IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
solar heating and
cooling programme

Task III Subtask F
Service Life Prediction for
Solar Collector Components and Materials

WORKSHOP ON SERVICE LIFE OF SOLAR COLLECTOR COMPONENTS AND MATERIALS

Proceedings from the IEA-Task III workshop,
held at the Technical University of Denmark.
December 6-8, 1983.

THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK

PROCEEDINGS FROM
WORKSHOP ON SERVICE LIFE OF SOLAR COLLECTOR COMPONENTS AND MATERIALS

DECEMBER 6-8, 1983 AT THE
TECHNICAL UNIVERSITY OF DENMARK

Peder Vejsig Pedersen
Thermal Insulation Laboratory
Technical University of Denmark

August 1984

This report is part of the work within the IEA Solar Heating and Cooling Programme,
Task III: Performance Testing of Solar Collectors,
Subtask F: Service Life Testing of Solar Collector Components and Materials.

Distribution: unrestricted

Additional copies can be ordered from:
Peder Vejsig Pedersen
Thermal Insulation Lab.
Technical Univ. of Denmark
2800 Lyngby
Denmark

Printed at the
Thermal Insulation Laboratory,
Technical University
of Denmark

ABSTRACT

This report presents the proceedings of the workshop on Service Life of Solar Collector Components and Materials held at the Technical University of Denmark in December 1983. 16 Participants from 10 different countries of the IEA Solar Heating and Cooling Programme, Task III were present at the workshop, and 15 papers were presented. The paper presentation and discussion covered: 1. Accelerated material tests and service life testing, 2. Complete collector tests and, 3. Operational experience with solar collector systems.

The report includes a short summary of each of the presented papers and discussion and conclusions reached in this connection. A proposal for a common experiment of how to measure the inside solar collector environment evolved from the discussions, is also included.

TABLE OF CONTENTS

4. Papers presented at the workshop of Service Life
of Solar Collector Component Materials.
December 6-7 1983, Technical University of Denmark

4.1 Accelerated Materials Tests - Service Life Testing

Sweden.

USA.

PREFACE

IEA SOLAR HEATING AND COOLING PROGRAM

International Energy Agency was formed in November 1974 to establish Cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under af special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contributions to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), supported by a small Secretariat staff is the focus of IEA RD_d activities. Four Working Parties (in Conservations, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976-77, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia
Austria
Belgium
Canada
Denmark
Commission of the European Communities
Federal Republic of Germany
Greece
Italy
Japan
Netherlands
New Zealand
Norway
Spain
Sweden
Switzerland
United Kingdom
United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme, their respective Operating Agents, and current status (ongoing or completed) are as follows:

Task I	Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark (Completed).
Task II	Coordination of Research and Development on Solar Heating and Cooling - Solar Research Laboratory - GIRIN, Japan (Completed).
Task III	Performance Testing of Solar Collectors - University College, Cardiff, U.K.
Task IV	Development of an Insulation Handbook and Instrument Package - U.S. Department of Energy (Completed).
Task V	Use of Existing Meteorological Information for Solar Energy Application Swedish Meteorological and Hydrological Institute (Completed).

Task VI	Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - U.S. Department of Energy (Ongoing).
Task VII	Central Solar Heating Plants with Seasonal Storage - Swedish Council for Building Research (Ongoing).
Task VIII	Passive and Hybrid Solar Low Energy Buildings - U.S. Department of Energy (Ongoing).
Task IX	Solar Radiation and Pyranometry Studies - Canadian Atmospheric Environment Service (Ongoing).
Task X	Materials Research & Testing - Solar Research Laboratory, GIRIN, Japan (Ongoing).

TASK III - PERFORMANCE TESTING OF SOLAR COLLECTORS

The objective of this Task is to advance the understanding of the performance of solar collectors and to develop and utilize common test procedures to assess the performance of a broad class of collectors for use in heating and cooling systems and the performance of domestic hot water systems. These test procedures will allow for the determination of thermal performance, as well as the reliability and durability of solar collectors.

The subtasks included in this project are as follows:

A. Test Procedures to Determine Thermal Performance
B. Development of Reliability and Durability Test Procedures
C. Investigation of the Potential of Solar Simulators
D. Characterization of the Thermal Performance of Solar Collectors
E. Test and Evaluation of Domestic Hot Water System Performance

F. Service Life Prediction for Solar Collector Components and Materials

Subtasks A - C have been completed.

The Participants in this Task are:

Australia, Austria, Belgium, Canada, Commission of the European Communities, Denmark, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland, United Kingdom and the U.S.A.

1. INTRODUCTION

A workshop on Service Life of Solar Collector Components and Materials was held at the Technical University of Denmark. The workshop was initiated as a common activity contributing to the co-operation within the Solar Heating and Cooling Programme of the International Energy Agency (IEA). The participants of the workshop are all active within Task III, Subtask F: Service Life Prediction for Solar Collector Components and Materials.

The workshop included a presentation of 15 different papers and a discussion of important topics covered by the paper presentations. A proposal for a new Task X on research and testing of materials for solar heating and cooling was also discussed by the participants.

Sixteen participants from 10 different IEA-countries took part in the workshop. Six papers covered the topic of "Accelerated Materials Tests and Service Life Testing", 5 papers covered "Complete Collector Tests" and 4 papers dealt with "Operational Experience with Solar Collector Systems".

A list of participants and addresses is given in Annex 1 and 2.

Peder Vejsig Pedersen
Thermal Insulation Laboratory
Technical University of Denmark

2. A SHORT SUMMARY OF THE PRESENTED PAPERS AT THE WORKSHOP ON SERVICE LIFE OF SOLAR COLLECTOR SYSTEM COMPONENTS AND MATERIALS

2.1 ACCELERATED MATERIALS TESTS - SERVICE LIFE TESTING

2.1.1 H. Wennerholm, Sweden - Accelerated testing of absorber materials.

Preliminary results concerning accelerated testing of absorber materials were presented. The accelerated test methods are intended to be used for evaluation and certification of absorber materials. To ensure the validity of the methods tasks were performed to:

1. Identify performance requirements.
2. Develop test methods to evaluate performance and durability according to the requirements.
3. Perform laboratory and field evaluations to ensure that mechanisms of failure in accelerated tests are the same as those to be expected in service.
4. Develop draft standards.

The laboratory and field evaluations were of seven selective and ten non-selective absorber materials. The coatings were of black chrome, anodized aluminium, phtalimide, acrylic, silicone, alkyd, porcelain enamel and polyester. Substrates included steel, stainless steel, aluminium and copper. The key degradation factors which should be covered by the tests were identified as: elevated temperatures, temperature cycles, UV-radiation, moisture, and atmospheric pollutants.

After the tests, a visual examination was always performed, and chalking, flaking, scaling and blistering were evaluated. With some of the tests the absorbtance α and emittance ϵ were measured.

2.1.2 D. Waksman, USA. A comparison and assessment of outdoor and indoor laboratory exposure tests for flat-plate solar collector absorber and cover materials.

In 1977, a program was initiated by the National Bureau of Standards to help provide an experimental basis for the development of consensus standards for assessing the reliability and durability of solar collectors and their materials. In this program, eight different types of flat-plate solar collectors and small scale cover and absorber materials coupon specimens, representative of those in use at that time, were exposed outdoors at four sites located in different climatic regions. Periodic measurements were made of their performance as a function of exposure time. Indoor laboratory aging tests were conducted concurrently on specimens of the same materials to provide basis for comparison with the outdoor exposure tests.

Outdoor exposure conditions at the materials coupon specimen level included "real time" exposure in simulated collectors and exposure to concentrated radiation in machines, described in ASTM E838, having a six to one concentration level. Indoor laboratory tests conducted included exposure to: (1) temperature, (2) combined temperature and humidity, (3) combined temperature and radiation, and (4) thermal cycling (absorber materials only).

Cover materials investigated included: poly(ethylene terephthalate), polycarbonate, poly(vinyl fluoride), poly(methyl methacrylate), fluorinated (ethylene propylene) copolymer and several types of glass fiber reinforced plastics. Absorptive coatings studied included black nickel, black chrome on several types of substrates, copper oxide, lead oxide, aluminum oxide anodized and conversion coatings, black porcelain enamel, and several types of flat black paints.

Changes in the optical properties of these materials were measured as a function of exposure time. Visual observations of changes in appearance were made and microstructural studies were conducted on materials showing visible signs of degradation.

The paper summarizes the results obtained for the outdoor and laboratory aging tests conducted on these cover and absorber materials.

2.1.3 R. Yamasaki, Canada - Research on durability of solar absorber and cover plate materials at the National Research Council of Canada

To permit assessment of the durability of existing absorber and cover plate materials, and also to aid development of more durable ones, a rapid test for estimating long-term durability is desired. The durability of a material depends on two factors, its nature and the environment to which it is exposed.

At NRC in Ottawa, test collectors were instrumented and monitored during exposure outdoors under separate simulated space-heating or circulation and stagnation conditions. Weathering factors which are believed to be deleterious were determined for a period of one year. Test specimens of 15 absorbers of various coatings/substrate combinations were exposed for two years showing a more severe effect from stagnation than circulation condition on the optical properties. By simulating collector conditions which are most deleterious and also reducing idle time, short-term laboratory tests for estimating long-term durability of absorber and cover plate materials will be developed.

2.1.4 P. Andersen, Denmark - Proposal for standardized testing of solar collector coatings.

As a contribution to international co-operation Denmark has been asked to put forward a proposal for testing solar collector coatings. The purpose of the standardized testing is to provide a common basis for evaluation of:

- Anti-corrosion protection of solar collector coatings.
- Ability to retain optical properties with regard to absorption and emission.

The solar collector coatings are situated in an environment where gradual degradation is to be expected. The degradation factors will primarily be:

- High temperatures (as high as about 200 C)
- Temperature variations
- Moisture (often as condensation)
- Radiation

Secondarily there is the possibility of contaminators such as SO_2, Cl^-, O_3 and outgassing products.

The actual conditions in a solar collector box may be characterized by a relative air humidity of about 10-30%, a temperature variation of ÷ 20-180 C and a radiation of up to 1000 W/m^2.

The Danish proposal for testing solar collector coatings consists of two parts. Part 1 includes an exposure to high temperatures, and Part 2 is focussed on simulating the two most severe strains a solar collector absorber will meet. One has the emphasis on radiation exposure and the other stresses humidity and the condensation time. This test is performed in a QUV-test apparatus. Different combinations of the two tests are also made. After the tests, visual evaluations are made, adhesion is determined and α and ε are measured.

2.1.5 U. Frei & J. Keller, Switzerland. - Durability tests of solar absorbtive coatings

Within the framework of the Swiss research program "Reliability and Durability of Solar Energy Systems", 19 different absorber samples have been exposed to accelerated temperature and humidity tests as well as to an outdoor test under natural meteorological conditions. Some of the samples are cut out from collectors identical to those subjected to a stagnation test of two years. Before and after the exposure of the samples the absorptance and the emittance of the coating as well as its mechanical resistance (adhesion) have been measured. Moreover, photographs and scanning electron microscope pictures have been taken. The results of the experiments show that generally high temperatures (200 C) as well as the combined influence of temperature and humidity produce the most pronounced degradations. Furthermore, selective coatings with rather high emittances (i.e. $20\% < \epsilon < 50\%$) are substantially less stable than well made, selective or non selective coatings.

2.1.6 J.W. Martin, USA. - A Stochastic Model for Predicting the Service Life of Photolytically Degraded Polymethyl Methacrylate Films.

A stochastic model has been proposed and partially validated for predicting the service life of a nomical population of polymethyl methacrylate films subjected to photolytic degradation. Here, service life is defined as the time after which an unacceptable proportion of a nominal population of PMMA film subjected to photodegradation have failed; failure occurs when a performance property of the film falls below a predesignated minimum value. The stochastic model has two parts. The first part uses a Poisson distribution in computing the probability that exactly K photon related chain scissions will occur in the film in the interval (0, t). The parameter of the Poisson distribution are made functionally dependent on temperature and the intensity of radiation absorbed. The second part determines the probability that a performance property will be greater than a minimum value after K chain scissions. This part is called the damage process. Together, the two parts of the model form a compound Poisson process. The main points of the models are validated against twenty-five published data sets. The plausibility of the Poisson process was substantiated for modelling the number of chain scissions occurring in the interval (0,t). Also, it was demonstrated that the expected change in two performance properties of the films was functionally related to the expected number of chain scissions.

2.2. COMPLETE COLLECTOR TESTS

2.2.1 B.J. Brinkworth & B.M. Cross, United Kingdom - Outdoor Exposure Trials as Indicators of Collector Durability.

To enhance the economic attractions of solar energy systems improved durability which can lead to a life-cycle of about 20 years is needed. Researchers must provide information to manufacturers on how to eliminate materials and design features which shorten the service life unduly. Unless durable products are cheaper to produce, manufacturers must be forced to provide them by either market forces or mandatory standards designed to protect the customer. Standards are basically of two kinds, codes of practice and qualification tests. Qualification tests should within a short time be able to show clear signs of degradation that would occur in service. They have to accelerate degradation. In UC Cardiff, the outdoor stagnation test has been successful as a qualification test to reveal design shortcomings and material faults which lead to catastrophic failure. Usually one or two years is enough for this.

To evaluate the outdoor stagnation test as an accelerated ageing test 6 out of 20 collectors undergoing tests at UC Cardiff were tested for changes in thermal performance after two years exposure. Comparison of U/n_o values before and after exposure showed only small changes, which was surprising since visual examination had revealed significant discoloration of some absorbers and glazings. Measurements of solar transmittance and solar absorptance before and after cleaning of the inner surface of the glazing and the absorber surface showed only very small changes.

2.2.2 G. Riesch, CEC, JRC, Ispra, Italy - Test Procedures for Thermal Collectors used at the Joint Research Centre, Ispra.

The work at the JRC, Ispra on the durability of thermal collectors comprises tests in the following fields:

- Destructive failures (qualification tests).
- Slow efficiency degradations.
- Outer corrosion.
- Inner corrosion.

The work is mainly executed on complete collectors; studies on samples of materials are only complementary.

The qualification tests can be subdivided in the following items:

--Static pressure test, to check the resistance to overpressure and the leak tightness of the absorber.
--Static and dynamic loads on the collector glazing: (wind and snow pressure, wind suction).
--Hail resistance (of glazing or of evacuated tubes etc.).
--Resistance to thermal shocks.

In the field of slow efficiency degradation the following tests are made:
--Test for rain water tightness.
--Exposure to ultraviolet irradiation.
--Exposure to sun and weather in dry conditions (outdoor exposure).
--Exposure to simulated sun (indoor exposure).

Experimental investigations on the corrosion of the outer parts of the collector (everything except the inside of the absorber) comprise:
--Treatment in a climatic chamber in corrosive atmosphere containing sulphur dioxide, humidity and ozone.
--Normalized corrosion tests in salt mist atmosphere.
--Outdoor correlation exposure in normal operating conditions in two (later three) exposure fields.

The inner corrosion finally is studied by means of a test loop permitting to circulate different liquids through three absorbers with variable parameters such as flow rate or temperature.

A description of tests and results is given in the paper.

2.2.3 G. Riesch, CEC, JRC, Ispra, Italy - Results of slow efficiency decrease tests made at the Joint Research Centre, Ispra.

