Accelerated Life Testing of Solar Absorber Coatings

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Testing Procedure and Results

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Abstract

A procedure for accelerated life testing of solar absorber surfaces was developed within the framework of the working group *MSTC (Materials in Solar Thermal Collectors)* of the *IEA-SHCP (International Energy Agency - Solar Heating and Cooling Programme).* The intensive material and micro-climatic investigations on solar thermal collectors and solar systems within the preceding IEA task X (1985 - 1991) as well as further studies in this field by the group itself formed a basis for this work.

The procedure was formulated as a standard, and submitted to ISO at the beginning of 1997 as a 'Draft Proposal'. It carries the designation *ISO/CD 12592,2 'Solar Energy - Materials for flat-plate collectors - Qualification test procedure for solar surface durability'.* The proposed standard describes in detail a procedure for the examination of the long-term stability of solar absorber coatings used in flat-plate collectors for domestic hot water systems. The minimum lifetime of the absorber surface is estimated to be 25 years. Possible degradation caused by the thermal load, by condensation and high humidity are considered as well as by air pollutants (sulphur dioxide).

In order to examine the feasibility and reliability of the standard procedure, a 'Round Robin' test was performed in a further project of the working group *MSTC*. Within this 'Round Robin' the durability of five different absorber coatings was tested in accordance with the proposed standard by three independent laboratories. The outcome of this test is that all of the laboratories obtained the same results for each of the coatings

As the sulphur dioxide test described in the standard procedure was performed by only one laboratory, a comparison of the results cannot be made. Therefore, this article will be limited to the accelerated ageing tests regarding the resistance to high temperature and to high humidity and condensation. The limitation is made for both the description of the testing method and the presentation of the results of the 'Round Robin' test.

1. Introduction

The market for solar thermal applications is growing rapidly [1]. Therefore the number of manufacturers of solar thermal systems and their components constantly increasing also. New products extend existing ones or replace them. Of course, one of the most important components of a solar thermal system is no exception: the absorber in a collector.

The function of the absorber of a solar collector is to transform the incident solar irradiation into heat and to suppress heat losses due to thermal radiation. These requirements, maximum absorptance of the solar irradiation (in the wavelength range from 0.29 µm – 2.5 µm) and minimum emittance in the thermal infrared (> 2.5 µm) are met by applying a spectrally selective coating onto the absorber substrate material (usually copper, aluminium or steel).

For a long time, mainly thin black chromium layers (chromium particles embedded in a chromium oxide matrix of a few 100 nm thickness, galvanically deposited on nickel-plated copper) or also nickel-pigmented alumina (on aluminium) have been used for this purpose. However, advanced coating processes such as physical or chemical vapour deposition (PVD or CVD) promise some advantages. These include the optical characteristics of the coatings, the constancy of product quality and an improvement of the ecological balance. Whether these expectations can be fulfilled, is still to be confirmed.

The most important sales argument for solar absorber coatings, apart from the price, concerns their optical characteristics such as solar absorptance and thermal emittance. These values are already optimised during the development process and constantly monitored in production. However, they are only valid for the virgin product. Manifold micro-climatic influences can degrade the absorber in a collector, causing the optical properties to deteriorate. Thus, a leading product can already lose its superiority after several years. In order to avoid such surprises, it is advisable to predict the ageing behaviour of these coatings. For this reason, methods for the accelerating ageing testing of solar absorber coatings were introduced by the work of the IEA Task X [2]. The IEA Working Group MSTC (Materials in Solar Thermal Collectors) was founded in 1994 as a continuation of Task X.

Within a project of this working group, predictions of the long-term stability of a coating in collectors made by accelerated ageing investigations in Task X were confirmed by examples in the field [3]. Furthermore, a procedure was worked out which allows the suitability of a solar absorber surface for use in a single glazed, flat-plate collector for domestic hot water systems to be assessed by performing constant load tests in the laboratory (Carlsson, 1997). "Suitability" means that the solar fraction of the system would decrease less than 5% due to degradation of the coating within an estimated lifetime of 25 years. High thermal load, condensation and high humidity, and atmospheric corrosion by sulphur dioxide are considered as possible causes for the degradation

This procedure (Carlsson, 1997) was formulated as a proposal for a standard and submitted to ISO in January 1997 [5]. In order to check the feasibility and reliability of the proposed standard, a ' Round Robin ' test was performed by the working group MSTC. The test examed the resistance to ageing of five different solar absorber coatings in accordance with the standard procedure. Three laboratories took part in the investigations.

As the sulphur dioxide test described in the standard procedure was performed by only one laboratory, a comparison of the results cannot be made. Therefore, this article will be limited to the accelerated ageing tests regarding the resistance to high temperatures and to high humidity and condensation. The limitation is made for both the description of the testing method and for the presentation of the results of the 'Round Robin' test.

2. The Test Procedure

In the following the principles of accelerated life-time testing will be presented briefly. A more detailed description can be found in (B. Carlsson et al., 1994). Another reference (B. Carlsson et al., 1999b) describes the basis for and the development of this qualification test procedure more comprehensively. It should be emphasised that one aim of the 'Round Robin' was to gain practical experience in order to improve the procedure. Therefore, the test procedure used in the described 'Round Robin' differs slightly from the one described in (B. Carlsson et al., 1999b). Publication of a Draft International Standard is planned for the near future (ISO 12592).

2.1. Service Lifetime and 'Performance Criterion'

In order to define a criterion for the lifetime of a solar absorber coating, the following assumptions are made:

- the absorber coatings are dedicated to the application in single glazed, flat-plate collectors for domestic hot water systems
- the maximum service lifetime of the absorber coating is reached if the annual solar fraction of a domestic hot water system is decreased by 5% due to deterioration of its optical properties caused by degradation
- the service lifetime is 25 years at least

In IEA Task X, Hollands et. al. carried out comprehensive parameter studies with the aid of computer simulations in order to quantify the influence of the optical properties of an absorber coating on the system performance. It turned out that the so-called performance criterion (PC) will be a useful property to describe the influence of the changes in the solar absorptance $\Delta\alpha_S$ and the thermal emittance $\Delta\varepsilon$ on the solar fraction:

$PC = -\Delta\alpha_s + 0.25 * \Delta\varepsilon$

In this definition, a value of the performance criterion of 0.05 corresponds to a decrease of the annual solar fraction of a typical domestic hot water system by 5%. The time passing until this value is reached is called the 'failure time'.

2.2. Environmental Influences, Time Transformation and Accelerated Testing

Extensive investigations of the microclimate in flat-plate collectors, as were undertaken by the IEA Task X and the working group MSCT, make it possible to determine the factors which are relevant for the degradation of solar energy absorber surfaces. These are in detail:

(a) degradation due to thermal load (oxidation)

(b) degradation due to high humidity or condensation of water on the absorber surface (hydratisation and hydrolysis)

(c) degradation due to air pollutants such as sulphur dioxide (atmospheric corrosion)

These factors were measured and observed over several years in different collectors sited at different locations in Europe. Both normal working conditions and stagnation periods (as could occur for instance during summer vacations) were considered. The long-term measurements yield specific load profiles for both types of loads, (a) and (b), as temperature frequency functions (see figure 1). The observation period is at least one calendar year, in order to assess all seasonally dependent operating conditions.

