t - I_C curve leading to close agreement between theoretical values and average measured gastemperatures. This could be done for all 30 tests in /A/, including some with fire load of real furniture. Further tests were analysed in /B/ with the same result.

The I_C - t curves given in this way will obviously be affected by uncertainties in the heat transfer terms and may therefore be inexact measures on the actual heat release. But combined with empirical information about the rate of weight loss R and its dependence on various parameters, useful conclusions could be drawn from the said analyses.

A given I_C - t curve can in its main features be characterized by two quantities, the maximum value $I_{C,max}$ and the duration T of maximum burning intensity. For a given value of $I_{C,max}$ T is approximately given by the fire load density which is a predetermined quantity in this connection. Accordingly, the influence of various parameters on the rate of heat release in compartment fires can be discussed in terms of the quantity $I_{C,max}$. $I_{C,max}$ in turn is in some way or another connected to the maximum rate of weight loss or rate of burning R_{max}, which can readily be measured in fire tests.

As mentioned in the introduction the behaviour of fully-developed fires broadly falls into two categories, ventilation-controlled and fuel bed controlled respectively. In the ventilation controlled regime the rate of burning is given by /2/:

$$R_{max} = 5.5\, A\sqrt{H} \qquad (\mathrm{kg \cdot min^{-1}}) \qquad (3)$$

whereas in the fuel bed controlled regime the rate of burning depends on a number of parameters, of which the most significant is the exposed surface area of the fuel.

In a deterministic prediction of the fire exposure for design purposes, we have to start from a given compartment geometry, a given ventilation factor, and a given fire load density. Generally speaking, with these parameters predetermined the fire can be either ventilation controlled or fuel bed controlled depending on the properties of the fuel bed. If the fire is ventilation controlled the fire burns rapidly during a short time while in the case of fuel bed control the rate of burning will be lower but the duration longer. Since the severity of a fire with respect to an exposed structural member is largely an integral effect, the difference in this sense between the two kinds of behaviour is not very marked. It is quite obvious, however, that the fuel bed controlled fire will in general be less severe than the ventilation controlled fire, the difference depending on the thermal performance of the exposed structure.

For the purpose of specifying the fire exposure with regard to its impact on structural members, it was found appropriate to assume ventilation control in all cases. Under this assumption generalized I_C - t curves were constructed (paper A) with $I_{C,max}$ given by

$$I_{C,max} = W_{eff} \cdot R_{max} \quad MJ \cdot min^{-1} \tag{4}$$

where R_{max} was taken from (3). On the basis of the information obtained from the burn-out tests analysed W_{eff} was taken to 10,8 $MJ \cdot kg^{-1}$ (This value expresses the net production of heat excluding the feed back and has nothing to do with the calorific heat value of the fuel).

The generalized curves were used to compute gastemperature-time curves for a systematic variation of fire load density, ventilation opening and type of structure bounding the fire compartment. The design curves are compiled in an appendix to paper A.

The reasonableness of the assumptions made was further discussed in paper /B/. The fact that a ventilation controlled fire is generally more severe than a fuel bed controlled fire, was directly demonstrated for fire exposed steel structures with varying degree of insulation. The consequences of different conceivable deviations from the assumptions regarding the rate of heat release and the rate of gas flow were examined. The general conclusions arrived at were that the application of the design curves gives a reliable description of the fire severity with regard to structural members and that the favourable effect of fuel bed control, if any, could at the time not be taken into account. The reason for this is that the main parameter of interest in the fuel bed controlled regime, the exposed surface area of the fuel, can not be specified for the type of fire loads occurring in real life.

In a later work by Nilsson /9/ the heat balance model Eq. 1, in the form used in /A/, /B/ and /C/, was employed in an analysis of a large number of model fire tests. The usefulness of the model was then further demonstrated for a wide range of conditions. As a result Nilsson presented a basis for the prediction of the variation in rate of heat release for wood crib fires, valid also for the fuel bed controlled regime. Basic parameters were ventilation, fire load density, crib porosity and stick dimensions. Nilsson proposed that fires occurring in practice could be described in terms of equivalent crib parameters, which may be determined from systematic calibrating tests with practically representative fire loads.

Further progress of any importance as regards the behaviour of compartment fires can only be made on a basis of a better physical understanding of the combustion process. A problem of immediate practical interest is how the fire process is affected by the increasing use of plastic in furniture and linings. The knowledge so far is on the whole limited to fuels of wooden type.

The design curves presented in /A/ have been accepted by the Swedish National Board of Urban Planning as a base for a design of fire-exposed structural elements. The curves are employed in a general design prodedure for fire exposed steel structures, recently developed and published in a manual /10/. The design procedure is essentially following the principles in Figure 1 and is systematized and presented in charts, diagrams and tables, ready to use in practical design.

3. Mechanical behaviour of concrete under fire exposure conditions. Papers /D/ and /E/

The publishing of /10/, implies that the design of fire exposed steel structures now can be made in a sophisticated manner in accordance with modern concepts of safety /11/. In the design of reinforced and prestressed concrete structures under fire exposure one still has to resort to the traditional classification system, which is greatly simplified in comparison. In this situation it is important that research efforts are made in order that concrete and steel may be put on equal footing in this respect.