In the field of slow efficiency degradation the following tests are made:

--Test for rain water tightness.
--Exposure to ultraviolet irradiation.
--Exposure to sun and weather in dry conditions (outdoors).
--Exposure to simulated sun (indoor exposure).

In a pressure chamber collectors can be exposed to rain conditions and cyclic air pressure (200 Pa) which causes the collector to "breath". After test in a normal rain facility the tested collectors are weighed to indicate water penetration. Between 7-281 grams of water had penetrated into 10 collectors which were tested for two hours in this rain facility.

Exposure to UV-degradation showed no significant results for the tested collectors here.

Collectors are also tested outdoors where they are exposed to sun and weather in dry conditions. The ratio of specified integrals of A (temperature difference between absorber and outside air) and B (solar insolation) is a good measure of collector quality. Tests of two collectors for several years showed that changes of this parameter are a good indicator of collector degradation.

Degradation tests can also be made in a special solar simulator.

2.2.4 H. Wenzel, Germany. - Development of Practical Methods for the Determination of the Stagnation Temperature and the Durability of Solar Collectors.

In 1979, a program was initiated to find suitable methods to determine the stagnation temperature of solar collectors. For this purpose, 6 different types of flat plate solar collectors representative of those in use at that time were exposed outdoors in Munich. From September 1979 up to October 1980, the stagnation temperature was measured continuously from 9 a.m. up to 4 p.m.

The findings are shown in a diagram. Curves representing stagnation temperature, ambient air temperature (°C), the monthly hours of sunshine and the monthly rainfall (mm) are shown. A correlation between the hours of sunshine and stagnation temperature or ambient air temperature and stagnation temperature was not found. The best correlation was obtained between the rainfall and the stagnation temperature. This surprising result may come from a few measurements which were carried out between the rainy days while the diffuse radiation was extremely low.

The result of these measurements is that there are only few days in the year for which the same value of stagnation temperature is obtained. If you want to take the stagnation temperature as a scale for the degradation of the collector, then you better take two collectors of the same type, expose one outdoors and one in a room with constant air conditions and protect the cover and the coating by a non-transparent plate.

2.2.5 H. Koelemy, The Netherlands. - Presentation and Evaluation of Indoor Test Procedures for the Durability of Solar Collectors, as Presently used in the Netherlands.

Since 1982 IBBC-TNO have been involved in the development of durability tests for solar collectors. The functional durability of a solar collector in operation is indicated by the decrease of the efficiency over the years.

The efficiency of a solar collector in operation partly depends on the soundness of the joints in the collector case. As a result of the penetration of water into the collector, the efficiency will decrease and corrosion of the collector will be stimulated.

The efficiency may also decrease as a result of airleakage.

A collector, in operation or in stagnation conditions, is exposed to various thermal loads which can affect the joints. Within the test programme the influence of several thermal loads on the efficiency (as measured in the laboratory), the airleakage and the raintightness of the solar collector is to be determined.

Tests and results are descibed in details in the paper.

2.3. OPERATIONAL EXPERIENCE WITH SOLAR COLLECTOR SYSTEMS.

2.3.1 M. Bruck, Austria. - Prevention of corrosion, scale-formation and fouling damage in low - and medium temperature closed loop collector systems.

An overview of the state of the art of the ongoing "corrosion activities" of the "solar group" of the Austrian Standards Institution is presented. Characteristics of low and medium temperature closed loop collector systems are mentioned as well as important properties of circulating water: pH, hardness, alcalinity and conductivity.

Problems with corrosion, scale and fouling occuring in closed loop systems are described, and in conclusion recommendations to prevent corrosion, scale and fouling induced damage are given, with an indication of important requirements for materials, water, inhibitors, antifreezing agents, pretreatment and control.

2.3.2 K.H. Wiedemann, Switzerland. - Corrosion Surveillance of the EIR Solar Heating Plant OASE

For a corrosion surveillance programme of the EIR solar heating unit (OASE), the coolant of the flat plate collector circuit has been controlled and material samples mounted in a circuit by-pass have been tested periodically. The results of the first 13 months are published in the EIR-Report No. 457. This report presents the results of the coolant tests as well as the material samples tests after 25.5 or 33 months of surveillance, respectively.

At the start of the program the composition of the coolant was 65 Vol. % deionized water, 35 Vol. % ethylenglycol, and 15 g/l inhibitor. This composition remained practically constant.

The metal contents of the coolant samples showed large differences, because deposits of metal-containing precipitates varied in amount with time and position. The values of pH and electrical conductivity remained practically constant, however. Therefore, corrosion in the circuit cannot be recorded by pH or electrical conductivity readings or by chemical analysis of coolant samples.

The metal losses at the material samples in the by-pass have been determined after two years:

Aluminium	c. 60 µm;
mild steel St 37	c. 0.3 µm;
red brass RG-5	c. 0.4 µm;
stainless steel Cr Ni 18 10	c. 0.1 µm.

The greatest quantity of metal loss occurred during the first year and increased only slightly during the second year. Pitting corrosion has not been observed on any material.

2.3.3 P. Vejsig Pedersen, Denmark. - Improvement of Reliability, Durability and Expected Lifetime for Solar Collector Systems.

The work to improve reliability, durability and expected lifetime of solar collector systems in Denmark is strongly linked with the collaborative work within the Solar Heating and Cooling Programme of the International Energy Agency (IEA), Task III, Subtasks B and F. The aim here is to achieve knowledge of operating solar collector systems, with respect to reliability and durability, to be able to identify performance requirements, and to make qualified predictions of expected lifetime of solar collector materials and components.

Until now there have been 3 different important activities:

1. To compile and anlyse operational experience with solar collector systems
2. Development of accelerated materials tests and service life testing
3. Development of complete collector tests

To evaluate the reliability and durability of operating solar collector systems in the IEA-participating countries, inspections of 52 solar collector systems in 11 different IEA-countries have taken place since 1982 as a collaborative effort. Researchers at the Thermal Insulation Laboratory have compiled and analysed the reports. Some of the results from the analyses are presented in the paper.

Also some of the results from indoor and outdoor testing of 22 different solar collectors in Denmark are mentioned together with a description of the test methods.

Investigation of how solar collectors can best be integrated into buildings is considered: a very important task in Denmark. The ideal lifetime of a building-integrated solar collector system, which is regularly maintained along with the other building components, should be the same as the normal lifetime of the buildings. At the Thermal Insulation Laboratory several valuable results have been obtained from the work on building-integrated collector designs. Experience with roof-integrated collectors and a new wall-integrated compact solar water heater with natural circulation is also presented in the paper.

2.3.4 P. Vejsig Pedersen, Denmark. - Condensation Problems with Roofintegrated Solar Collectors in Climates in Northern Countries

Condensation on the inside of the glass cover in solar collectors is a well known problem in northern humid climates. Radiation of heat from the glass cover to the sky during nighttime results in a temperature decrease of a few degree Celsius from the ambient temperture. In humid and cold climates this will often lead to condensation on the inside of the glass cover.

Built-in ventilation of a solar collector can often remove the condensate in a few hours when the absorber temperature is incereased due to the solar insolation. We know from experience that many solar collectors, as a sign of a humid atmosphere in the collector itself, will show heavy condensation over long periods, especially in the winter. Three important reasons for this should be mentioned:

1. rainwater might have penetrated the collector if it is not raintight,

2. the collector construction is not protected adequately against humid air coming from the interior of the house to which the collectors are mounted, or

3. the collector construction has not been provided with necessary ventilation openings to the outside air. Here it is important to allow a chimney effect in the collector. Heated ventilation air at the top of the collector, to which condensate from the glass cover has been evaporated, must be able to leave the collector without condensing again in unwanted places. Under some circumstances the result has been a complete degradation of the solar absorber surface treatment after only few years of operation.

The most important aspects to be aware of in avoiding serious condensation problems, as identified from experience gained at the Thermal Insulation Laboratory, are listed in the paper.

3. DISCUSSION AND CONCLUSIONS REACHED IN CONNECTION WITH THE PAPER PRESENTATION AT THE IEA-WORKSHOP ON SERVICE LIFE FOR SOLAR COLLECTOR COMPONENTS AND MATERIALS

The workshop was organized as part of the collaborative work within the IEA Task III Subtask F on Service Life Prediction for Solar Collector Components and Materials.

It is the aim of Subtask F to focus on the development of models to predict service life of solar collector components and materials based on laboratory tests and field studies.

Solar collectors in operating solar systems are inspected to provide a data base on failure modes, degradation mechanisms and environmental factors. The information will be used to identify the reliability and durability test procedures needed. It will also be of help for the development of tests that accelerate degradation and failures of material samples or complete solar collectors in the laboratory, and for defining performance requirements, by comparing accelerated failure rates with failure rates observed in the field. Both the whole solar collector and solar collector system components such as the absorber, the cover or the piping system should be tested.

The following is a summary of the discussion and conclusions reached in connection with the paper presentation.

3.1. ACCELERATED MATERIAL TESTS AND SERVICE LIFE TESTING

Five papers covered outdoor and indoor tests of absorber and cover materials. Participants from USA, United Kingdom, Canada, Switzerland, Sweden and Denmark discussed and compared the results from testing the 2 IEA round robin absorber materials from TI-Limited in UK and PPG in USA. To identify differences in the measurement of optical properties, α and ϵ, Dr Waksman from USA proposed that participants who had taken part in the round robin testing should send the tested samples to him and that he could measure α and ϵ as an extra control of the measurements.

There was a general discussion of how to indicate absorber degradation in a consistent way. Besides changes in α and ϵ and visual appearence, also changes of film thickness, adhesion, and degree of blistering, rusting, cracking and flaking can be measured.

The paper on service life testing by Dr Martin from USA showed that based on knowledge of environmental factors, degradation mechanisms and mathematical modelling it is possible to predict service life of plastic materials as covers in solar collectors. The participants discussed whether it would be possible in the same way to make service life prediction of absorber plate materials.

It was agreed by the participants that the degradation mechanism here were more difficult to model and measure, and that the environment had to be known better than now. And that a data base of environments inside and outside of solar collectors in different areas of the IEA countries could be useful to evaluate test procedures and to identify a methodology for performance requirements under different conditions. A simple presentation of such a methodology, developed at a previous expert meeting is shown in Appendix 2. It was concluded that it would be valuable if the participants could agree on doing a common experiment of how to measure the environment in stagnant and operating solar collectors. A proposal from the Danish participant based on the discussion is shown in Appendix 3.

Several participants showed interest in the new moisture sensor, Epitek SMMS-01/R, which has been developed in Canada and was mentioned in Dr Yamasaki's paper. A brochure with the address of the Canadian manufacturer has been sent to the participants after the workshop.

3.2. COMPLETE COLLECTOR TESTS

In connection with the presentation of 5 papers on complete collector tests there was a long discussion on outdoor stagnation tests. Dr Andersson from Sweden asked an important question: "What should stagnation temperature measurement outdoors indicate about service life"?

It was agreed that many parameters such as, time of day, thermal capacity, wind speed, diffuse light and clouds affect the stagnation temperatures. To avoid the influence of wind, a protective layer of a plastfoil or the use of a ventilator was proposed. Dr Riesch from ISPRA in Italy said that the method proposed by Dr Birnbreier several years ago had proven useful at his laboratory. Mr Pedersen from Denmark mentioned that experiments at the Thermal Insulation Laboratory indicated that also clear day values of stagnation temperatures measured around noon were a good measure of collector quality. Dr Waksman from USA distributed copies of technical papers that indicated that stagnation temperature measurements are as sensitive to changes in the properties of solar collector materials as the thermal efficiency measurement method and much simpler to perform experimentally. The integrated all-day performance method, originally proposed by Dr. Birnbreier is somewhat more disirable since it resolves problems associated with the method based on steady-state temperatures, such as short term transients in solar irradiance and wind speed. However, neither stagnation temperature measurements nor thermal efficiency measurements are very sensitive to changes in the properties of solar collector materials. Mr Bruce Cross from UK mentioned that in his opinion neither changes in efficiency nor changes of the stagnation temperature were effective measures of absorber degradation or other material changes in solar collectors. He proposed to use a solar collector which can be disassembled so material changes can be investigated, i.e. something like what has been done in the USA. It was agreed that it would be important to agree on a common way to make stagnation temperature measurements and moisture measurements in solar collectors. Where do you, for example, measure the stagnation temperature on the absorber - at the midpoint of the absorber or 1/3 the distance from the top? It was agreed that inspections of collectors tested in outdoors stagnation reported with the IEA-inspection format could be useful. Dr Wennerholm from Sweden stated that he had measured stagnation temperatures for 30 solar collectors outdoors in 2-3 years, and that he uses the IEA inspection format to identify changes.

Dr Riesch from the Joint Research Center in ISPRA and Mr Pedersen from Denmark mentioned that also indoor tests of reliability and durability of complete collectors were important to work with. In rainy climates, a solar simulator is useful as it is able to make temperature tests all the year, and in sunny climates, collectors can be exposed to heavy rain and simulated frost and wind conditions in indoor facilities. A measurement of ventilation rates can be used to indicate if condensation will be a problem.

Dr Wenzel from Germany told that at his laboratory he simulated condensation cycles with a cooling machine and accelerated the influence of condensation by using a fluid with a lower PH-value than water.

3.3. OPERATIONAL EXPERIENCE WITH SOLAR COLLECTOR SYSTEMS

Four papers were presented on Operational Experience with solar collector systems. Many participants felt that it was about time not only to look into the solar collector system but also into the whole solar system including the storage system. Mr Tanemura from Japan said that it was his experience that problems of the installation and the control system were the most severe. Other participants indicated that the corrosivity of the heat transfer fluids also was an important problem to look into, for example, the problem of glycol degradation which could lead to glycol acid formation at high temperatures.

Mr Pedersen from Denmark reminded the participants of the fact that it was decided at a previous experts meeting not only to focus on the solar collector, but also on all other components of the solar collector system. This includes the piping system with heat transfer fluids and also the heat exchanger.

It was concluded that periodic inspections of solar systems and solar components were an important activity which, with the help of the IEA-inspection format, should be continued in the future. There was also a general discussion of the question of what this experts group could do to spread the information gathered on operational experience with solar collector systems. The participants agreed that it could be worthwhile to make a compilation of the present knowledge in the group and that a means for this could be that each participant deliver an article as a state of the art of different essential parts of solar collectors and solar collector systems. These should include examples of both good design features and common failures and have proposals of how to avoid failures. It should not have prescriptive suggestions of how to make solar designs, but it should be possible to be used as a guide for designers of solar systems and solar components.

4. PAPERS PRESENTED AT THE WORKSHOP OF

SERVICE LIFE OF SOLAR COLLECTOR COMPONENTS AND MATERIALS

DECEMBER 6 - 7 1983
TECHNICAL UNIVERSITY OF DENMARK

ACCELERATED TESTING OF ABSORBER MATERIALS

Hans Wennerholm

This study sponsored by the Swedish Council for Building Research, was performed to aid in the development of accelerated test methods needed for evaluation and certification (or approval) of absorber materials.

In Sweden solar collectors have to be certified or approved before government grants can be awarded.

This report presents preliminary results of the research concerning accelerated testing. Before draft standards can be developed results from the accelerated tests have to be compared with results from absorbers subjected to outdoor exposure in complete collectors.