One way to accelerate degradation caused by atmospheric gases is to increase their concentration. This is possible for example with sulphur dioxide, which occurs in the natural environment only in ppb concentrations. The draft standard for the durability testing of solar absorber coatings with regards to atmospheric corrosion makes use of this acceleration mechanism.

However, if degradation is caused by oxidation and/or hydratisation and hydrolysis, acceleration must be achieved by raising the temperature, since oxygen and/or water already occur in the atmosphere of the collector in relatively high concentrations.

If t_{ref} is the time period during which a sample is exposed to a specific load (such as oxidation at temperature T_{ref}) and t_n is the time period for which a sample of the same absorber has to be exposed to another load (for instance oxidation at a higher temperature T_n) in order to achieve the same degradation, then the acceleration obtained by temperature change is given by:

$$a_n = \frac{t_{ref}}{t_n} \qquad (1)$$

For degradation caused by diffusion processes, chemical reactions or desorption, the temperature dependence of the process can be described by the Arrhenius' relationship:

$$a_n = \exp\left[\frac{E_T}{R}\cdot\left(\frac{1}{T_{ref}}-\frac{1}{T_n}\right)\right] \tag{2}$$

with

E_T activation energy according to Arrhenius

R ideal gas constant (R = 8.314 J/K/mol)

The effective mean temperature T_{eff} of the absorber coating turns out to be suitable as a measure of the load during an operating time of one year:

$$\exp(-\frac{E_T}{R}\cdot T_{eff}^{-1}) = \int_{T_{min}}^{T_{max}} \exp(-\frac{E_T}{R}\cdot T^{-1})\cdot f(T)\cdot dT \tag{3}$$

with

f(T)	the temperature frequency function valid for the observed load over one year: if the thermal degradationis observed, f(T) is the time in one year, during which the absorber temperature lies between T und T+dT (see also figure 1a); with respect to degradation by condensation and high humidity, f(T) is the time in one year, during which the absorber temperature lies between T und T+dT and the relative humidity in the collector exceeds 99% or condensation takes place on the absorber surface (see figure 1b)
T_{max}, T_{min}	maximum7 minimum absorber temperature of the load.

The varying load which an absorber surface experiences in a collector during one year therefore corresponds to a constant load at the effective temperature T_{eff} determined according to (3) during the same time period. However, the same degradation can be achieved by exposure at a higher temperature for a shorter time interval according to (1) and (2). Therefore, in the case of a minimum service lifetime of 25 years, the failure time in an accelerated test at a constant temperature T_R must be at least t_R (years):

$$t_R = 25\cdot\exp\left[-\frac{E_T}{R}\cdot\left(\frac{1}{T_{eff}}-\frac{1}{T_R}\right)\right] \tag{4}$$

Obviously, t_R does not only depend on the effective mean temperature T_{eff} and the (higher) testing temperature T_R. This time period is also determined by the activation energy of the degradation mechanism.

For this reason, usually two tests at different temperature levels are necessary for each type of load in order to characterise an absorber coating. Using these two temperature levels, it is possible to estimate whether the activation energy is high enough to ensure sufficient durability under operating conditions or at T_{eff}.

In figure 2, the failure time is plotted as a function of the activation energy for different tests at constant temperatures, all corresponding to a service lifetime of 25 years. Initially, it may be surprising that substantially longer testing periods are needed for processes of low activation energy. However, this becomes plausible after examining equation (2) more closely. In the case of processes with a high activation energy, the acceleration caused by a temperature rise from T_{ref} to T_n is obviously much larger than for processes of low activation energy.

As can be seen from (3), the effective mean temperature T_{eff} also varies with the activation energy E_T. If T_{eff} from equation (4) were constant, then the resulting curves for the failure time in the logarithmic graph of figure 2 would be straight lines with a negative gradient. The gradient would become smaller as the testing temperature T_R, decreased, until the lines became horizontal for $T_R = T_{eff}$, and intercepted the y – axis at t_R = 219000 hours (or 25 years).

A further decrease of the testing temperature below the effective load given by T_{eff} (thus $T_R < T_{eff}$) would cause "lifetime extension". The straight lines then will show a positive gradient and a higher activation energy will lead to a longer failure time.

These test procedures are based on the assumption that the temperature dependence of degradation can be described by an Arrhenius relation. Furthermore, it is presumed that only one mechanism of degradation is active. These assumptions mean that an absorber coating does not need to be disqualified immediately if it fails the accelerated durability test described in the draft standard. More detailed ageing tests which could lead to qualification are recommended in this case.

Furthermore, it is important to mention that it is impossible to derive the stability of the coating in real operation from one single ageing test performed at one specific testing temperature. This means, for example, that a coating which degrades much faster than another coating at an accelerated testing temperature of 250°C, can have a better thermal stability under operating conditions, because the acceleration of the ageing process caused by a temperature rise may be higher due to a higher activation energy.

2.3. *Initial Characterization*

Up to 21 testing samples sized about 50x50 mm^2 are required in order to perform all the tests foreseen in the draft standard. In order to qualify for the test, the standard deviation of the optical properties of these 21 samples should not exceed 0.01 for the solar absorptance α_s and 0.04 for the thermal emittance ε.

The adhesion of the absorber coating to the substrate is tested on 3 selected samples, either according to *the procedure standardised in ISO 4624 or by applying a simple tape test. The adhesion for each of the 3* test samples must exceed 0.5 MPa if ISO 4624 is applied.

2.4. *Test procedure for qualification of the temperature stability*

A circulating air oven which provides a temperature accuracy and distribution better than ±1 K at testing temperatures from 200°C to 300°C for the examination of the thermal stability of a solar absorber coating, because the time needed for heating up such ovens is usually rather long, the samples are put into the furnace after the chosen testing temperature has been reached. Cooling has to be faster than 10 K/min until the temperature has dropped to at least 100K below testing temperature.

Always, three samples are tested simultaneously always. The test results to be considered for the performance criterion PC refer to the average value of these three samples. The testing procedure is shown in the flow chart of figure 3. The test starts with TESTING i1:

TESTING i1: The samples are exposed to a temperature of 250°C for 200 hours. If PC(i1) <= 0.05 the adhesion is checked. If it is not sufficient, the coating cannot qualify. If the adhesion is sufficient and if PC(i1) < 0.01, *the coating has qualified, otherwise the test has to be* continued with TESTING f1. If PC(i1) > 0.05, the test has to be continued with TESTING i2.

QUALIFICATION: The coating has qualified if PC(i1) < 0.01 after TESTING i1 and the adhesion is sufficient.

Note: in the revised testing procedure (ISO/DIS 12592) the criterion is PC(i1) < 0.015.

TESTING i2: as PC(i1) > 0.05 after TESTING i1, 3 new samples are exposed to 250°C for a period of 10 / PC(i1) (in hours).