Any attempt to analyse the structural behaviour of a reinforced or prestressed concrete member under thermal exposure and static load involves an estimate of stresses and deformations in the concrete and the steel. For steel the mechanical behaviour at high temperatures is rather well-known, while an analysis of stresses and deformations in loaded, heated concrete, is very difficult to make. This is due to the fact that a realistic constitutive equation for concrete under transient, high-temperature conditions has not yet been formulated. To achieve this end, further information is required about the deformation under load of concrete exposed to high temperatures.

In paper /D/ the problems involved in making a theoretical stress analysis of concrete structures at high temperatures are formulated and discussed to some extent. The information available in literature on deformation properties of concrete at elevated temperatures is reviewed from the point of view of high temperatures and rapid processes of heating, i.e. the conditions characterizing fire exposure. Possible methods of calculation are briefly outlined and the needs of data for applying these methods are accounted for.

Relatively much information was found in the literature regarding creep at temperatures below 200°C, while practically no studies of time-dependent deformations have been performed at higher temperatures. The results in literature clearly showed that the influence of moisture content, moisture change and moisture migration is very significant for lower temperatures. It was established that the deformations became much larger under changing temperature and moisture state than under stable conditions. This is a parallell to the distinction between basic creep and sorption creep which is a well-known feature for creep at normal temperatures.

As regards the instantaneous strains the most important aspect is the marked influence of the previous stress history. Concrete which has been subjected to stress during heating exhibits different strength and accordingly different stress-strain relation compared with concrete which have been unstressed during heating.

The possibility of applying an ultimate load approach on concrete at high temperatures was briefly discussed. The main question in this context is whether the deformability of heated concrete is large enough for the redistribution of stresses to take place. Another aspect is the definition of the ultimate stress, since in tests, this quantity has been found to depend on the previous stress history. It was suggested that the ultimate stress might be determined from tests, where the specimens are first loaded to certain stress levels and then heated until failure occurs.

The problem of calculating the complete stress and deformation behaviour of a fire exposed concrete structure can be tackled by using a stepwise procedure. In this case thorough knowledge of the constitutive relations between stresses and strains including time-dependent behaviour is needed. These relations must be valid at transient as well as steady-state conditions.

Paper /E/ is devoted to a study of this complex problem. The intention is to make a fundamental study of the deformation behaviour of concrete under load at transient high-temperature conditions. The study is made on the basis of tests of plain concrete in pure torsion, which makes it possible to study the deformations under changing temperatures without simultaneous thermal expansion being included. The test series comprises for four different types of tests, viz. torque vs. twist at constant temperature, creep at constant stress and temperature, heating to failure under constant load and heating to a maximum temperature level under constant load.

Compared with metal or ceramic materials, concrete exhibits a special feature, namely that the deformations under transient conditions can not be predicted from tests made at constant temperatures. During the first heating of stressed concrete considerable deformations develop that do not occur under stabilized temperature.

This has been shown for moderate temperatures ($< 100^{\circ}C$) by several investigators. In /E/ the same was found for temperatures at least up to $500^{\circ}C$ and the effect was found to be even more pronounced at higher temperatures. The results show that the deformations occurring as a result of heating constitutes the major part of the total deformation.

Based on the test results, a constitutive equation is formulated in terms of the following three strain components:

Elastic strain
Constant temperature creep strain
Transient strain

This is valid for concrete in pure torsion; in the uniaxial case we also have to include thermal expansion and shrinkage.

The elastic strain is determined by the shear modulus, which is a function of temperature. The constant temperature creep is the time dependent strain measured under constant stress and temperature, whereas the transient strain component occurs only if the temperature increases in the concrete under load.

All three strain components are linearly related to the stress, which gives good agreement between theory and experiments. The model can, however, easily be modified to a non-linear stress dependence when and if this is necessary.

The different components are formulated mathematically in a constitutive equation, which is employed in a theoretical analysis of stresses and strains in circular cross sections under pure torsion. The agreement between tests and theory is remarkably good for a wide range of loading and temperature conditions, a fact which proves the reliability of the model.

The author believes that the suggested constitutive model in a qualitative sense also can be used to describe the strain behaviour in compression and direct tension, though in these cases the thermal expansion must be taken into account. In a coming paper by the author and Anderberg the strain behaviour in compression will be analyzed on the basis of a comprehensive test series involving the same types of tests as those accounted for in /E/.

The purpose with these studies is to establish a realistic and accurate constitutive model of the concrete at high temperatures, valid in compression and tension, for steady and non-steady thermal conditions. This knowledge is fundamental for an analysis of the structural behaviour of reinforced and prestressed concrete structures under thermal exposure. An advance understanding of this behaviour is in turn necessary for the development of simplified methods which can be used for design purposes.

Acknowledgements

As regards the papers /A/, /B/ and /C/, Magnusson is responsible for the computer program and the numerical problems connected with the programming. In /A/, chapter 3, some aspects on the rate of gas flow originate from a graduate thesis by Ahlquist & Thelandersson. Otherwise the work accounted for in /A/, /B/ and /C/ has been carried out in close cooperation between the authors and it is virtually impossible to specify individual contributions.

Paper /D/ is the first paper from a joint research project between the author and Anderberg. The work on the project as a whole is carried out in close cooperation between the authors. In particular, paper /D/ was outlined and written by the authors in close connection, though Thelandersson to a greater extent contributed to its final shape.

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