In order to meet the stated objectives, tasks were performed to:

1) identify performance requirements
2) develop test methods to evaluate performance and durability according to the requirements
3) perform laboratory and field evaluations to ensure that mechanisms of failure in accelerated tests are the same as those to be expected in-service
4) develop draft standards

The laboratory and field evaluations include seven selective and ten nonselective absorber materials used primarily for building heating and domestic hot water applications. Sometimes but not always the optical properties of the absorbers were measured in conjunction with aging tests. Visual examination after test was always performed. The aging tests include accelerated laboratory exposure as well as outdoor exposure of complete solar collectors.

According to ANSI/ASTM E632-78 key degradation factors were identified as elevated temperature, temperature cycles, UV-radiation, moisture and atmospheric pollutants.

Absorber materials included in the test program were black chrome, anodized aluminium, phtalimide, acrylic, silicone, alkyd, porcelain enamel and polyester. These coatings were selected because they were the only ones available in the Swedish market at the time when the study was started. Substrates included steel, stainless steel aluminium and copper. A single test specimen was used at each measurement point in the laboratory tests.

Elevated temperature (oven aging)

Test specimens were exposed in an oven to elevated temperatures of 150, 200 and 250 °C. While few absorbers in heating or domestic hot water applications would be expected to reach temperatures greater than 175 °C, higher temperatures were used in the laboratory tests to aid in acceleration of degradation.

First specimens were exposed to 150 °C for 4 weeks. The specimens were evaluated by visual examination after the test period. No α- or ε-values were measured after test. See table 1. As you can see no visual change was found after 4 weeks at 150 °C.

Next, another set of test specimens were exposed to 200 °C for 4 weeks. See table 2. No α- or ε-values were measured after test but the specimens were evaluated by visual examination. Here we recognized that some painted absorbers were subjected to chalking. Chalking is by definition that phenomenon manifested in paint films by the presence of loose removable powder, evolved from the film itself, at or just beneath the surface. Chalking may be detected by rubbing the film with the fingertip or other means. There are different degrees of chalking numbered from 10 to 2, where 10 means no chalking and 2 means very much chalking.

Next set of test specimens were exposed to 250 °C for 4 weeks. See table 3. The specimens were examined by visual inspection after test. Here all paints were subjected to heavy chalking, as could be expected. All selective coatings, enamel and number 14 (anodized aluminium) were not subjected to visible degradation.

Thermal cycling for 15 days

Test specimens were exposed to thermal cycling with each cycle consisting of:

1 Heating at 200 °C for 5 hours
2 Cooling to room temperature over a 30 minute period
3 Cooling at -10 °C for 18 hours
4 Warming to room temperature over a 30 minute period

No α- or ε-values were measured after test but the specimens were evaluated by visual examination. See table 4. No chalking but small colour changes were observed.

Ultraviolet radiation, 1000 h

Test specimens were exposed to UV radiation using ASTM G26-77,using a xenon arc accelerated weathering machine of measured solar intensity. A quartz window was used around the light source. There was no glass cover mounted between the light source and the test specimens to simulate the effect of a cover plate in a solar collector. The temperature on the surfaces of the black specimens was approximately 60 °C during the exposures. After test the specimens were evaluated by visual examination. See table 5. No α- or ε-values were measured.

Ultraviolet radiation, 0,5 ppm ozone, 500 h

Test specimens were exposed to UV radiation and 0,5 ppm ozone gas using ASTM G26-77, using a xenon arc accelerated weathering machine of measured solar intensity. A quartz window was used around the light source . There was no glass cover mounted between the light source and the test specimens to simulate the effect of a cover plate in a solar collector. The temperature on the surfaces of the black specimens was approximately 60 °C during the exposures. After testing for 500 h the α- and ε-values were measured. See table 6. No change in α- or ε-values were detected.

Ultraviolet radiation, 0,5 ppm sulphurdioxide, 500 h

This test was performed as the previous test, but instead of ozon gas there was 0,5 ppm sulphur dioxide in the weathering machine. After testing for 500 h the α- and ε-values were measured. See table 7. No changes in α- or ε-values were detected.

Moisture 10 weeks

Test specimens were exposed in a humidity cabinet at 90 °C and 95 percent relative humidity for 10 weeks. After testing the α- and ε-values were measured and visual examination was performed. See table 8. Chalking was evaluated according to ASTM D659 as before. Flaking was evaluated according to ASTM D772. Flaking or scaling is by definition that phenomenon manifested in paint films by the actual detachment of pieces of the film itself either from its substrate or from paint previously applied. Flaking scaling is generally preceded by cracking or checking or blistering, and is the result of loss of adhesion, usually due to stress - strain factors coming into play.

There are different degrees of flaking numbered from 10 to 2, where 10 means no flaking and 2 means heavy flaking.

There is a remark for absorber No. 17: "Blisters 8F". Blistering is evaluated according to ASTM D714. Blistering is reported as a number designating the size of the blisters and a qualitative term or symbol indicating the frequency.
Reference standards have been selected for four steps as to size on a numerical scale from 10 to 0, in which No. 10 represents no blistering. Blistering standard No. 8 represents the smallest size blister easily seen by the unaided eye. Blistering standards Nos. 6, 4 and 2 represent progressively larger sizes.

Reference standards have also been selected for four steps in frequency at each step in size, designated as follows:

D	dense
MD	medium dense
M	medium
F	few

Intermediate steps in size or frequency of blisters may be judged by interpolation.

Moisture, 4 weeks

Test specimens were exposed in a Cleveland humidity cabinet at 38 °C and 100 percent relative humidity for 4 weeks according to ASTM D 2247. After testing the specimens were examined by visual examination. See table 9. The two selective aluminium absorbers were terribly destroyed.

Thermal cycling at high RH, 10 weeks

Test specimens were exposed to thermal cycling at 95 percent relative humidity with each cycle consisting of

1 Heating from 25 to 95 °C at 95 % RH over a 6 h period
2 Heating at 95 °C at 95 % RH for 6 h
3 Cooling from 95 to 25 °C at 95 % RH over a 12 h period

After test the specimens were evaluated by visual examination and α- and ε-values were measured, see table 10. No changes in α- or ε-values were detected.

Neutral salt spray test, 14 days

Test specimens were exposed to neutral salt spray for two weeks using ASTM B117. The salt spray consisted of 5 % sodium chloride and the temperature was 35 °C. The specimens were examined by visual examination after 1, 2, 4, 7 and 14 days. No α- and ε-values were measured. See table 11. Degree of rusting is evaluated according to ASTM D610, where 10 means no rusting and 0 means approximately 100 % of surface rusted. Blistering is evaluated according to ASTM D714 as before.

Water bath, 4 weeks

Test specimens were immersed in distilled water at 23 °C for 4 weeks. α- and ε-values were measured after test. See table 12. The two selective aluminium absorbers were degraded to the greatest extent of all the absorbers

Table 1

150 °C, 4 weeks

No	Substrate	Coating	α	ϵ	Remarks
			t=0	t=0	
1	Aluminium	Phtalimide paint	0,95	0,90	No remark
2	Stainless Steel	Unknown	0,92	0,18	No remark
3	Aluminium	Acrylic paint	0,96	0,93	No remark
4	Aluminium	Silicone paint	0,94	0,89	No remark
5	Steel	Black chrome	0,98	0,23	No remark
6	Aluminium	Alkyd paint	-	-	No remark
7	Steel	Enamel	0,97	0,91	No remark
8	Aluminium	Anodized + Ni	0,98	0,14	No remark
9	Aluminium	Phtalimide paint	-	-	No remark
10	Copper	Blach chrome	0,97	0,44	No remark
11	Steel	Alkyd paint	0,96	0,92	No remark
12	Aluminium	Unknown	0,99	0,17	No remark
13	Stainless steel	Black chrome	0,93	0,15	No remark

Table 2

200 ^{o}C, 4 weeks

No	Substrate	Coating	α t=0	ε t=0	chalking ASTM D 659	Remarks
1	Aluminium	Phtalimide paint	0,95	0,90	4	Dull
2	Stainless steel	Unknown	0,92	0,18	10	-
3	Aluminium	Acrylic paint	0,96	0,93	4	Brown reddish
4	Aluminium	Silicone paint	0,94	0,89	6	Dull
5	Steel	Black chrome	0,98	0,23	10	-
6	Aluminium	Alkyd paint	-	-	2	Violet
7	Steel	Enamel	0,97	0,91	10	-
8	Aluminium	Anodized + Ni	0,98	0,14	10	-
9	Aluminium	Phtalimide paint	-	-	6	-
10	Copper	Black chrome	0,97	0,44	10	-
11	Steel	Alkyd paint	0,96	0,92	10	Dull
12	Aluminium	Unknown	0,99	0,17	10	-
13	Stainless steel	Black chrome	0,93	0,15	10	-
14	Aluminium	Anodized	0,99	0,95	10	-
15	Aluminium	Polyester	-	-	6	-
16	Stainless steel	Anodized + Ni	0,98	0,11	10	Tape loosened ~5 mm
17	Aluminium	Polyester paint	0,96	0,89	10	-

Table 3

250 °C, 4 weeks

No	Substrate	Coating	α t=0	ε t=0	chalking ASTM D 659	Remarks
1	Aluminium	Phtalimide paint	0,95	0,90	2	Dull, white spotted
2	Stainless steel	Unknown	0,92	0,18	10	-
3	Aluminium	Acrylic paint	0,96	0,93	2	Brown reddish
4	Aluminium	Silicone paint	0,94	0,89	2	Grey
5	Steel	Black chrome	0,98	0,23	10	-
6	Aluminium	Alkyd paint	-	-	2	Violet
7	Steel	Enamel	0,97	0,91	10	-
8	Aluminium	Anodized + Ni	0,98	0,14	10	-
9	Aluminium	Phtalimide paint	-	-	2	-
10	Copper	Black chrome	0,97	0,44	10	-
11	Steel	Alkyd paint	0,96	0,92	2	Dull, white spotted
12	Aluminium	Unknown	0,99	0,17	10	-
13	Stainless steel	Black chrome	0,93	0,15	10	-
14	Aluminium	Anodized	0,99	0,95	10	-
15	Aluminium	Polyester	-	-	2	-
16	Stainless steel	Anodized + Ni	0,98	0,11	10	Tape loosened, 80 % of surface
17	Aluminium	Polyester paint	0,96	0,89	6	Dull

Table 4

TEMPERATURECYKLING, 15 days

1 cycle:
- 200 ^{o}C, 5 h
- Cooling to roomtemperature, 30 min
- -10 ^{o}C, 18 h
- warming to room temperature, 30 min

No	Susbstrate	Coating	α t=0	ε t=0	chalking ASTM D 659	Remarks
1	Aluminium	Phtalimide paint	0,95	0,90	10	Dull
2	Stainless steel	Unknown	0,92	0,18	10	-
3	Aluminium	Acrylic paint	0,96	0,93	10	Dull
4	Aluminium	Silicone paint	0,94	0,89	10	Dull
5	Steel	Black chrome	0,98	0,23	10	Small spots
6	Aluminium	Alkyd paint	-	-	10	Weakly greyish
7	Steel	Enamel	0,97	0,91	10	-
8	Aluminium	Anodized + Ni	0,98	0,14	10	-
9	Aluminium	Phtalimide paint	-	-	10	-
10	Copper	Black chrome	0,97	0,44	10	-
11	Steel	Alkyd paint	0,96	0,92	10	Dull
12	Aluminium	Unknown	0,99	0,17	10	-
13	Stainless steel	Black chrome	0,93	0,15	10	-
14	Aluminium	Anodized	0,99	0,95	10	-
15	Aluminium	Polyester	-	-	10	-
16	Stainless steel	Anodized + Ni	0,98	0,11	10	Tape loosened ~5 mm
17	Aluminium	Polyester paint	0,96	0,89	10	Dull

Table 5

ASTM G26-77, 1000 h No cover

No	Substrate	Coating	α t=0	ε t=0	Remarks
1	Aluminium	Phtalimide paint	0,95	0,90	Greyish
2	Stainless steel	Unknown	0,92	0,18	-
3	Aluminium	Acrylic paint	0,96	0,93	-
4	Aluminium	Silicone paint	0,94	0,89	Greyish
5	Steel	Black chrome	0,98	0,23	Very weakly patchy
6	Aluminium	Alkyd paint	-	-	Greyish
7	Steel	Enamel	0,97	0,91	-
8	Aluminium	Anodized + Ni	0,98	0,14	Weakly patchy
9	Aluminium	Phtalimide paint	-	-	-
10	Copper	Black chrome	0,97	0,44	-
11	Steel	Alkyd paint	0,96	0,92	Very weakly patchy
12	Aluminium	Unknown	0,99	0,17	Very weakly patchy
13	Stainless steel	Black chrome	0,93	0,15	-

Table 6

ASTM G26-77, 0,5 ppm O_3, 500 h No cover

No	Substrate	Coating	α t=0	α t=500 h	ε t=0	ε t=500 h
1	Aluminium	Phtalimide paint	0,95	0,95	0,90	0,90
2	Stainless steel	Unknown	0,92	0,92	0,18	0,18
3	Aluminium	Acrylic paint	0,96	0,96	0,93	0,93
4	Aluminium	Silicone paint	0,94	0,94	0,89	0,89
5	Steel	Black chrome	0,98	0,98	0,23	0,23
6	Aluminium	Alkyd paint	-	-	-	-
7	Steel	Enamel	0,97	0,97	0,91	0,91
8	Aluminium	Anodized + Ni	0,98	0,98	0,14	0,14
9	Aluminium	Phtalimide paint	-	-	-	-
10	Copper	Black chrome	0,97	0,97	0,44	0,44
11	Steel	Alkyd paint	0,96	0,96	0,92	0,92
12	Aluminium	Unknown	0,99	0,99	0,17	0,17
13	Stainless steel	Black chrome	0,93	0,93	0,15	0,15
14	Aluminium	Anodized	0,99	0,99	0,95	0,95
15	Aluminium	Polyester	-	-	-	-
16	Stainless steel	Anodized + Ni	0,98	0,98	0,11	0,11

Table 7

ASTM G26-77, 0,5 ppm SO_2, 500 h. No cover

No	Substrate	Coating	α	α	ε	ε
			t=0	t=500 h	t=0	t=500 h
1	Aluminium	Phtalimide paint	0,95	0,95	0,90	0,90
2	Stainless steel	Unknown	0,92	0,92	0,18	0,18
3	Aluminium	Acrylic paint	0,96	0,96	0,93	0,93
4	Aluminium	Silicone paint	0,94	0,94	0,89	0,89
5	Steel	Black chrome	0,98	0,98	0,23	0,23
6	Aluminium	Alkyd paint	-	-	-	-
7	Steel	Enamel	0,97	0,97	0,91	0,91
8	Aluminium	Anodized + Ni	0,98	0,98	0,14	0,14
9	Aluminium	Phtalimide paint	-	-	-	-
10	Copper	Black chrome	0,97	0,97	0,44	0,44
11	Steel	Alkyd paint	0,96	0,96	0,92	0,92
12	Aluminium	Unknown	0,99	0,99	0,17	0,17
13	Stainless steel	Black chrome	0,93	0,93	0,15	0,15
14	Aluminium	Anodized	0,99	0,99	0,95	0,95
15	Aluminium	Polyester	-	-	-	-
16	Stainless steel	Anodized + Ni	0,98	0,98	0,11	0,11