CALCULATION: The failure time is determined by interpolation from the pairs (t, PC) of TESTING i1 and TESTING i2 as well as the initial value (0, 0). The failure time is the period which would correspond to a PC = 0.05. With the help of diagram 2a, the activation energy corresponding to this failure time is determined. This activation energy leads to an appropriate failure time for a 200°C test.

TESTING f2: 3 new samples are exposed to 200°C for the duration of the appropriate failure time.

QUALIFICATION: The coating has qualified, if PC(f2) < 0.05 after TESTING f2 and the adhesion is sufficient.

TESTING f1: as after TESTING i1, PC(i1) <= 0.05, 3 new samples are exposed to 300°C for a period of 75 hours

QUALIFICATION: The coating has qualified, if after TESTING f1, PC(f1) > PC(i1) or if the difference between PC(f1) and PC(i1) is smaller than 0.01

2.5. Test procedure for qualification regarding moisture

The condensation tests are performed in a climatic chamber at (chamber) temperatures between 35°C and 65°C. The relative humidity is kept constant at 95% (±3%) for all tests. The temperature accuracy and homogeneity must be better than ±1 K.

Always, 3 samples are tested simultaneously. The samples are electrically insulated from each other and mounted with good thermal contact onto a cooled sample holder, which is tilted at an angle of 45° to the horizontal. The temperature of the sample holder is controlled by a cooling circuit with an accuracy of ±0.5 K in the range between 30°C and 60°C.

It should be noted that the testing temperature is the sample temperature and the temperature in the climatic chamber is always kept 5K higher. Due to the high humidity, condensation occurs constantly on the surface of the samples.

The test procedure is illustrated in the flow chart of figure 3. The test starts with TESTING i1:

TESTING i1: The samples are exposed to a temperature of 40°C for up to 600 hours. In order to determine the performance criteria, optical measurements are made after 80, 150, 300 and 600 hours. As soon as a PC(i1) > 0.05, the test is continued with TESTING i2.

If PC(i1) <= 0.05 after 600 hours of testing, the adhesion is checked. If the adhesion is not sufficient, the coating cannot qualify. If the adhesion is sufficient and if PC(i1) < 0.01, the coating has qualified, otherwise the test is continued with TESTING f1.

QUALIFICATION: The coating has qualified, if PC(i1) < 0.01 after TESTING i1 and the adhesion is sufficient.

Note: in the revised testing procedure (ISO/DIS 12592) the criterion is PC(i1) < 0.015

TESTING i2: During TESTING i1, PC(i1) was found to exceed 0.05. If this was the case after (80 / 150 / 300 / 600) hours, then the new testing time will be (40 / 115 / 225 / 450) hours, at a sample temperature of 40°C.

CALCULATION: The failure time is determined by interpolation from the pairs (t, PC) of TESTING i1 and TESTING i2 as well as the initial value (0, 0). The failure time is the period which would correspond to a PC = 0.05. With the help of diagram 2b, the activation energy corresponding to this failure time is determined. This activation energy leads to an appropriate failure time for a 30°C test.

TESTING f2: 3 new samples are exposed to condensation at 30°C for the duration of the appropriate failure time.

QUALIFICATION: The coating has qualified, if PC(f2) < 0.05 after TESTING f2 and the adhesion is sufficient.

TESTING f1: as after TESTING i1 PC(i1) <= 0.05, 3 new samples are exposed to condensation at 60°C for a period of 85 hours.

QUALIFICATION: The coating has qualified, if after TESTING f1, PC(f1) > PC(i1) or if the difference between PC(f1) and PC(i1) is smaller than 0.01.

3. The participants in the Round Robin test routine

Three institutes took part in the Round Robin as testing laboratories. All of them have many years of experience concerning ageing tests for solar energy absorber coatings:

SP Swedish National Testing and Research Institute,
S-501 15 Boras, Sweden
ISE Fraunhofer Institut für Solare Energiesysteme,
D-79100 Freiburg, Germany
SPF Institut für Solartechnik Prüfung Forschung, Hochschule Rapperswil,
CH-8640 Rapperswil, Switzerland

Five manufacturers of absorber coatings participated with their products (see table 1). The products include two black chrome coatings that have been produced for over 20 years, on copper by MIT and on high-grade steel by Energie Solaire. A new manufacturer of a black chrome coating on copper is from Denmark (ChromeCoat). New coatings are represented by the selective paint, developed by the National Institute of Chemistry Lubljana (on aluminium) and the sputtered coating of TeknoTerm. Concerning the latter, it should be mentioned that the substrate material fo the coating tested here is stainless steel (and not aluminium). Two further coating manufacturers, whose products would have been of interest for this test, withdrew before the beginning of the test.

4. Results and discussion

All tests were made according to the test procedure described in (Carlsson, 1997). This corresponds to the status of the draft standard dated January 1997. An exception is the adhesion test of the coating, which should be performed according to ISO 4624 (as prescribed in Carlsson, 1997). However, it was found that the adhesion tests could also be carried out by the simple tape test. The complex test according to ISO 4624 was performed by only one laboratory. The values for the adhesion determined in this way were in all cases well above the minimum requirements of 0.5 MPa for the unaged samples or 0.15 MPa for the aged samples.

4.1. Optical homogeneity of the samples

As an initial test, the values for the solar absorptance α_S and thermal emittance ε of each of the 21 samples (per candidate coating) must be determined. In figure 4, the optical values of all 5 coatings are shown as determined by the 3 laboratories. The values for the absorptance and the emittance can be found in the upper and lower parts of the diagram resectively. As well as the average values, the extreme values and the standard deviations are plotted. All coatings qualified for the test by in laboratories, since the standard deviations in all cases were below the required minimum values.

The optical values determined by the different laboratories show very good agreement. Only the emittance values from SP show a systematic deviation with respect to those from ISE or SPF. This is due to different measurement principles. While SP measures with an 'Emissometer' (broadband measurement), ISE and SPF use a spectrometer with integrating spheres. However, this is of minor importance, since only differences of the optical properties are used for the accelerated ageing investigation.

4.2. Thermal stability

The testing route was the same for all of the 5 coatings. It is described by the right part of the flow chart in figure 3. The resulting values for the performance criteria are plotted in figure 5.

For all 5 coatings, the PC values resulting from TESTING i1 (200 hours with 250°C) are smaller than 0.05. Samples K, L and M have already qualified, as their PC(i1) is even smaller than 0.01. With coatings F and G, the test has to be continued with TESTING f1 (75 hours with 300°C), from which PC(f1) is obtained. For inter-laboratory comparison purposes, the materials K, L and M were also exposed to this load. Coatings F and G qualify, if one of the following criteria is fulfilled after TESTING f1:

$PC(f1) > PC(i1)$ (qc1)

or $|PC(f1) - PC(i1)| < 0.01$ (qc2)

It is worth noting that (qc1) and (qc2) can be integrated into a single criterion due to the logical OR linkage:

$PC(f1) > PC(i1) - 0.01$ (qc1 OR qc2)

As can be seen in figure 5, all laboratories obtain the same result: qualification by the coatings F and G with respect to their thermal stability. Even the resulting PCvalues are in very good agreement.