Table 8

90 °C, 95 % RH, 10 weeks

No	Substrate	Coating	α t=0	α t=10W	ε t=0	ε t=10W	Chalking ASTM D 659	Flaking ASTM D 772	Remarks
1	Aluminium	Phtalimide paint	0,95	0,96	0,90	0,90	8	8	Dull. A little white spotted
2	Stainless steel	Unknown	0,92	0,77	0,18	0,24	10	10	Colour change
3	Aluminium	Acrylic paint	0,96	0,96	0,93	0,94	10	10	Dull
4	Aluminium	Silicone paint	0,94	0,95	0,89	0,92	8	10	-
5	Steel	Black chrome	0,98	0,98	0,23	0,18	-	10	Small spots
6	Aluminium	Alkyd paint	-	-	-	-	8	10	Greyish
7	Steel	Enamel	0,97	0,95	0,91	0,90	10	10	A little white spotted
8	Aluminium	Anodized + Ni	0,98	0,92	0,14	0,23	10	10	Greyish, Small spots
9	Aluminium	Phtalimide paint	-	-	-	-	8	6	A little white spotted
10	Copper	Black chrome	0,97	0,97	0,44	0,50	10	10	-
11	Steel	Alkyd paint	0,96	0,95	0,92	0,90	10	10	Weakly dull
12	Aluminium	Unknown	0,99	0,95	0,17	0,20	10	10	Greyish. Small spots
13	Stainless steel	Black chrome	0,93	0,90	0,15	0,13	10	10	Colour change
14	Aluminium	Anodized	0,99	0,98	0,95	0,97	10	10	-
15	Aluminium	Polyester	-	-	-	-	8	10	-
16	Stainless steel	Anodized + Ni	0,98	0,96	0,11	0,09	10	10	Greyish
17	Aluminium	Polyester paint	0,96	0,97	0,89	0,89	10	10	Blisters 8F

Table 9

ASTM D 2247, 38 ^{o}C, 100 % RH, 4 weeks

No	Substrate	Coating	α t=0	ε t=0	Remarks
1	Aluminium	Phtalimide paint	0,95	0,90	-
2	Stainless steel	Unknown	0,92	0,18	-
3	Aluminium	Acrylic paint	0,96	0,93	Greyish
4	Aluminium	Silicone paint	0,94	0,89	-
5	Steel	Black chrome	0,98	0,23	-
6	Aluminium	Alkyd paint	-	-	-
7	Steel	Enamel	0,97	0,91	-
8	Aluminium	Anodized + Ni	0,98	0,14	Strongly greyish
9	Aluminium	Phtalimide paint	-	-	-
10	Copper	Black chrome	0,97	0,44	-
11	Steel	Alkyd paint	0,96	0,92	Very small blisters
12	Aluminium	Unknown	0,99	0,17	Strongly greyish
13	Stainless steel	Black chrome	0,93	0,15	-

Table 10

TEMPERATURECYCLING AT HIGH RH, 10 weeks

1 cycle ·25 - 95 °C, >95 % RH 6 h
·95 °C >95 % RH 6 h
·95 - 25 °C, >95 % RH 12 h

No	Substrate	Coating	α t=0	α t=10W	ε t=0	ε t=10W	Remarks
1	Aluminium	Phtalimide paint	0,95	0,95	0,90	0,90	-
2	Stainless steel	Unknown	0,92	0,92	0,18	0,18	-
3	Aluminium	Acrylic paint	0,96	0,96	0,93	0,93	-
4	Aluminium	Silicone paint	0,94	0,94	0,89	0,89	-
5	Steel	Black chrome	0,98	0,98	0,23	0,23	Small pale spots
6	Aluminium	Alkyd paint	-	-	-	-	-
7	Steel	Enamel	0,97	0,97	0,91	0,91	Small pale spots
8	Aluminium	Anodized + Ni	0,98	0,98	0,14	0,14	-
9	Aluminium	Phtalimide paint	-	-	-	-	-
10	Copper	Black chrome	0,97	0,97	0,44	0,44	-
11	Steel	Alkyd paint	0,96	0,96	0,92	0,92	Very small blisters
12	Aluminium	Unknown	0,99	0,99	0,17	0,17	-
13	Stainless steel	Black chrome	0,93	0,93	0,15	0,15	-
14	Aluminium	Anodized	0,99	0,99	0,95	0,95	Weak colour change
15	Aluminium	Polyester	-	-	-	-	-
16	Stainless steel	Anodized + Ni	0,98	0,98	0,11	0,11	-

Table 11

SS-ISO 3768 (ASTM B 117), 14 days

Neutral Salt Spray Test

No	Substrate	Coating	α t=0	ε t=0	1 day ASTM D610	1 day ASTM D714	2 days ASTM D610	2 days ASTM D714	4 days ASTM D610	4 days ASTM D714	7 days ASTM D610	7 days ASTM D714	14 days ASTM D610	14 days ASTM D714
1	Aluminium	Phtalimide paint	0,95	0,90	10	10	10	9M	10	8M	10	6MD	7	4D
2	Stainless steel	Unknown	0,92	0,18	10	10	10	10	10	10	10	10	10	10
3	Aluminium	Acrylic paint	0,96	0,93	10	10	10	10	10	10	10	10	10	10
4	Aluminium	Silicone paint	0,94	0,89	10	10	8	10	8	8F	8	8MD	8	6MD
5	Steel	Black chrome	0,98	0,23	9	8F	8	8F	7	8F	6	8M	5	8M
6	Aluminium	Alkyd paint	-	-	10	10	10	10	10	10	10	10	10	10
7	Steel	Enamel	0,97	0,91	10	10	10	10	10	10	10	10	10	10
8	Aluminium	Anodized + Ni	0,98	0,14	10	8F	8	8F	7	8F	7	8F	6	8F
9	Aluminium	Phtalimide paint	-	-	10	10	10	10	10	10	10	10	10	4F
10	Copper	Black chrome	0,97	0,44	10	10	10	10	10	10	10	10	10	10
11	Steel	Alkyd paint	0,96	0,92	10	8F	9	8M	8	8MD	8	6MD	6	2MD
12	Aluminium	Unknown	0,99	0,17	10	10	9	10	9	10	8	10	7	10
13	Stainless steel	Black chrome	0,93	0,15	10	10	10	10	10	10	10	10	10	10
14	Aluminium	Anodized	0,99	0,95	10	10	10	10	10	10	10	10	10	10
15	Aluminium	Polyester	-	-	10	10	10	10	10	10	10	10	10	4M
16	Stainless steel	Anodized + Ni	0,98	0,11	10	10	10	10	10	10	10	10	10	10
17	Aluminium	Polyester paint	0,96	0,89	10	10	10	10	10	10	10	10	10	10

Table 12

Water bath, 23 ^{o}C, 4 weeks

No	Substrate	Coating	α t=0	α t=4W	ε t=0	ε t=4W	Remarks
1	Aluminium	Phtalimide paint	0,95	0,95	0,90	0,89	-
2	Stainless steel	Unknown	0,92	0,87	0,18	0,17	-
3	Aluminium	Acrylic paint	0,96	0,96	0,93	0,93	-
4	Aluminium	Silicone paint	0,94	0,94	0,89	0,90	-
5	Steel	Black chrome	0,98	0,97	0,23	0,21	-
7	Steel	Enamel	0,97	0,94	0,91	0,88	-
8	Aluminium	Anodized + Ni	0,98	0,88	0,14	0,47	Dull
10	Copper	Black chrome	0,97	0,97	0,44	0,56	-
11	Steel	Alkyd paint	0,96	0,95	0,92	0,89	-
12	Aluminium	Unknown	0,99	0,94	0,17	0,63	Dull
13	Stainless steel	Black chrome	0,93	0,91	0,15	0,13	-
14	Aluminium	Anodized	0,99	0,99	0,95	0,97	-
16	Stainless steel	Anodized + Ni	0,98	0,97	0,11	0,08	-
17	Aluminium	Polyester paint	0,96	0,96	0,89	0,88	-

"A Comparison and Assessment of Outdoor and Indoor Laboratory Exposure Tests for Flat-Plate Solar Collector Absorber and Cover Materials"

David Waksman

Center for Building Technology
National Bureau of Standards
Washington, DC 20234

Abstract

In 1977, a program was initiated at the National Bureau of Standards to help provide an experimental basis for the development of consensus standards for assessing the reliability and durability of solar collectors and their materials. In this program, eight different types of flat-plate solar collectors representative of those in use at that time, were exposed outdoors at four sites located in different climatic regions. Small scale cover and absorber materials coupon specimens consisting of samples taken from a collector of each of the eight types used and a number of additional materials were exposed concurrently with the full-size collectors. Periodic measurements were made of specimen performance as a function of exposure time. Indoor laboratory aging tests were conducted concurrently on specimens of the same materials to provide a basis for comparison with the outdoor exposure tests.

Outdoor exposure conditions at the materials coupon specimen level included "real time" exposure in simulated collectors and exposure to concentrated sunlight in machines described in ASTM E 838. Indoor laboratory tests conducted included exposure to: (1) temperature, (2) combined temperature and humidity, (3) combined temperature and radiation, and (4) thermal cycling (absorber materials only).

Cover materials investigated included: poly(ethylene terephthalate), polycarbonate, poly(vinyl fluoride), poly(methyl methacrylate), fluorinated (ethylene propylene) copolymer and several types of glass fiber reinforced plastics. Absorptive coatings studied included black nickel, black chrome on several types of substrates, copper oxide, lead oxide, aluminum oxide, anodized and conversion coatings, black porcelain enamel, and several types of flat black paints. Changes in the optical properties of these materials were measured as a function of exposure time. Visual observations of changes in appearance were made and microstructural studies were conducted on materials showing visible signs of degradation.

This paper summarizes the results obtained for the outdoor and laboratory aging tests conducted on these cover and absorber materials.

Introduction

Efforts in the development of reliability/durability tests for solar collectors and their materials have been hampered by the lack of real time and accelerated degradation data that can be correlated with in use conditions. The focus of this paper is on research undertaken at the National Bureau of Standards (NBS) to help generate the data required to develop methods for predicting the long term durability and reliability of flat plate solar collectors and their materials.

Experimental

Coupon specimens of cover plate and absorber materials were subjected to several different types of laboratory and outdoor environmental exposure tests. These specimens consisted of samples taken from the eight types of full-size collectors used in the test program and of several additional materials of interest. Changes in the optical properties of these materials were measured as a function of exposure time. The solar transmittance of the glass materials was obtained using the full cover and a pyranometer (ASTM Standard E 424, Method B [1]). The solar transmittance of nonglass cover materials and the solar absorptance values were obtained from spectral measurements using an integrating sphere (ASTM Standard E 424, Method A [1]). Emittance was measured using a portable instrument employing a thermopile and using an infrared reflectance technique, in accordance with ASTM Standard E 408, Method A [2]. Microstructural studies were conducted on materials showing visible degradation.

Outdoor exposure conditions at the materials coupon specimen level included "real time" exposure in simulated collectors and exposure to concentrated sunlight in machines, described in ASTM E 838 [3]. Indoor laboratory tests included exposure to: (1) temperature, (2) combined temperature and humidity, (3) combined temperature and radiation, and (4) thermal cycling (absorber materials only). Additional materials exposure tests were conducted in xenon arc and tungsten lamp solar simulators.

The outdoor "real time" materials exposures were conducted concurrently with those on full-scale collectors at four outdoor exposure test sites located in Phoenix, Arizona, Cape Canaveral, Florida, Palo Alto, California and Gaithersburg, Maryland. These sites were selected as being representative of the median and extreme climatic conditions found in the United States.

The absorber and cover materials used in this study are identified in table 1. Exposure test conditions are summarized in table 2. The test procedures and simulated collector designs used in this study are described in detail in NBS Technical Note 1136 [4].

Results of Environmental Exposure

The influence of exposure conditions on the optical properties of cover materials is shown in tables 3 and 4. Cover materials E, G, L and M were significantly affected by exposure to high humidity at 70° C and 90 C. Materials J and N showed some whitening and an increase in brittleness when exposed to high humidity at 90°C and material H became very brittle and broke into little flakes after 2000h of exposure at this temperature. Pronounced changes in transmittance were measured for materials G and M at 90°C and 125°C. The transmittance of materials E, G and M changed considerably after exposure to xenon arc radiation at 90°C. Outdoor "real time" exposure of cover material G on both full-size stagnating collectors and cover mini boxes at all four outdoor sites resulted in significant transmittance changes. Material H changed in transmittance after exposure on full-size collectors at Cape Canaveral and Palo Alto and on cover mini-boxes at Cape Canaveral for 480 days with solar radiation levels greater than 17,000 kJ/sq-m/day. Accelerated outdoor exposure of cover materials G, H and M also resulted in changes in transmittance. Material H also became quite brittle after 480 days of "real time" exposure at all four test sites and after accelerated outdoor exposure. Extensive microcracking was observed on the exposed surfaces of materials G, H and J as a result of both "real time" and accelerated outdoor exposure. However, this microcracking was not reproduced by any of the indoor laboratory tests performed. Varying degrees of yellowing occurred with virtually all of the polymeric cover materials exposed.

Absorber materials optical properties are shown in table 5. Many more changes were observed with emittance than with absorptance. Selective coatings, in particular, were affected by temperature and humidity (materials A, D, J, L, M, N and P). Temperature and xenon arc exposure affected the optical properties of materials F, I, L, N and P. Materials A, F, L and N showed considerable optical property changes after exposure to elevated temperature. Optical changes similar to those which occurred in the "real time" outdoor exposure also occurred in the accelerated outdoor exposure of materials D, F, L, N and one of two samples of material A. The optical property changes in material J which were observed for outdoor "real time" exposure only at the Palo Alto site were not observed following accelerated outdoor exposure. Materials A, F, L and N had significant optical changes following the thermal cycling test; material M was slightly affected. This test also caused changes similar to those observed in full-size collectors. The temperature and humidity exposure resulted in unusually severe corrosion.

Comparison and Assessment of Cover Test Procedures

The "real time" outdoor mini-box testing and accelerated outdoor testing both appear to be good ways of duplicating the types of changes observed in full-size collectors. However, outdoor "real time" exposure of 480 days having solar radiation greater than 17,000 kJ/m^2/days is required with the cover mini-boxes to make many of the changes observed at shorter times with full-size stagnating collectors evident. The accelerated outdoor test appears to be capable of doing this in 120 actual exposure days. This is most likely because the temperatures of cover samples mounted on the mini-boxes were typical of those measured on operating solar collectors whereas those of samples in the accelerated test apparatus were typical of those measured on the covers of stagnating collectors. The changes used for comparative purposes include spectral changes, microcracking, embrittlement on bending, visual yellowing, and in the case of PMMA, molecular weight measurements. The amount and extent of microcracking observed in outdoor "real time" exposure appeared to be closely related to the amount of moisture and condensation present at the exposure site with the greatest changes observed at sites with high prevailing humidity i.e., Cape Canaveral rather than Phoenix. The cumulative amounts of solar radiation received at all four sites were roughly comparable. The microcrack patterns observed with accelerated outdoor testing appeared to be finer and less open than those observed with outdoor "real time" exposure. This is probably due to the higher stress levels and loading rates caused by exposure to concentrated solar radiation in conjunction with an intermittent water spray.

The indoor laboratory tests duplicated some but not all of the changes observed outdoors. The temperature and xenon arc radiation tests appeared to be reasonable methods for determining changes due to these parameters. However, the indoor temperature and humidity testing produced changes that were not observed in outdoor exposure under conditions representative of those occurring in actual solar collectors. The primary value of this type of long-term test would be for glazing for trickle down collectors and polymeric water storage tanks where continuous exposure to moisture at elevated temperatures is likely. None of the indoor laboratory tests performed duplicated the extensive microcracking observed outdoors. Some of the glass fiber reinforced plastics produced microcracking as a result of temperature and moisture exposure; however, as mentioned above, the exposure conditions used in this study for humidity testing are believed to be too severe, i.e., there was extensive delamination between the glass fiber reinforcement and the resin in all of the glass fiber reinforced plastics subjected to this test.

With regard to optical measurements, emphasis in current ASTM methods concerned with the durability of cover materials [5, 6, 7] has been placed on the use of integrated spectral transmitance values. These integrated values are not sensitive to spectral changes that occur in a limited part of the solar spectrum, i.e., at short wavelengths in many polymers. Since little or no energy is found in the solar spectrum in this short wavelength region, integrated spectral transmittance values are of little value in detecting these changes which are sensitive indicators of degradation in many polymers. More emphasis should be placed on the analysis of spectral curves obtained using spectrophotometers both with and without integrating spheres. This is also true for absorptance.

Comparison and Assessment of Absorber Test procedures

The test boxes used for the outdoor "real time" exposure for absorber coupon specimens appear to be a good way of exposing a large number of samples to determine their thermal stability under stagnation conditions.

However, the boxes, which were carefully constructed and designed to be watertight, did not have the moisture and condensation problems that were observed for virtually all of the full-size collectors. The problem of how to determine the proper test conditions for assessing the moisture stability of absorber materials is very complex, i.e., the presence of moisture on the inner surface of the glazing of a collector that is stagnating on a clear day does not mean that the relative humidity in the vicinity of the absorber is any where near as high as that in the vicinity of the glazing since absorber temperatures are much higher than cover temperatures. In addition, the presence of porosity in many absorptive coatings means that moisture can condense in these pores at humidities lower than 100 percent RH. It is more likely that moisture would condense out on the absorber at night when it is cool rather than in the daytime. The thermal cycling test was the test which most closely simulated the types of corrosion and other changes that were observed in full-size collectors. In this test, coupon specimens were removed from a chamber at -10 °C and allowed to equilibrate at room temperature prior to being placed in an oven at 177 °C. During this equilibration process, moisture condensed on the test specimen surface; this most likely led to the corrosion observed. The accelerated outdoor test, in which test specimens were exposed to concentrated solar radiation and stagnation temperatures, appeared to provide results comparable to the "real time" coupon specimen exposure, but it was not obvious that the concentrated solar radiation accelerated the photolytic degradation of absorber materials. Laboratory testing at stagnation temperatures brought out a number of thermal stability problems; however, these problems and a number of additional ones were also brought out by the thermal cycling tests. The temperature and humdity testing caused corrosion problems different from those observed in "real time" exposure and is believed to be unduly severe. Exposure to temperature and xenon arc radiation made evident some appearance changes not observed with other tests. The importance of this test will be determined to a large extent by the wavelength transmission of the collector glazing used in conjunction with the absorber.

Acknowledgements

This work was performed as part of a solar collector reliability/durability test program conducted by the National Bureau of Standards (NBS) with funding from the Office of Solar Heat Technology of the United States Department of Energy. The contributions of Willard E. Roberts of NBS in performing optical property measurements, and Elmer R. Streed (now retired from NBS) in areas too numerous to mention are gratefully acknowledged.

References

1. "Test for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials," ASTM E 424-71, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103
2. "Test for Normal Emittance of Surfaces Using Inspection-Meter Techniques," ASTM E 408-71, ibid
3. "Practice for Performing Accelerated Outdoor Weathering Using Concentrated Natural Sunlight," ASTM E 838-81, ibid
4. Waksman, D., Streed, E.R., and Seiler, J., "NBS Solar Collector Durability/Reliability Test Program Plan," NBS Technical Note 1136, National Bureau of Standards, Washington, D.C. 20234
5. "Practice for Evaluation of Cover Materials for Flat-Plate Solar Collectors," ASTM E 765-80, op. cit. 1.
6. "Practice for Exposure of Cover Materials for Solar Collectors to Natural Weathering Under Conditions Simulating Opertional Mode," ASTM E 782-81, op. cit. 1.
7. "Practice for Exposure of Solar Collector Cover Materials to Natural Weathering Under Conditions Simulating Stagnation Mode," ASTM E 881-82, op. cit. 1.

Table 1. Absorber and Cover Test Materials

Code [1]	Absorber Material		Cover Material
	Coating	Substrate	
A	Black Nickel	Steel	—
C	Black Velvet Paint	Copper	—
D	Black Chrome	Steel (nickel flashed)	—
E	Black Lacquer Primer	Copper	FRP[3] Type Ia
F	Copper Oxide	Copper	—
G	Black Porcelain Enamel	Steel	FRP[3] Type II
H	Black Siliconized Polyester Paint	Aluminum	PET[4] / FEP[5,2] (outer) / (inner)
I	Black Chrome	Stainless Steel	
J	Black Chrome	Aluminum	Polycarbonate
K	—	—	Poly(vinyl fluoride)
L	Lead Oxide	Copper	FRP[3] Type Ib
M	Oxide Anodized	Aluminum	FRP[3] Type III
N	Oxide Conversion Coating	Aluminum	Poly(methyl methacrylate)
O	—	—	Glass[6] / Poly(vinyl fluoride)[2] (outer) / (inner)
P	Black Chrome	Copper (nickel flashed)	—

[1] Code letters A through H indicate materials coupon specimens cut from solar collectors A through H. Codes I to P tested at the materials level only.

[2] Materials exposed as a combination in the cover mini-boxes and in the accelerated exposure cover mini-boxes. Materials exposed individually in all other tests. Glass and FEP materials were not studied individually because proven stability.

[3] Glass fiber reinforced plastic.

[4] Poly(ethylene terephthalate).

[5] Fluorinated (ethylene propylene) copolymer.

[6] Ordinary plate glass.

Table 2. Exposure Tests for Cover and Absorber Materials

Exposure Condition	Cover Materials		Absorber Materials	
	Value or Range	Exposure Time	Value or Range	Exposure Time
Temperature (indoor)	a) 70°C b) 90°C c) 125°C	500, 1,000, and 2,000 h	a) 150°C b) 175°C	1,000 and 2,000 h
Temperature and Humidity (indoor)	a) 70°C and 95% RH b) 90°C and 95% RH	500, 1,000, and 2,000 h	90°C and 95% RH	1,000, and 2,000 h
Thermal Cycling (indoor)	—	—	~-10°C to 175°C	5, 15, and 30 cycles
Temperature and Radiation (indoor)	Xenon arc weathering machine a) 70°C b) 90°C	500, 1,000, and 2,000 h	Xenon arc weathering machine at 90°C	1,000 and 2,000 h
Solar Simulator	a) Tungsten b) Xenon simulators with irradiance of ~ 950 W/m^2 and ~ 70°C	30, 60, and 120 cycles*	a) Tungsten b) Xenon simulators with irradiance of ~ 950 W/m^2 and ~ 130°C	30, 60, and 120 cycles*
"Real Time" Outdoor	1 sun at ~ 60°C	80, 160, 240, and 480 days**	1 sun at ~ 140°C and ~ 160°C	80, 160, 240, and 480 days**
Accelerated Outdoor	~ 6 suns at ~ 70°C	6, 12, and 24 equivalent months***	~ 6 suns at ~ 150°C	6, 12, and 24 equivalent months***

* Each cycle consists of 5 h irradiation and 1 h cooling

** Radiant exposure must exceed 17,100 kJ/m^2 for each day to be counted.

*** One equivalent month equals 6.625 x 10^8 J/m^2 (15,835 Langleys).

Table 3. Effect of Laboratory Exposure on Cover Sample Transmittance

Temperature:		70 C			90 C			70 C and 95% RH			90 C and 95% RH			70 C and Xenon Arc			90 C and Xenon Arc		
		Hours Exposure			Hours Exposure			Hours Exposure			Hours Exposure			Hours of Exposure			Hours of Exposure		
Sample	Control	500	1000	2000	500	1000	2000	500	1000	2000	500	1000	2000	500	1000	2000	500	1000	2000
E	0.85	0.83	0.85	0.81	0.84	0.84	0.82	0.72	0.64	--	0.50	0.46	0.30	0.85	0.85	0.84	0.78	0.79	0.77
G	0.84	0.82	0.80	0.79	0.73	0.73	0.78	0.15	0.13	--	0.10	0.08	0.07	0.80	0.78	0.81	0.78	0.78	0.74
H	0.85	0.84	0.85	0.84	0.84	0.84	0.85	0.85	0.85	--	0.84	0.83	--	0.85	0.85	0.85	0.86	0.86	0.85
J	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	--	0.86	0.84	0.74	0.86	0.86	0.86	0.85	0.85	0.84
K	0.89	0.91	0.91	0.91	0.90	0.91	0.91	0.90	0.91	--	0.91	0.91	0.87	0.92	0.93	0.92	0.91	0.89	--
L	0.84	0.83	0.81	0.83	0.83	0.80	0.83	0.54	0.51	--	0.31	0.25	0.21	0.82	0.84	0.83	0.83	0.83	0.80
M	0.78	0.81	0.79	0.80	0.75	0.64	0.66	0.35	0.31	--	0.24	0.23	0.18	0.79	0.78	0.80	0.74	0.73	0.70
N	0.90	0.89	0.90	0.90	0.90	0.90	0.89	0.88	0.89	--	0.76	0.82	0.64	0.89	0.89	0.90	0.89	0.38	0.88

Table 4. Effect of "Real Time" and Accelerated Outdoor Exposure on Cover Sample Transmittance

		Phoenix				Cape Canaveral				Palo Alto				Gaithersburg				Sample 1, Mini-box			Sample 2, Mini-box		
		Days Exposure*				Days Exposure				Days Exposure				Days Exposure				Days Exposure°			Days Exposure		
Sample	Control	80	160	240	480	80	160	240	480	80	160	240	480	80	160	240	480	30	60	120	30	60	120
E	0.85	0.83	0.83	0.80	0.84	0.84	0.81	0.81	0.81	0.85	0.82	0.80	0.77	0.82	0.81	0.80	0.81	0.83	0.84	0.83	0.83	0.83	0.83
G	0.84	0.80	0.80	0.83	0.68	0.81	0.79	0.79	0.63	0.81	0.80	0.80	0.73	0.82	0.80	0.80	0.75	0.83	0.83	0.78	0.81	0.82	0.74
H	0.85	0.85	0.85	0.85	0.85	0.84	0.85	0.85	0.79	0.84	0.85	0.83	0.84	0.84	0.86	0.87	0.85	0.84	0.85	0.81	0.84	0.85	0.81
J	0.88	0.87	0.86	0.86	0.85	0.85	0.85	0.84	0.84	0.84	0.85	0.83	0.83	0.86	0.86	0.85	0.84	0.86	0.86	0.84	0.84	0.86	0.85
K	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.84	0.90	0.90	0.89	0.91	0.89	0.90	0.90	0.90	0.90	0.93	0.92	0.92	0.92	0.92	0.91
L	0.84	0.83	0.83	0.83	0.84	--	-- --	--	0.84	0.84	0.85	0.85	0.84	0.84	0.84	0.82	0.80	--	--	--	--	--	--
M	0.78	0.80	0.74	0.78	0.78	0.78	0.77	0.73	0.75	0.80	0.83	0.74	0.80	0.74	0.75	0.76	0.70	0.77	0.79	0.74	0.81	0.79	0.80
N	0.90	0.89	0.88	0.89	0.89	0.88	0.88	0.88	0.90	0.89	0.89	0.88	0.89	0.89	0.89	0.89	0.88	0.89	0.89	0.89	0.89	0.89	0.89

* 17000 kJ/sq-m (1500 Btu/sq-ft) Minimum Days

° Equivalent Days; 5 Equivalent Days = 1 Month Real Time
= 6.625E+5 kJ/sq m

Table 5. Effect of Laboratory Exposure on Absorber Coatings

Temperature:				150 C					175 C				90 C & 95% RH				90 C & Xenon Lamp		Thermal Cycling Simulated Daily Cycles°			
	Absorptance			Emittance			Absorptance		Emittance		Absorptance		Emittance		Absorptance		Emittance		Absorptance		Emittance	
Sample	Control	1000*	2000	Control	1000	2000	1000	2000	1000	2000	1000	2000	1000	2000	1000	2000	1000	2000	15	30	15	30
A	0.87	0.86	0.86	0.11	0.09	0.13	0.87	0.91	0.11	0.52	0.73	0.84	0.70	0.51	0.86	0.87	0.10	0.11	0.87	0.87	0.16	0.25
C	0.96	0.97	0.97	0.92	0.91	0.92	0.97	0.97	0.91	0.91	0.97	0.97	0.91	0.91	0.97	0.98	0.91	0.91	0.97	0.97	0.91	0.91
D	0.97	0.96	0.96	0.07	0.06	0.04	0.95	0.98	0.07	0.07	0.95	0.95	0.13	0.19	0.96	0.96	0.06	0.06	0.95	0.96	0.06	0.06
E	0.95	0.96	0.96	0.07	0.06	0.07	0.96	0.96	0.09	0.09	0.92	0.92	0.88	0.89	0.96	0.97	0.09	0.09	0.96	0.96	0.66	0.65
F	0.96	0.91	0.90	0.75	0.66	0.65	0.89	0.89	0.47	0.70	0.93	0.93	0.76	0.77	0.90	0.89	0.73	0.71	0.91	0.91	0.64	0.63
G	0.93	0.93	0.93	0.86	0.85	0.85	0.94	0.95	0.86	0.82	0.93	0.94	0.89	0.87	0.94	0.94	0.86	0.86	0.92	0.93	0.85	0.85
H	0.95	0.96	0.96	0.89	0.88	0.88	0.95	0.95	0.88	0.87	0.94	0.94	0.90	0.90	0.95	0.96	0.87	0.87	0.95	0.95	0.88	0.88
I	0.88	--	--	0.19	0.19	--	0.47	--	0.18	--	0.88	--	0.17	--	0.85	--	0.15	--	0.88	--	0.17	--
J	0.98	0.98	0.98	0.14	0.12	0.12	0.97	0.97	0.11	0.13	0.96	0.96	0.22	0.26	0.98	0.98	0.12	0.11	0.97	0.97	0.16	0.12
L	0.99	0.99	0.99	0.29	0.37	0.35	0.98	0.99	0.41	0.38	0.85	0.81	0.81	0.85	0.98	0.90	0.37	0.39	0.95	0.94	0.45	0.43
M	0.94	0.95	0.91	0.10	0.12	0.08	0.93	0.92	0.12	0.12	0.59	0.54	0.62	0.65	0.94	0.95	0.10	0.11	--	0.94	--	0.14
N	0.93	0.85	--	0.51	0.49	--	0.80	--	0.50	--	0.50	--	0.81	--	0.79	--	0.45	--	0.85	--	0.53	--
P	0.96	0.95	0.95	0.08	0.07	0.06	0.95	0.95	0.08	0.10	0.95	0.95	0.12	0.14	0.95	0.96	0.11	0.12	0.95	0.95	0.09	0.09

* Hours Exposure

° -10 C to 175 C

RESEARCH ON DURABILITY OF SOLAR ABSORBER AND COVER PLATE MATERIALS AT THE NATIONAL RESEARCH COUNCIL OF CANADA

R.S. YAMASAKI

The viability of solar heating of buildings depends on the life-cycle cost of a solar hardware, which in turn depends to a great extent on the durability of its main components, i.e., solar absorber and cover plate. Although a 20-year life has been commonly assumed for purposes of estimating the cost of solar heating, relatively little is known with regard to long-term durability of absorber and cover plate materials to severe service conditions encountered in a solar collector.