Some values for PC(f1) from the laboratory SPF, resulting from the 300°C test are an exception. For coatings showing any degradation (i.e. F, G and L), it seems to be less pronounced in the Swiss lab.

As was discovered later, the cause of this disagreement was the temperature controller of the hot air furnace, which did not work correctly. Thus, the temperature for this test was not held at the specified 300°C (±1 K), but was only around 296°C over longer periods. This smaller thermal load results in less degradation, of course. A repetition of this test with some of the coatings yielded results corresponding to those of the other laboratories.

Apart from this case, all results are in good agreement. Coatings F and G qualify according to qualification criterion (qc1) after TESTING f1. The candidates K, L and M had already qualified after TESTING i1, since the 250°C load led to insignificant degradation ($PC(i1) < 0.01$).

4.3. Stability under high humidity and condensation conditions

The path of the condensation test is the same as for the high temperature test for all five coatings. It can be described with the right part of the flow chart in figure 3.

The tests start with TESTING i1 at 40°C sample temperature for a period of up to 600 hours. After 80, 150 and 300 hours the test is interrupted for the determination of the performance criteria (see figure 6). With one exception, all PCvalues remained smaller than 0.01 for the whole 600 hours period, leading to qualification after TESTING i1 already.

The exception is sample L at lab ISE, which just missed an early qualification with a $PC(i1) = 0.014$ after 600 hours at 40°C. Therefore, TESTING f1 (85 hours with 60°C) had to be executed in this case. For comparison purposes, the 60°C test was conducted by all laboratories with all coatings. In order to qualify with regard to high humidity and condensation (for layer L in the laboratory ISE), one of the following qualification criteria had to be fulfilled:

$PC(f1) > PC(i1)$ (qc1)

or $|PC(f1) - PC(i1)| < 0{,}01$ (qc2)

Similarly to high temperature testing, (qc1) and (qc2) can be integrated into a single criterion due to the logical OR linkage:

$PC(f1) > PC(i1) - 0.01$ (qc1 OR qc2)

As can be seen from the PC values in figure 6, laboratory ISE concludes with qualification for the layer L as well. Altogether, the values for the performance criteria for the different coatings determined by the different laboratories show good agreement. The behaviour of coating L, which shows a slightly more pronounced degradation in the laboratory ISE, is an exception. The reason for this may be a slightly stronger load applied in the climatic chamber at ISE. The other samples, which were tested parallel to L, show the same tendency. However, the observed degradation is in general a little too small to serve as a serious indication. The results reported by SP after 600 hours of testing at 40°C are afflicted with a small uncertainty. Due to a failure of the spectrometer, incorrect values for the solar absorptance were determined. This was noticed after adhesion testing, however. Thus, the area on the coating for performing the optical measurement was not the same after the condensation test as before. Furthermore, the samples were distorted a little by the adhesion test. This is most probably the reason for the small PC(i1)value of the layer M after 600 hours.

5. Summary

A testing method was developed with the standard procedure described in (Carlsson, 1997), which allows the resistance to ageing of solar absorber coatings to be characterised by clearly defined constant load tests in the laboratory. The Round Robin test executed in accordance with this procedure confirms that this procedure is practicable and leads to reproducible results. This is valid, not only for the main criterion of whether a coating qualifies for use in a single glazed, flat-plate collector for domestic hot water production or not. In addition, the results of the measured optical changes after the specific tests are in very good agreement.

The test procedure was submitted to ISO as the draft proposal ISO CD 12592,2.

Nomenclature

PC	performance criterion
α_s	solar absorptance
ε	thermal emittance
t	time
T	temperature, K
a	acceleration factor
E_T	activation energy according to Arrhenius
R	ideal gas constant ($R = 8.314$ J/K/mol)
f(T)	temperature frequency function

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Appendix

Tab. 1: Absorber coating manufacturers participating in the Round Robin

Label	Manufacturer	Name	Substrate
F	Energie Solaire S.A., CH-3960 Sierre	C2-80	stainless steel
G	MTI, Somerset, New Jersey 08873, USA	Solar-H-Foil	copper
H	Participation withdrawn		
K	ChromeCoat A/S, DK-4681 Herfolge	ChromeCoat	copper
L	TeknoTerm Energi AB, S-43634 Askim	Sunstrip – Sputter	stainless steel
M	Nat. Inst. of Chemistry, SI-1001 Ljubljana	selective paint	aluminium
N	Participation withdrawn		

List of figure captions

Figure 1a: Frequency distribution of the absorber temperatures of a typical flat-plate collector for one year as evaluated in the work of Task X [2].

Figure 1b: Reference load referring to condensation and humidity. The frequency distribution is based on measurements of the microclimate from TeknoTerm collectors in the Task X work [2] and is valid for the relative humidity in the collector above 99%. The observation period is one year.

Figure 2a: Shortest acceptable 'failure time' for an absorber coating in different temperature tests. The failure time in each case corresponds to a service lifetime of 25 years.

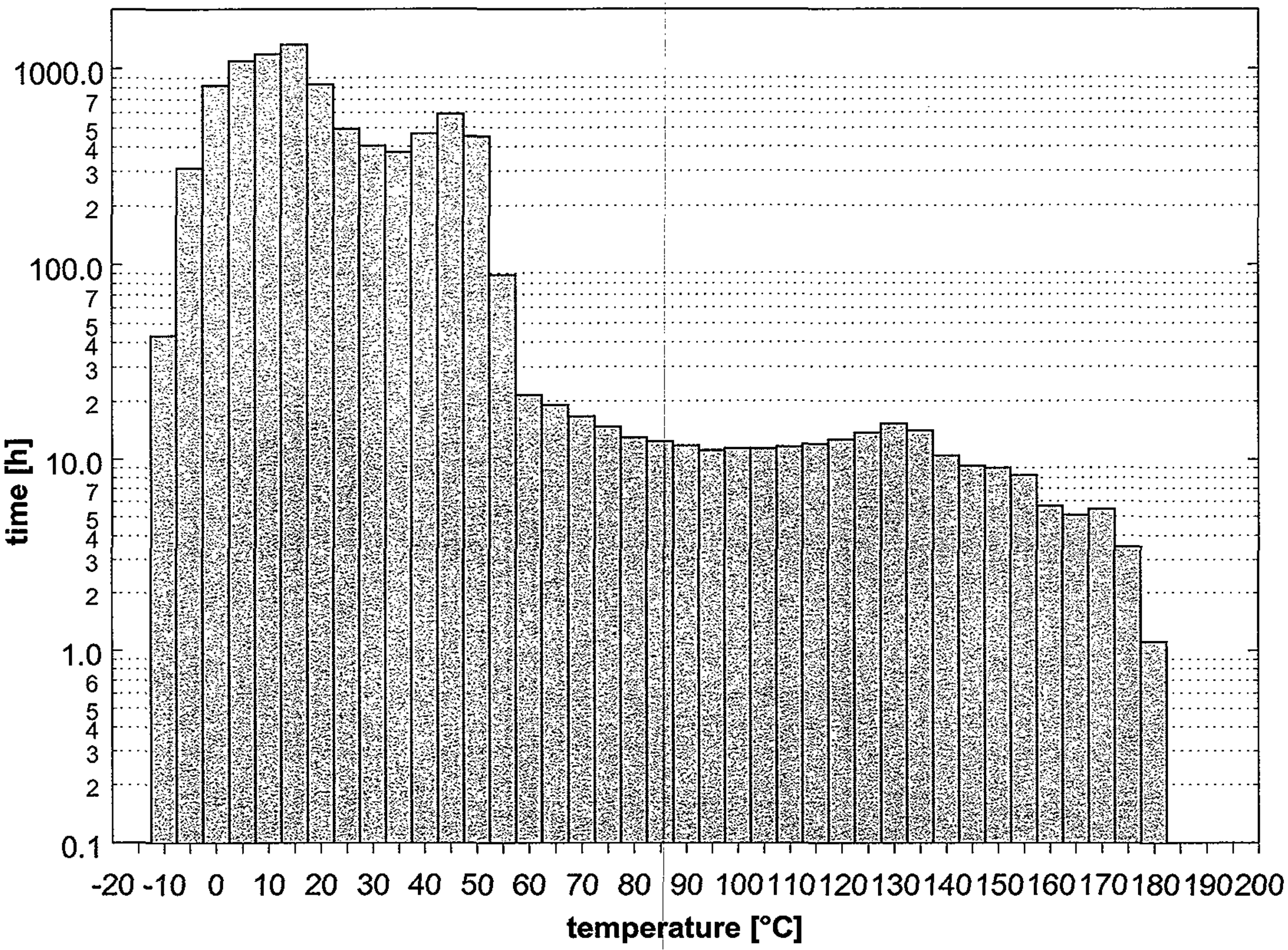
Figure 2b: Shortest acceptable 'failure time' for an absorber coating in different condensation tests. The failure time in each case corresponds to a service lifetime of 25 years.