To permit assessment of the durability of existing absorber and cover plate materials and also to aid development of more durable ones, a rapid test for estimating long-term durability is desired. Now the durability of a material depends on two factors: its nature and the environment to which it is exposed. To generally characterize the microenvironment of the absorber and cover plate, single- and double-glazed collectors, employing absorber of black chrome on a steel plate [absorptivity, 94%; emmissivity, 10%] and cover plate of tempered, low-iron glass with an anti-reflective surface [transmissivity, 96%] and a liquid heat transfer fluid, were instrumented and monitored during exposure at S/60° at Ottawa [latitude, 45° 27'N] under separate simulated space-heating and stagnation conditions. Weathering factors which are believed to be deleterious, i.e., temperature level and cycling, wet-dry cycling, relative humidity, incident UV and solar radiations, were determined for a period of one year. The results are being analyzed statistically and prepared for publication. Table 1 illustrates some of the more important parameters. The maximum temperatures for the circulating collector ranges from 81° C for the absorber to 49° C for the outer cover. The collector ambient is 63°C and the inner cover, 61°C. The corresponding temperatures under stagnation condition are generally higher by a factor of two, thus are expected to substantially accelerate deterioration reactions. The circulating collector absorber underwent some 400 temperature cycles, with a median temperature level at 56°C and increasing and decreasing temperature excursions of 5°C, with corresponding durations of 30 and 20 min. The temperature level and changes are greater under stagnation condition. The number of temperature cycles, however, is substantially lower, probably due to the absence of temperature cycling as a result of intermittent circulation of heat transfer fluid. Wet-dry cycling was determined because plastic cover plate material, such as glass-fibre reinforced polyester, undergo deterioration as a result of wet-dry cycling. Under circulating condition, there were 56 cycles with a median cycle of 2h{wet}-5h{dry}. For stagnation condition the median cycle was slightly longer and occurred at higher temperatures. Solar UV radiation is generally harmful to plastic cover plate material and occurred at 22 MJ/m^2, about 4% that of total solar radiation at 490 MJ/m^2.

In addition, test specimens of 15 absorbers of various coating-substrate combinations, i.e., black chrome, black nickel and organic coatings on copper, aluminum, steel and stainless steel, are being exposed, by attachment to an absorber plate, in double-glazed collectors to separate simulated space-heating or circulating, and stagnation conditions to not only study their behaviour but also to provide comparative specimens to validate short-term test to be developed. The results of two-year exposure are summarized in Table 2. It shows that stagnation condition is generally more severe on optical properties than circulating condition. SEM [scanning electron microscopy] examination also reveals greater erosion of paint coatings, and pitting of copper and steel substrates under stagnation. So far, black nickel is the most durable optically. The foil on which the black nickel is deposited, however, is gradually delaminating from the aluminum substrate. The effect of solar collector environment on various cover plate materials will also be studied.

Finally, exposure studies under controlled laboratory conditions will be carried out to identify those outdoor collector conditions which are most deleterious to the absorber and cover plate materials. By simulating such conditions in the laboratory and also reducing idle time, it is hoped to develop short-term tests for estimating long-term durability of absorber and cover plate materials.

Table 1. Some microenvironmental parameters of circulating and stagnant double-glazed solar collectors during August 1980.

Parameters	Coll.	Abs.	I. Cover.	O. Cover.	C. Amb.	RH
Maximum temp., °C or relative humidity, %	Circ.	81	61	49	63	64
	Stag.	185	122	75	139	
				Median		
	Coll.	No.	Temp., °C	Range, °C	Duration, Min.	
Temp. cycling of absorber during insolation	Circ.	402	56	5-5	30-20	
	Stag.	217	109	8-9	30-30	
	Coll.	No.	Median Cycle			
Wet-dry cycling of outer cover plate	Circ.	56	2 h (wet, 18°C) - 5 h (dry, 26°C)			
	Stag.	53	3 h (wet, 20°C) - 6 h (dry, 29°C)			
Incident solar UV radiation, MJ/m^2				22		
Incident solar radiation, MJ/m^2				490		

Table 2. The effect of two-year solar collector exposures on absorptivity and emissivity of absorbers.

Coating	Circulating Condition		Stagnation Condition	
	$\Delta\alpha$	$\Delta\varepsilon$	$\Delta\alpha$	$\Delta\varepsilon$
Black chrome	0.02 to -0.02	0.01 to -0.01	0.06 to -0.04	0.01 to -0.01
Black nickel (foil)	-0.002	-0.003	0.001	-0.001
Paint	0.008 to -0.018	to -0.03	0.018 to -0.034	0.02 to -0.12

1983.12.02
pa-mr/jb

Proposal for Standardized Testing of Solar Collector Coatings

P. Andersen, Technological Institute in Denmark, Department of Surface Coatings Technology.

Purpose

In connection with participation in international cooperation Denmark has been asked to contribute with a proposal for testing of solar collector coatings. The purpose of standardized testing is to procure a homogeneous basis for evaluation of:

- Anti-corrosion protection of solar collector coatings.
- Ability to retain optical properties with regard to absorption and emission.

Conditions

The solar collector coatings are situated in an environment where gradual degradation is to be expected.
The degradation factors will primarily be:

- High temperatures (as high as appr. 200°C)
- Temperature variations
- Moisture (often as condense)
- Radiation.

Secondarily there is the possibility of contaminators such as SO_2, Cl^-, O_3 and outgassing properties.

The actual conditions in a solar collector box may be carachterized by a relative air humidity of appr. 30-100%, a temperature variation of ÷ 20-180°C and a radiation of max. 1000 W/m^2.

Different countries have carried out testing of solar collector coatings and have developed individual national test programmes. A survey of these test procedures to be seen in Appendix.

Analysis

Both selective and non-selective solar collector coatings have been tested.

It appeared that there were variations with regard to relevance and suitability of the test methods, and some of them were unable to select the durability of the different solar collector coatings. The reason may be that the method is unfit for this purpose but some examinations show that the chosen solar collector coatings are of relatively good quality and that the problem here was too short an exposure period.

Synthesis

A survey of all test procedures showed that for the two types of solar collector coatings differentiation can be obtained at high temperatures and by a combination of condense and radiation.

Laboratory exposure like immersion in water and to neutral salt spray (fog) generally seems to be too severe for solar collector coatings. This means that almost all solar collecto coatings decompose - this, however, has no correlation to natural environment.

Contrary to this, exposure in humidity cabinet without condense only gives selection at very high temperatures. This has no bearing in natural environment and seems to be a temperature/ degradation-factor more than degradation because of moisture absorption.

We consider it relevant to expose the solar collector coatings partly to high temperatures partly to radiation and moisture (condense); and to examine the effect of a combination of both.

Our proposal for standardized testing of solar collector coatings in the following diagram:

Proposal for testing of solar collector coatings:

TEST NO. 1	Temperature	Time of exposure
Selective solar collector coatings	200°C	24 h, 168 h 336 h, 672 h
Non-selective solar collector coatings	150°C	- " -
TEST NO. 2		
ASTM G 53 Light source UV-A	Radiation temp./time	Condense temperature/time
	60°C/4 h	40°C/8 h
	60°C/8 h	40°C/4 h
TEST NO. 3		
Test No. 1 + Test No. 2		
TEST NO. 4		
Test No. 2 + Test No. 1		

Evaluation

Visual evaluation according to ISO 4628.

Determination of adhesion according to DS/ISO 2409

Measuring of α

Measuring of ε

Comments to above mentioned test procedure

As previously mentioned solar collector coatings are exposed to high temperatures, temperaturevariations, radiation and humidity in varying proportions amongst other things dependant on season, geographical placing and operational conditions.

This accellerated testing should include these 4 actions.

With the QUV-test apparatus it is possible to simulate these actions through cyclic and continuous test procedures.

The duration and intensity of the cycles is an important factor in our considerations.

The optimum test program will off course be to simulate accurately the practical operational conditions which however is unrealistic due to the limitations of accelerated testing.

Therefore we have selected two different types of strain. One with the mainweight on radiation and the other focusing on the condensation time in order to examine the influence of these parametres on solar collector coating.

The high temperatures which are introduced both alone and before and after QUV-testing is meant for reveal the significance of the stagnation periods.

We have in this aspect chosen 4 exposure times in order to see a possible relationship between coating degradation and time.

TECHNOLOGICAL INSTITUTE

SURFACE COATINGS TECHNOLOGY

APPENDIX 1

TEST PROCEDURES

EXPOSURE	DENMARK	SWEDEN	FRANCE	THE NETHERLANDS	SWITCHERLAND	CEC	OTHER STANDARDS	COMMENTS
HUMIDITY EXPOSURE	MIL STD 810C DIN 50017	ASTM D 2247 CONSTANT EXPOSURE: °C %RH H 90 95 1680 38 100 672 100 100 72			CONSTANT EXPOSURE: °C %RH H 50 98 672 95 98 672		ASTM D 1735 ASTM D 2246 ASTM D 2247	
SALT MIST EXPOSURE	ASTM B 117 ISO 3768	ASTM B 117	NF P 34-501 (11)	ASTM B 117		ASTM B 117-73 IEC 68-2-11 MIL STD 310 B	ASTM B 287 ASTM D 1654 BR 77	CEC: 500 h NF: 60 h
WEATHER O-METER EXPOSURE	ASTM G 26	ASTM G 26					ASTM G 23 ASTM G 53	
WATERBATH EXPOSURE	ISO 1521	ISO 1521	NF P 34-501 (13)		672 h			NF: 1000 h
OVEN TEMPERATURE EXPOSURE	BS 5918	672 h at: 150, 200 and 250°C			672 h at: 50, 100 and 200°C			
THERMAL CYCLING EXPOSURE		-10/200°C 25°C-95°C (95% RH) 50°C-100% 0%RH						
CYCLING EXPOSURE			NF P 34-501 (12)	40°C-100% 1h 80°C-<50%-1000 W/m^2 1h 80→20°C 2h			ASTM D 2933	

DURABILITY TESTS OF SOLAR ABSORPTIVE COATINGS

U. Frei
Technical Highschool (ITR)
CH-8640 Rapperswil
Switzerland

J. Keller
Swiss Federal Institute for Reactor Research (EIR)
CH-5303 Wuerenlingen
Switzerland

Abstract

Within the framework of the Siwss research program "Reliability and Durability of Solar Energy Systems", 19 different absorber samples have been exposed to accelerated temperature and humidity tests as well as to an outdoor test under natural meteorlogical conditions. Some of the samples are cut out from collectors identical to those subjected to a stagnation test of two years. Before and after the exposure of the samples the absorptance and the emittance of the coating as well as its mechanical restistance (adhesion) have been measured. Moreover, photographs and scanning electron microscope pictures have been taken. The results of the experiments show that generally high temperatures (200° C) as well as the combined influence of temperature and humidity produce the most pronounced degradations. Furthermore, selective coatings with rather high emittances (i.e. 20 % < ε < 50 %) are substantially less stable than well made, selective or non selective coatings.

1. INTRODUCTION

The service life of a solar energy system strongly depends on the longterm behaviour of the solar collector. On the one hand this component is exposed to varying weather conditions, on the other hand relatively high temperatures of the absorber plate may occur. One crucial part is the absorptive coating because its absorptance and emittance as well as its mechanical stability may be affected by temperatur and humidity.

Within the framework of the Swiss research program "Reliability and Durability of Solar Energy Systems", 19 different absorber samples (selective, partly selective and non selective ones) have been exposed for a few weeks to controlled temperature and humidity influences. Moreover, further samples have been exposed outdoors as well as in a water bath. Prior to and after each test the following properties have been measured: the absorptance in the wavelength range of the solar spectrum, the emittance in the thermal infrared as well as the adhesion on the substrate. Further indications are obtained by visual inspection, photographic and electronmicroscopic pictures.

The absorber samples originate from solar collectors available on the Swiss market. Some of these collectors are also tested as whole components in stagnation tests being part of another section of the program mentioned above. In addition a few manufacturers of absorptive coatings were participating to the absorber tests. Two coatings are samples made at ITR. Finally two samples were selected as a participation to a so called round robin test in the laboratories of members of the International Energy Agency (IEA).

This contribution is a summary of the final report "Beständigkeit von Absorberbeschichtungen" /1/ which may be ordered at ITR.

2. TEST CONDITIONS AND CHARACTERISTIC PROPERTIES OF THE ABSORBER SAMPLES

The following tests were selected:

A: No exposure (reference samples)

B: Outdoor-Test

- Site: Rapperswil
- tilt: 45°
- duration: 16 weeks
- registrated ambient data: air temperature, humidity, fall (type, amount), insolation, dust contamination

C: Water bath exposure

- duration: 4 weeks
- deionized water
- water temperature 20° C ± 1° C

D: Temperature test 100° C

- duration: 4 weeks
- air temperature 100° C ± 1° C
- relative humidity 0 %

E: Temperature test 200° C

- duration: 4 weeks
- air temperature 200° C ± 1.5° C
- relative humidity 0 %

F: Temperatur/humidity test 50° C/100 % relative humidity

- duration: 4 weeks
- air temperature 50° C ± 0.5° C
- relative humidity 98 ÷ 100 %

G: Temperature/humidity test 95° C/100 % relative humidity

- duration: 4 weeks
- air temperature 95° C ± 1° C
- relative humidity 98 ÷ 100 %

Each sample was exposed only to one of the conditions B to G, i.e. no cumulative tests were performed.

The different test conditions had to be selected according to the various effects which can happen within a collector. First the influence of the solar irradiance has to be taken into account (outdoor test). Second, measurements of the stagnation temperature of flat plate collectors showed that the maximum collector temperature does not exceed 200° C. Thus this temperature was chosen as the highest one in our tests (temperature tests). Third, a few collectors show condensation effects on the inner surface of the front cover indicating a temperature decrease below the dew point (temperature/humidity test). Finally the condensation may also wet the absorber surface (water bath).

The selected test durations are based on investigations performed at the National Bureau of Standards (NBS), USA /2/. These tests show significant degradations of the absorptive coatings only within the first four weeks of exposure.

After each test B to G the absorptance α in the wavelength of the solar spectrum and the emittance ε in the infrared were measured and compared with the initial values. Qualitative indications of possible changes are given by photographic and electron-microscopic pictures as well as by X-ray spectra revealing the chemical composition of the coating. Finally a so called cross-cut-test give information about the adhesion of the coating upon the substrate (Gt0: very good adhesion, Gt5: poor adhesion).