Figure 3: Flow chart of the test procedure.

Figure 4: Optical homogeneity of the samples used in the Round Robin test.

Figure 5: PC values resulting from the thermal stability test.

Figure 6: PC values resulting from the condensation test.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150
160
170
180
190
200
temperature [°C]

Figure 1a

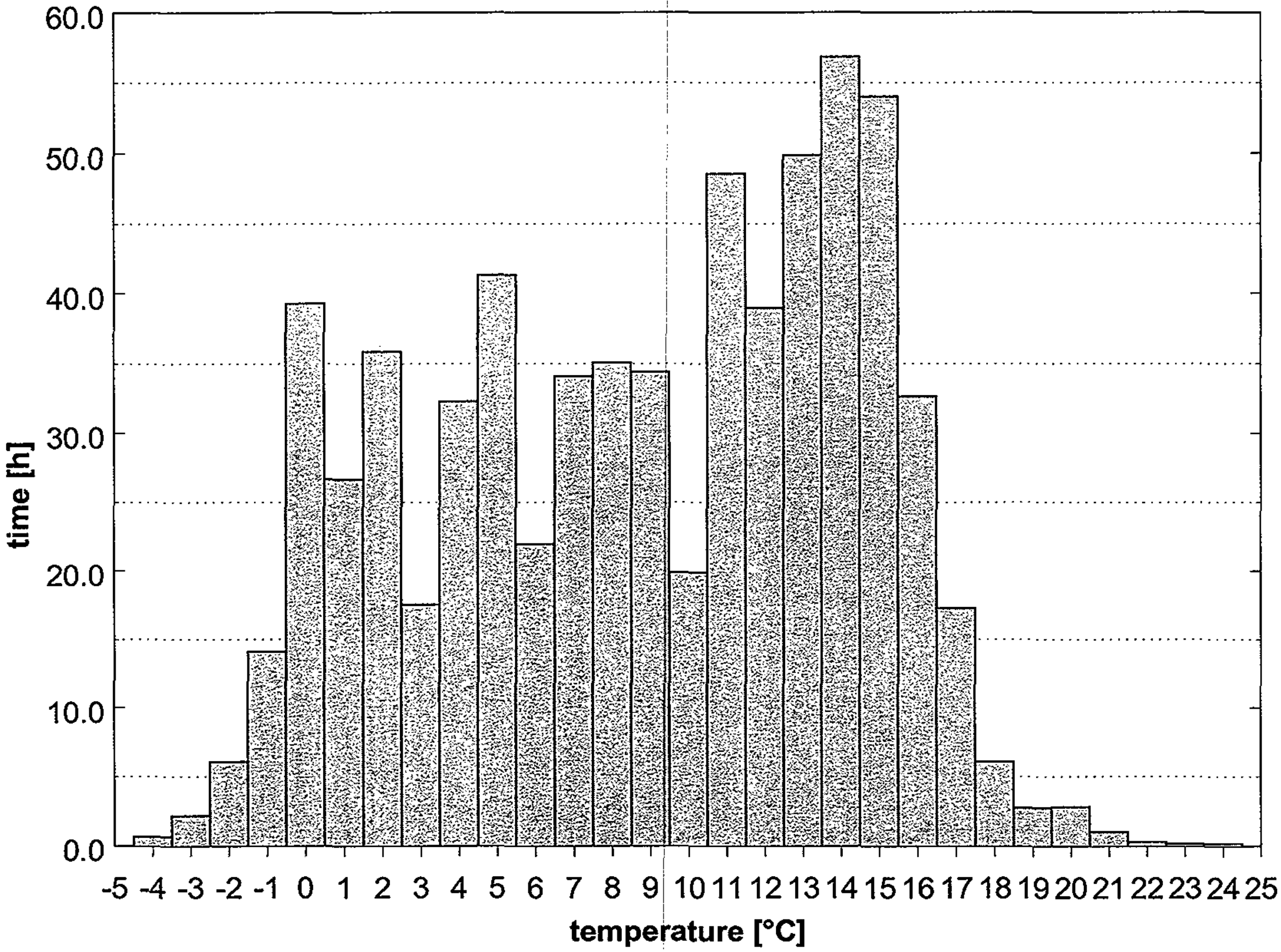
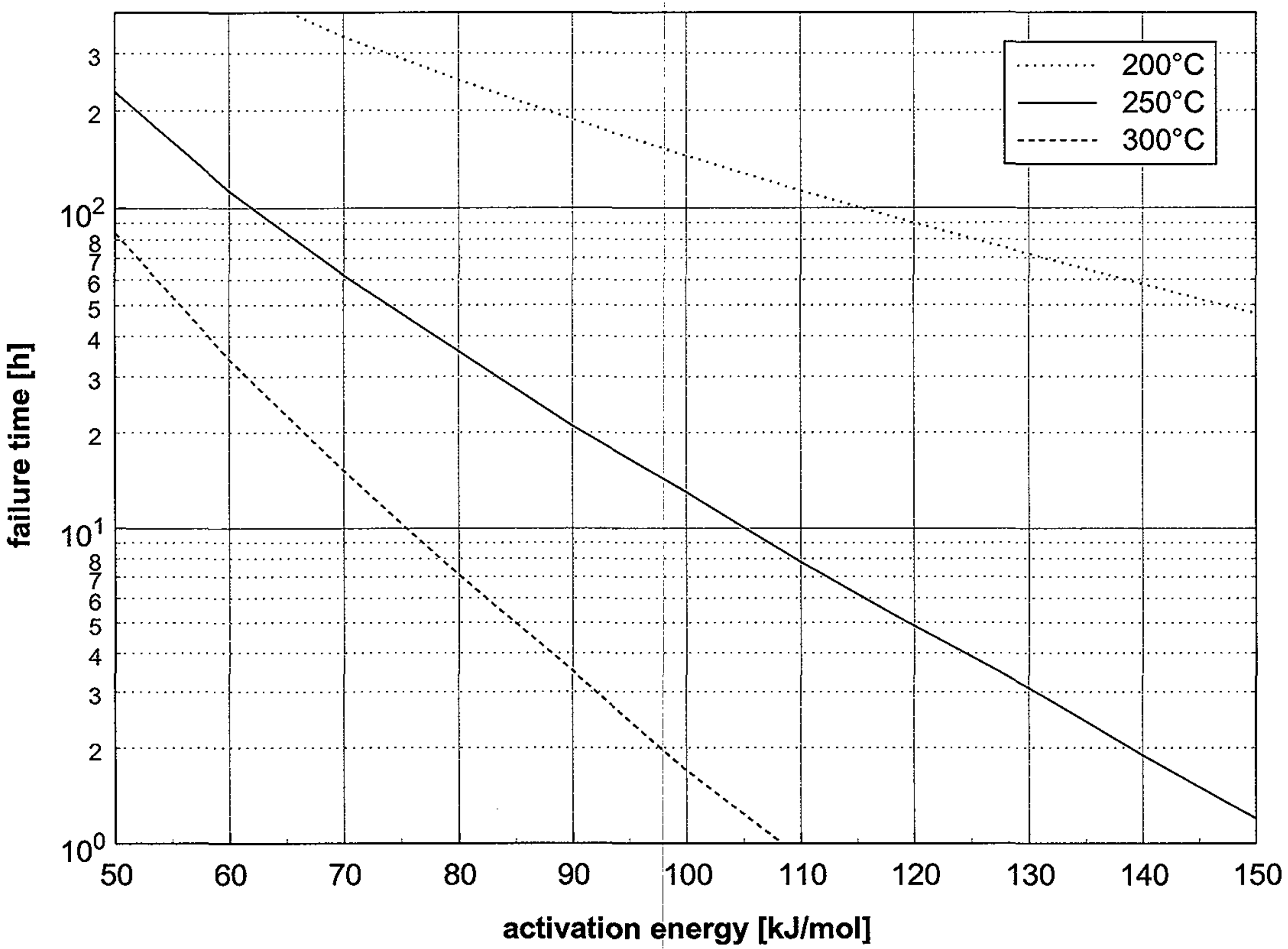