3. RESULTS

In Table 1 the initial values of the samples are shown. The coatings can be classified in selective ($\varepsilon \leq 20$ %), partly selective (20 % $< \varepsilon < 50$ %) and non selective ones ($\varepsilon \geq 50$ %).

Sample No.	Name (Manufacturer or collector)	measured values (reference)		Selectivity class	Gt
		α_A (%)	ε_A (%)		
1	Arbonia	93.7	12	s	0
2	Solar Tech	92.1	75	n	0
3	*	93.0	89	n	0
4	*	93.5	90	n	5
5	Batitherm	93.7	88	n	0
6	Aemisegger	91.9	80	n	0
7	Stiebel Eltron	94.5	86	n	1
8	Rüesch	93.9	85	n	1
9	VDM-Evidal	90.0	20	s	0
10	Bucher/AWL	87.3	17	s	0
11	TI Drynamels (IEA 1)	93.7	86	n	0
12	Koenig	90.0	17	s	0
13	Miromit	85.9	23	t	0
14	*	90.3	26	t	0
15	Schweizer	90.0	6	s	0
16	Indukta	85.8	47	t	1
17	Elox black (ITR)	67.1	88	n	0
18	Black Spezial (ITR)	92.7	88	n	5
19	PPG (IEA 2)	92.9	19	s	0

Table 1: Absorptance α_A, emittance ε_A, selectivity class and cross-cut class Gt of the reference samples. s: selective, t: partly selective, n: non selective.

*: The manufacturer of the coating or of the collector does not want his name to be published.

In Fig. 1a) and 1b) the variations of the absorptance of the non selective and of the selective/partly selective coatings after the tests B to G are shown. As an example the results of the samples 3 and 7 and of the samples 1 and 16 respectively are connected by solid lines. As a summary, in Fig. 2 the arithmetic average of the absorptances of the non selective (1), the selective (2) as well as the combination of the selective and partly selective (2 3) samples are given. As an illustration Fig. 3a) and 3b) show the reflectance $1-\alpha$ as a function of wavelength valid for a stable and an unstable coating.

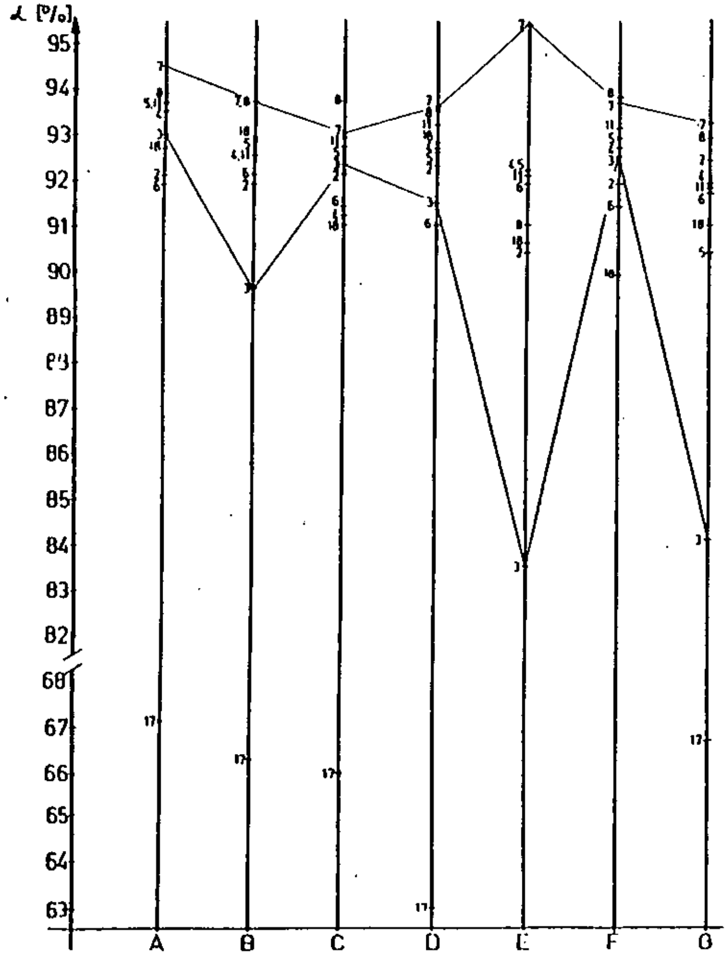


Fig. 1a: Absorptance α of the non selective coatings.

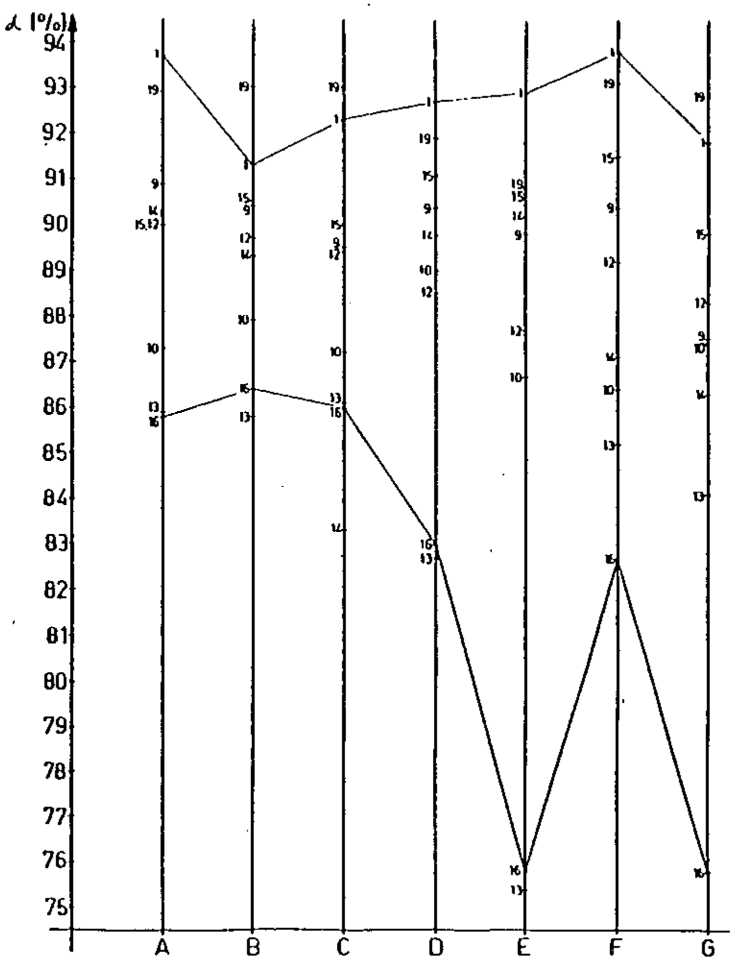


Fig. 1b: Absorptance α of the selective and partly selective coatings.

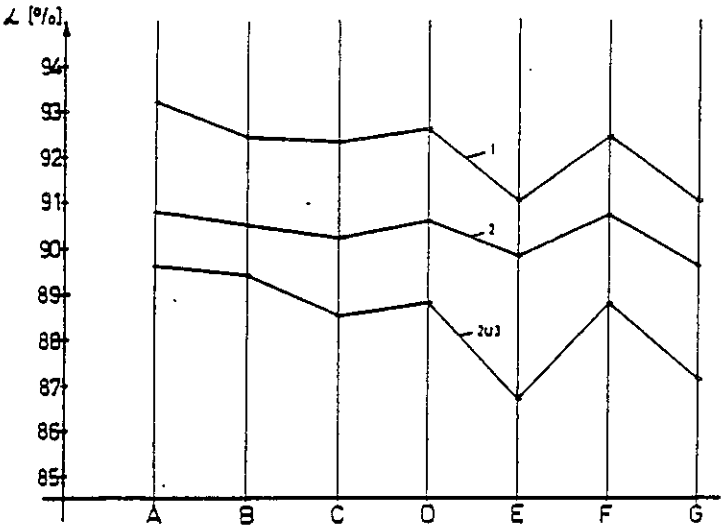


Fig. 2: Average of the absorptances of the non selective (1), selective (2) as well as of the combination of the selective and partly selective samples.

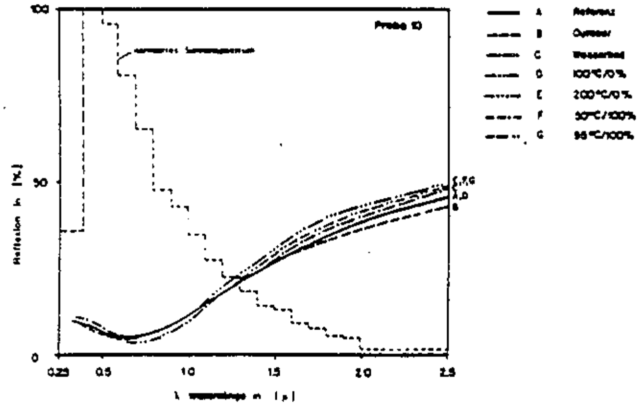


Fig. 3a: Example of a stable coating.

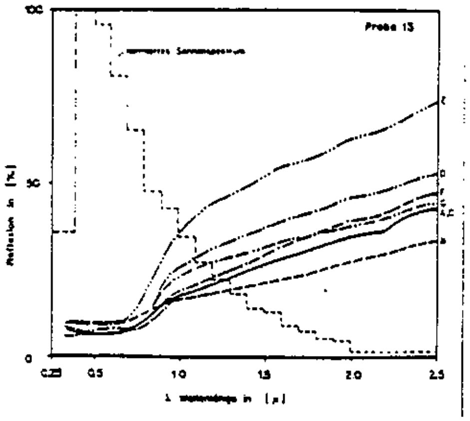


Fig. 3b: Example of an unstable coating.

The results indicate that selective and non selective coatings are in a similar way sensitive to environmental influences. In particular, both classes are affected by high temperatures as well as by temperature/humidity combinations (tests E and G). The behaviour of the partly selective coatings is similar to the remaining ones, but the stability is substantially worse. Finally, the emittance of the selective and partly selective samples show similar variations as their absorptance (Fig. 4).

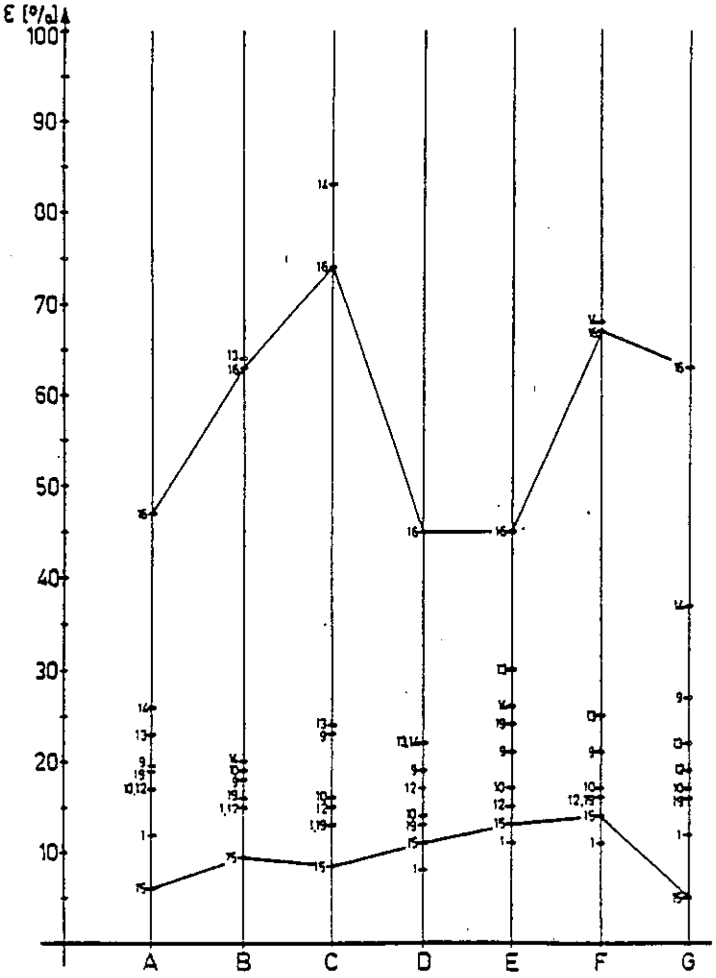
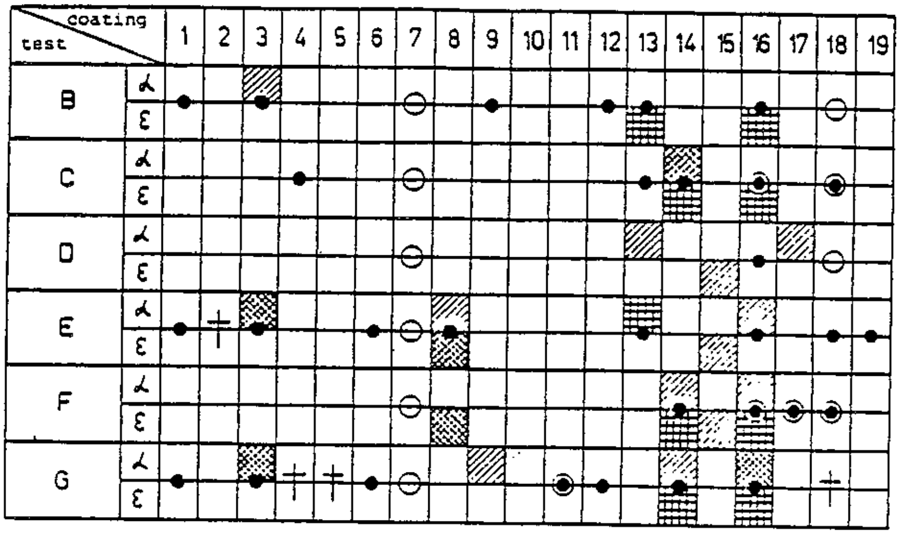


Fig. 4: Emittance ε of the selective and partly selective coatings.

It follows from the analysis of the cross-cut-tests that the adhesion of most of the coatings is hardly influenced by the tests. The low quality coatings however peel off easily even prior to the tests.

The test results can be summarized in Fig. 5.



- change in the optical and thermal radiative properties:

0,0% ≤ Δ α < 2,5% → □ 0,0% ≤ Δ ε < 5,0% → □

2,5% ≤ Δ α < 5,0% → ▨ 5,0% ≤ Δ ε < 10,0% → ▨

5,0% ≤ Δ α < 10,0% → ▩ 10,0% ≤ Δ ε < 20,0% → ▩

Δ α ≥ 10,0% → ▤ Δ ε ≥ 20,0% → ▤

- change of appearance: ●
- change of adhesion: ○
- destroyed: +

Fig. 5: Summary of the test results.

4. CONCLUSION

- The most substantial degradations of the optical and thermal radiative properties as well as of the adhesion are caused by the temperature test 200° C (E) and by the temperature/humidity test 95° C/100 % relative humidity (G).

- It is meaningful to classify the coatings in selective ($\varepsilon \leq 20$ %), partly selective ($20 \% < \varepsilon < 50 \%$) and non selective ones ($\varepsilon \geq 50$ %). The second class is substantially less stable than the other ones.

- The durability of the selective samples is comparable to that of the non selective coatings.

- A change of the appearance of a coating is not necessarily an indication for a possible degradation of the optical and thermal radiative performance. Moreover, a coating which looks black in the visible spectrum is not always an optimal absorber.