60.0
50.0
40.0
30.0
20.0
10.0
0.0
time [h]
-5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
temperature [°C]

Figure 1b



200°C
250°C
300°C
3
2
10^2
8
7
6
5
4
3
2
10^1
8
7
6
5
4
3
2
10^0
50
60
70
80
90
100
110
120
130
140
150
failure time [h]
activation energy [kJ/mol]

Figure 2a

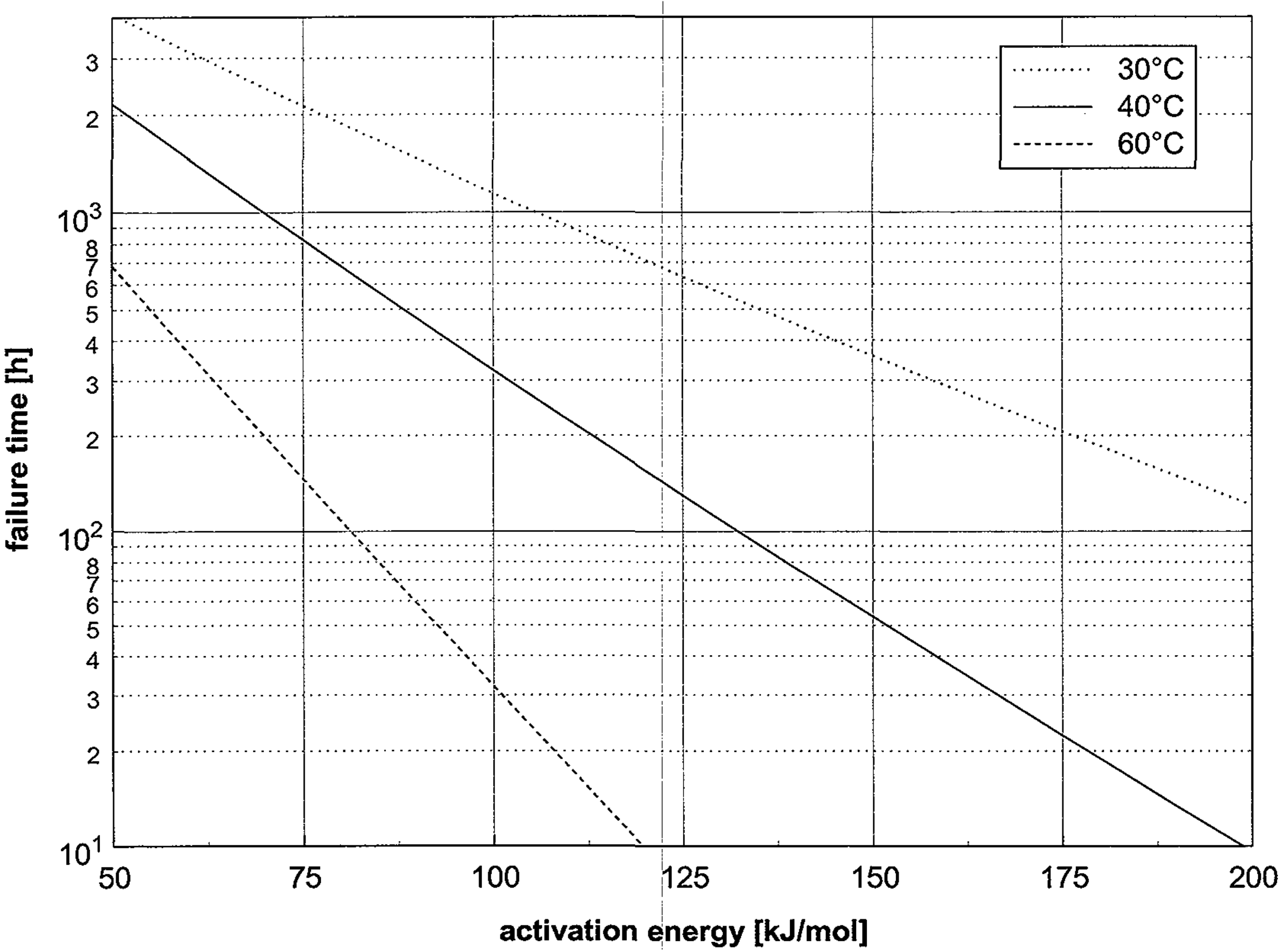

failure time [h]
3
2
10^3
8
7
6
5
4
3
2
10^2
8
7
6
5
4
3
2
10^1
50
75
100
125
150
175
200
activation energy [kJ/mol]
30°C
40°C
60°C

Figure 2b

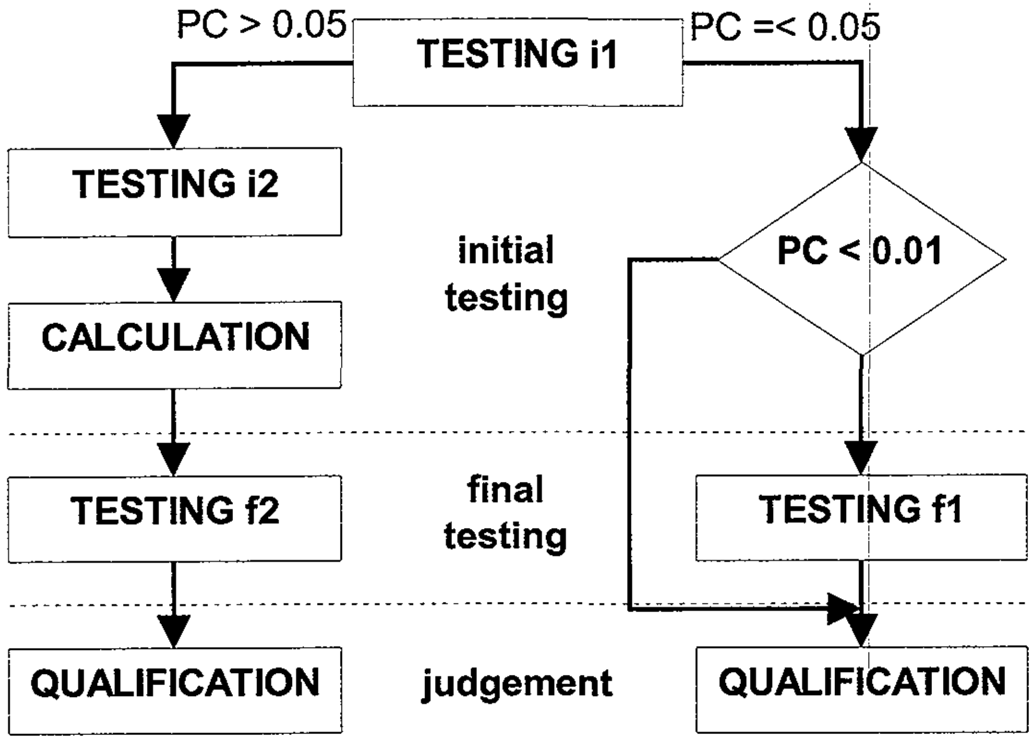

PC > 0.05
TESTING i1
PC =< 0.05
TESTING i2
initial
testing
PC < 0.01
CALCULATION
TESTING f2
final
testing
TESTING f1
QUALIFICATION
judgement
QUALIFICATION

Figure 3

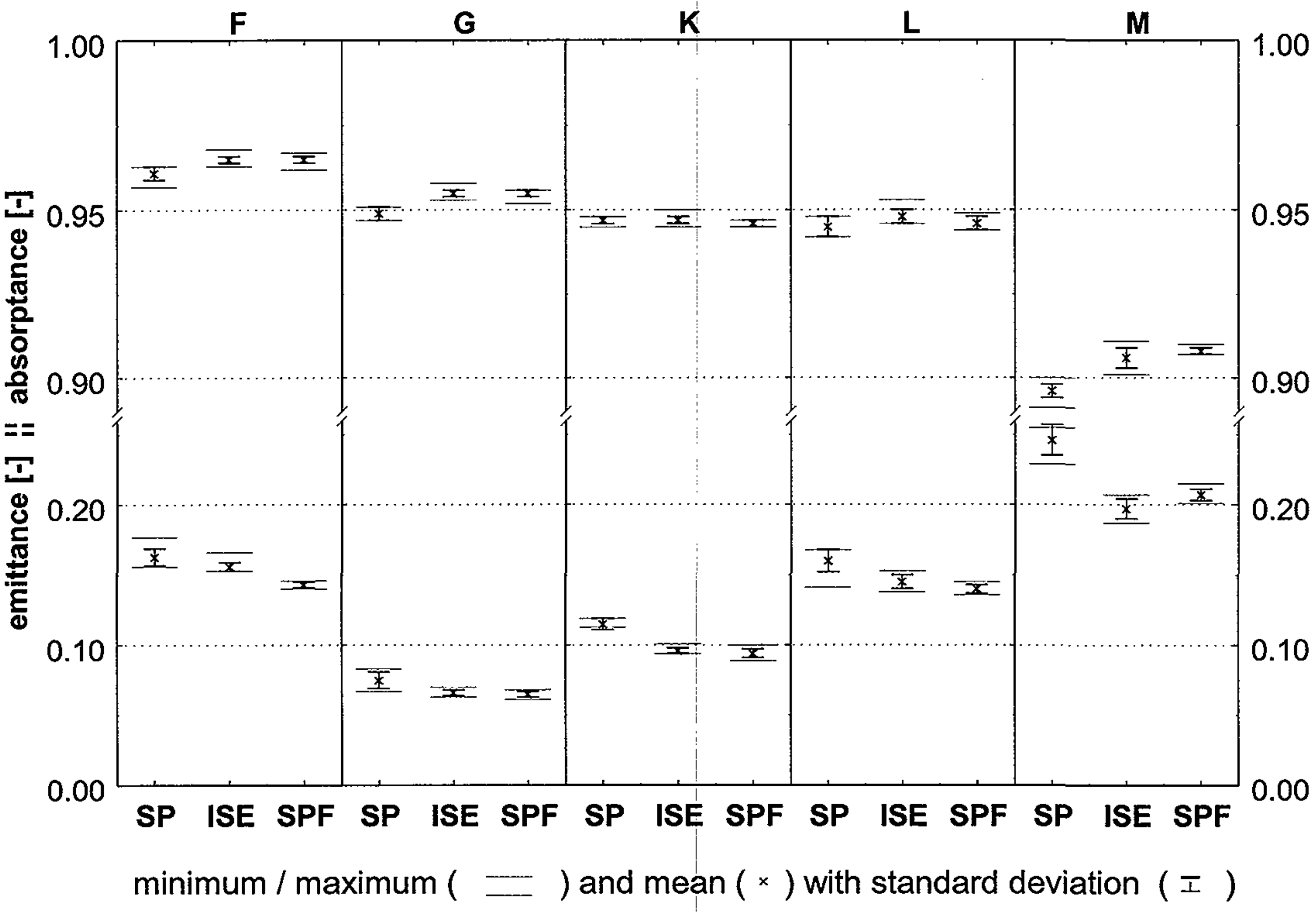

F
G
K
L
M
1.00
0.95
0.90
0.20
0.10
0.00
emittance [-] :: absorptance [-]
SP
ISE
SPF
SP
ISE
SPF
SP
ISE
SPF
SP
ISE
SPF
SP
ISE
SPF
minimum / maximum ( ) and mean (×) with standard deviation (⌶)

Figure 4

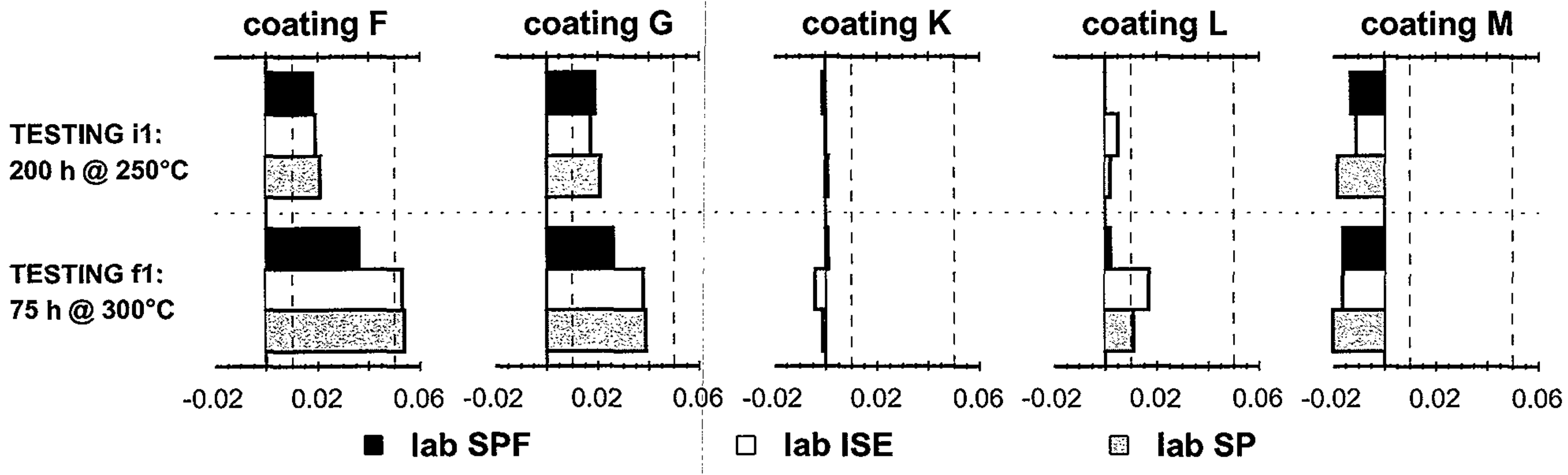

coating F
coating G
coating K
coating L
coating M
TESTING i1:
200 h @ 250°C
TESTING f1:
75 h @ 300°C
-0.02
0.02
0.06
■ lab SPF
□ lab ISE
▨ lab SP

Figure 5

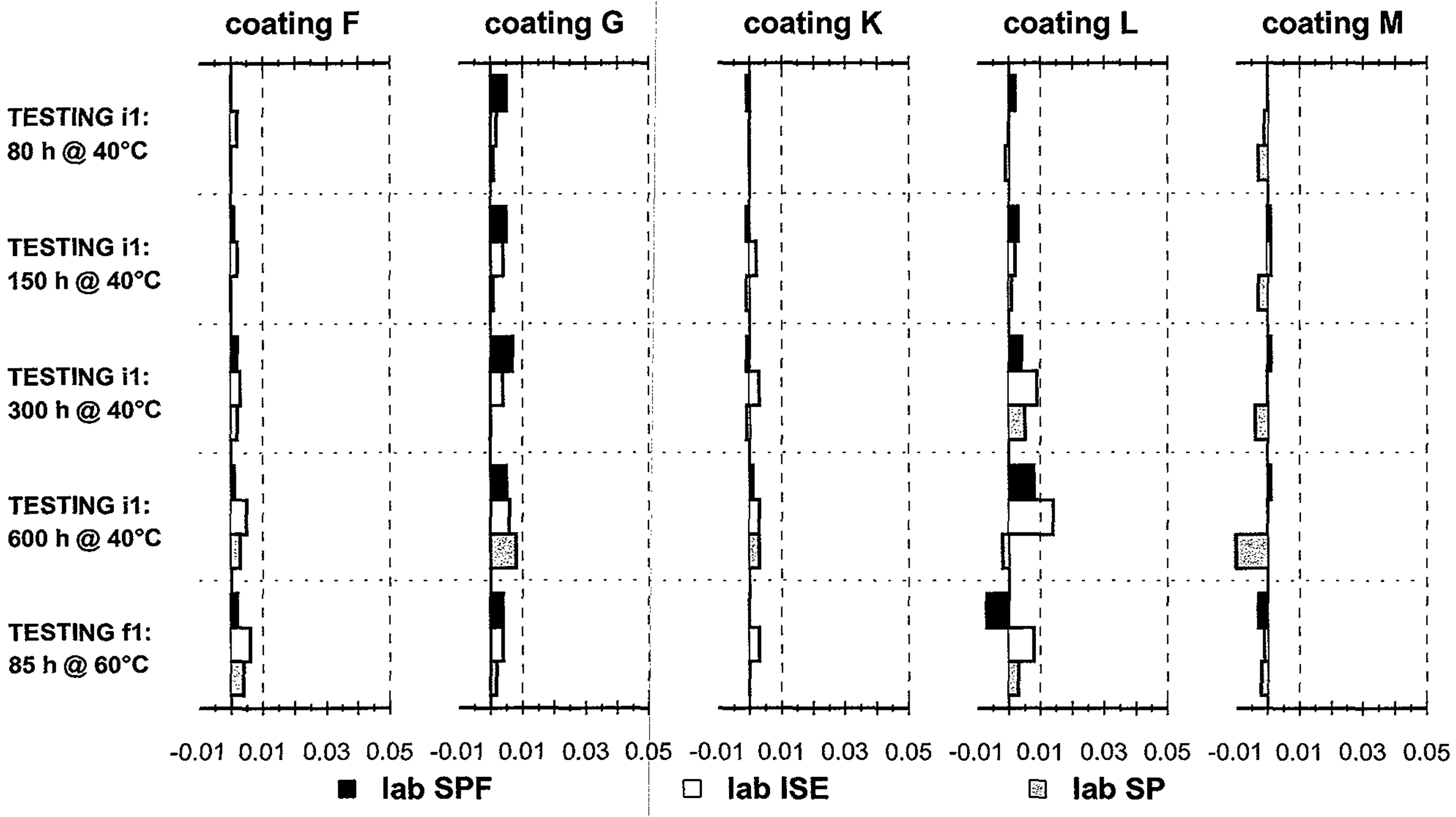

coating F
coating G
coating K
coating L
coating M
TESTING i1:
80 h @ 40°C
TESTING i1:
150 h @ 40°C
TESTING i1:
300 h @ 40°C
TESTING i1:
600 h @ 40°C
TESTING f1:
85 h @ 60°C
-0.01
0.01
0.03
0.05
-0.01
0.01
0.03
0.05
-0.01
0.01
0.03
0.05
-0.01
0.01
0.03
0.05
-0.01
0.01
0.03
0.05
■ lab SPF
□ lab ISE
▨ lab SP

Figure 6