- Globally considered, the absorptance values of the selective samples are smaller than those of the non selective ones ($\Delta\alpha = 2\ \%$).

- In the case of an absorber being a component of a hermetically sealed collector the temperature tests 100° C and 200° C are relevant. If the collector is naturally ventilated, in addition, humidity tests have to be taken into account.

- The rating of the adhesion and of the mechanical durability may be very difficult, particularly in the case of selective (electro-deposited) coatings.

- Based on the experiences described above the conditions for future tests have to be modified; e.g. the following tests should be introduced: temperature test 150° C, cyclic temperature tests, glass cover above the samples exposed outdoors.

5. ACKNOWLEDGEMENTS

The authors wish to thank all their colleagues participating to the projects "Reliability and Durability of Solar Energy Systems" (ITR) and "Solar Heating" (EIR) who gave substantial assistence in building up experiments, performing measurements, evaluating data and interpreting the results.

This work has been realized within the framework of the cooperation in the field of research and development projects of the International Energy Agency (IEA). It has been ordered by the Swiss Federal Office of Energy (BEW) and partly supported by the Swiss National Energy Research Foundation (NEFF). The conclusions and opinions expressed in this paper are only binding for the authors.

6. REFERENCES

/1/ U. Frei, J. Keller,
"Beständigkeit von Absorberbeschichtungen. Teil 4 des Forschungsprojektes Lebensdauer und Betriebssicherheit von Solaranlagen." (in German)
Interkantonales Technikum Rapperswil, Februar 1983.

/2/ L.W. Masters, J.F. Seiler, E.J. Embree, W.E. Roberts
"Solar Energy Systems-Standards for Absorber Materials",
NBSIR 81-2232, 1981

A PRELIMINARY STOCHASTIC MODEL FOR SERVICE LIFE PREDICTION OF A PHOTOLYTICALLY AND THERMALLY DEGRADED POLYMERIC COVER PLATE MATERIAL

Jonathan W. Martin
David Waksman
Dale P. Bentz

Center for Building Technology
National Bureau of Standards

James A. Lechner
Center for Applied Mathematics
National Bureau of Standards

Brian Dickens
Center for Materials Science
National Bureau of Standards

ABSTRACT

A preliminary stochastic model has been developed and partially validated for predicting the service life of a polymeric film, such as poly(methyl methacrylate) (PMMA), which is subjected to both thermal and photolytic degradation. The exposure conditions under which degradation is induced simulate those expected for a polymeric cover plate material in an active solar collector. Service life for a population of films is defined as that time beyond which an unacceptable portion of the population fails. The criterion used for failure of a film is that its number average molecular weight has fallen below a specified threshold value.

Key Words: Molecular weight, photolytic degradation, polymer degradation, polymer photooxidation, thermal degradation, stochastic model.

INTRODUCTION

Due to their low cost, generally suitable physical and optical properties, and light weight, polymers appear to be good candidates for cover plates in active solar collectors. The selection of these materials, however, should be determined by their stability in the expected operating environment. In active solar collectors, the expected operating environment may be close to the performance limits of many commercially available films. This is especially true during stagnation conditions (i.e., when all the solar energy absorbed is being dissipated as heat within the collector). In order to make effective material selections, it is necessary that a methodology be developed and experimental data be provided for predicting the useful service life of each of the candidate materials.

Accurate service life predictions for any material or component are generally difficult to make, and require success in the following three areas [1]: 1) characterizing the factors comprising an environment, 2) identifying the pertinent material degradation mechanisms, and 3) developing mathematical procedures which are general enough to include all of the important environmental and material degradation factors, but still powerful enough for making accurate service life predictions. For active solar collectors, many of the important environmental factors have been identified by Clark, et al. [2]. In this paper, a preliminary stochastic model for making service life predictions is presented. It addresses the case where 1) the radiation intensity and the temperature are constant, 2) the initial number average molecular weight for each specimen is known, and 3) the properties of each specimen are uniform and identical in every way. Variations to these conditions will be explored in future publications.

RELIABILITY THEORY AND LIFE TESTING ANALYSIS

Reliability theory and life testing analysis is a systematic probabilistic procedure for making quantitative service life predictions [3, 4, 5]. The procedure is used extensively in the electronics, medical, and aerospace industries for predicting the service life of components and systems. Its use in predicting building materials performance is, as yet, limited.

The reliability and life testing procedure is presented graphically in figure 1. In this figure, densities representing changes in a performance property of a population of a material or component are plotted against time. The performance property is a physical or chemical property of the material or component whose value determines its operating state. When this value is above some threshold, the material or component is said to be functioning. Conversely, when it falls below this threshold, it is said to have failed. The time between installation and failure is called the service life. An example of a performance property for the cover plate of an active solar collector is its transmittance; due to thermal efficiency considerations, the cover plate may be designated as having failed when its transmittance falls below a certain percentage of its initial value.

For a population composed of specimens of a material or component, a variation is often observed in the initial performance property values. This initial variation results from measurements errors and, for polymer sheets, variations introduced during fabrication. During exposure of the film, other sources of variation are introduced resulting from differences in the degradation rates of different members of the population. These variations in the estimates of the performance property are depicted in figure 1 by probability density functions at different exposure times.

The values of the performance property eventually decrease with increased exposure and will eventually fall below the threshold. The passage through this threshold will in general occur at different times for different components. From reliability theory, the service life for the nominal population is defined as that time at which an unacceptable portion, $1-\bar{H}(t)$, of the population fails. A model of the survival fraction, $\bar{H}(t)$, is developed here for a commerical poly(methyl methacrylate) film which has been subjected to both thermal and photolytic degradation.

MATERIAL ASPECT S OF PHOTOLYTIC AND THERMAL DEGRADATION OF PMMA

PMMA is a commercially important polymer and is extensively used in outdoor applications such as signs and glazings. Its use as a solar cover plate material is limited, however, because of its relatively low glass transition temperature (105 to 115°C) and the fact that it degrades both thermally and photolytically. The glass transition temperature is the maximum useful operating temperature of a polymer in outdoor applications. A low glass transition temperature becomes important during stagnation conditions, where temperatures in the cover plate of a single glazed flat plate solar collector can theoretically reach 100°C given the right environmental conditions [2]. Photolytic and thermal degradation are long term degradation processes resulting in film embrittlement, increased absorption of the shorter wavelengths in the solar spectrum; and a reduction in the glass transition temperature of the film. At least the first two of these physical property changes are related to decreases in the number average molecular weight of the film. The molecular weight of a polymer is highly related to its mechanical properties [6].

Decreases in molecular weight occur through scission of the polymer backbone or chain. Random chain scission is the breakage of the polymer chain at a random location along its length to give two smaller chains. Chains can be broken either from the absorption of a photon or from a thermally activated scission process. The number average molecular weight, M_n, is a sensitive indicator of the number of random chain scissions. The number average molecular weight is readily measured via such laboratory techniques as gel permeation chromatography. For this property to be useful, however, the changes in it must be modeled as a function of the number of chain scissions which have occurred.

The initial number average molecular weight, M_{n_o}, of a polymer is defined by

$$M_{n_o} = \Sigma n_i m_i / \Sigma n_i$$

where n_i is the number of molecules having molecular weight m_i; therefore, $\Sigma n_i m_i$ is the total mass of the polymer and Σn_i is the total number of chains in the sample. After K chain scissions have occurred, the new number average molecular weight M_{n_K} is given by

$$M_{n_K} = \Sigma n_i m_i / (\Sigma n_i + K), \tag{1}$$

assuming no mass loss occurs. Equation 1 is equivalent to

$$M_{n_K} = A_1 / (A_2 + K) \tag{2}$$

where A_1 is a constant and A_2 is a function of the initial molecular weight M_{n_o}. Thus, equation 2 gives the number average molecular weight after K chain scissions have occurred. Models for predicting the number of photolytically and thermally caused random chain scissions will now be derived.

STOCHASTIC MODEL FOR PHOTOLYTIC DEGRADATION

When a transparent film is subjected to a photolytic source having constant radiation intensity I_o, the number of photons striking the surface of the film in the time interval $[0,t)$ is $I_o t$. Of these only a fraction, p, are actually absorbed by the film. If we assume that the light source is at normal incidence to the film, then the fraction of photons absorbed per unit time by the film is given by the Lambert-Beer law to be $1 - I/I_o$, where I is the intensity of radiation transmitted through the film; and the expected number of photons, N_t, absorbed by the film in the time interval $[0,t)$ is given by $pI_o t$.

Although N_t photons are absorbed, only some fraction of these lead to chain scissions. This fraction is the quantum yield of main chain scission ϕ_{cs}. Quantum yield of main chain scission is wavelength dependent. For polychromatic light, it is experimentally difficult to determine the quantum yield at every wavelength. Instead, we determine the product of the quantum yield and the number of photons absorbed for all wavelengths. This product is the expected number of random chain scissions, N_t, in the time interval [0,t). For thin films, at temperatures which are sufficiently below the glass transition temperature, it has been shown that the number of scissions for any exposure interval may be represented as a Poisson process [7 and the Appendix]. The probability that such a film will undergo exactly k_p chain scissions in the time interval [0,t), is given, therefore, by

$$P(k_p;\lambda t) = \frac{e^{-\lambda t}(\lambda t)^{k_p}}{k_p!};\ k_p=0,1,2,\ldots \tag{3}$$

where

$$\lambda t = p\phi_{cs}I_0 t.$$

For thick films, Dickens et al. [8] found that commercial PMMA degrades via photooxidation. In this case, equation 3 is still applicable, but its time axis must be transformed to account for oxygen diffusion [7]. Justification for equation 3 stems from its success in modeling the arrival of electromagnetic radiation particles in many scientific disciplines including health physics [9,10], electronics [11], and physics [12,13]. A survey of the application of the Poisson distribution for particle counting is given by Haight [14].

The Poisson parameter λ must be modified to reflect changes in the quantum yield of main chain scission as the temperature and intensity of radiation absorbed increase. Koike and Tanaka [15] and MacCallum and Schoff [16] have represented changes in this parameter as a function of temperature and radiation intensity by

$$\lambda = \left\{\exp\left[-\left(\frac{E(T_0-T)}{RTT_0}\right)\right]\right\}\left\{\left(\frac{I_a}{I_\alpha}\right)^{\eta}\right\}\lambda_0 \tag{4}$$

where the first term is the Arrhenius acceleration factor and the second term is an acceleration factor for intensity of radiation absorbed. Also, T_0 is a reference absolute temperature; T is the absolute temperature at which the absorbed radiation occurred; I_α is a reference intensity of radiation absorbed; I_a is the intensity of absorbed radiation; Λ_0 is the expected number of main chain scissions occurring at the reference temperature T_0 and the reference intensity of radiation I_α, and n has a value between 0 and 1. E is an activation energy, and R is the gas constant.

STOCHASTIC MODEL FOR THERMAL DEGRADATION

Specimens of commercial PMMA were thermally degraded in air at 85, 100, 115, and 125°C. At all of these temperatures, the number average molecular weight of the polymer was observed to decrease rapidly as a function of time while the loss in film weight was negligible [8]. A rapid loss in molecular weight is associated with random chain scissions, while loss in film weight is a good indicator of chain unzipping; that is, the formation of small molecules which, at sufficiently high temperatures, diffuse out of the film. The decrease in number average molecular weight was unexpected, in as much as the lowest reported temperature for a thermally activated random chain scission process, proceeding at a moderate rate for pure PMMA in vacuum, is 270°C [17, 18]. At temperatures above 160°C, the film would have incurred a rapid loss in weight resulting from unzipping [19, 20]. Reported studies of the thermal degradation of pure PMMA in air were not found. The thermal degradation of commercial PMMA films in air, where random chain scission is the dominant mode of degradation, has been previously reported in the same temperature range as our experiment [20]. It is most likely that the cause of thermal degradation of commercial PMMA was introduced during fabrication.

By plotting the number of chain scissions versus time for 85, 100, and 115°C, it was determined that the linear model proposed by Cameron and Kerr [21] adequately describes changes in the number of chain scissions, K_T, as a function of time except for very short exposure times; that is,

$$K_T = \beta_T + \alpha_T t \tag{5}$$

where β_T and α_T are empirical constants. For the 125°C data, a weak link model like the one proposed by Oakes and Richards [22] fits the number of chain scissions versus time data better than equation 5. Since we are mainly interested in temperatures below the glass transition temperature of the polymer, we will use equation 5. In equation 5, the intercept, β_T, was higher for higher temperatures (figure 2), while the slope α_T, was smaller (figure 3). These observations and the limiting behavior found at 125°C suggest that a limited number of chain scissions per molecule exists for thermal degradation and that this limiting number of chain scissions is the same at all temperatures within the experimental range. A limiting number of 2.2 chain scissions per molecular chain was found. This is equivalent to approximately 0.05 % of the bonds in the initial molecule being broken and is consistent with our previous results [8]. This limit was computed by extrapolating the linear regression line for the slope, α_T, versus temperature (figure 3) to that temperature at which the slope parameter has a value of zero, and then substituting this computed temperature into the linear regression equation modeling changes in the intercept, β_T, as a function of temperature. If this computed limit is indeed meaningful, then the form of equation 5 must be changed to reflect a limit at long exposure times. The nature of these changes should become apparent in our study of the mechanisms of thermal degradation.

If we assume that the number of thermally activated chain scissions is a normal random variable, then, from equation 5, the probability density for the number of chain scissions is given by

$$N(k_T) = \left(\frac{1}{2\pi\sigma^2}\right)^{1/2} \exp\left(- \frac{(k_T - \beta_T - \alpha_T t)^2}{2\sigma^2}\right) \tag{6}$$

for $0 \leq k < \infty$ so that k_T has an expected value

$$E(k_T) = \beta_T + \alpha_T t$$

and variance

$$\mathrm{var}(k_T) = \sigma^2.$$

The variance, σ^2, is due to variations in the initial properties of the material and differences in the rates of degradation. If a limiting number of thermal chain scissions exists with certainty, then the normal distribution would be truncated at this maximum number of chain scissions.

SERVICE LIFE PREDICTION MODEL

The service life of the population has already been defined as that exposure at which an unacceptable portion, $1 - \overline{H}(t)$ of the population has failed. A model for this survival fraction $\overline{H}(t)$, is obtained for PMMA films by combining the distributions for the number of random chain scissions resulting from photolytic and thermal degradation with the distributional model describing changes in the number average molecular weights as a function of increasing number of scissions.

The distribution of the number of chain scissions resulting from photodegradation is given by equations 3 and 4, while the distribution for thermal degradation is given by equation 6. Using the normal approximation to the Poisson distribution, which is acceptable because the Poisson parameter λ is large [23], and assuming that the two degradation processes act independently of each other, we can then add the thermal and photolytic random chain scission processes together. The distribution of this sum is again normal with mean $\beta_T + \alpha_T t + \lambda t$ and variance $\lambda t + \sigma^2$.

Defining $K = K_p + K_T$, the density function of k is

$$N(k) = \left(\frac{1}{2\pi(\sigma^2+\lambda t)}\right)^{1/2} \exp\left(-\frac{(-\beta_T - \alpha_T t - \lambda t)^2}{2(\lambda t + \sigma^2)}\right) . \tag{7}$$

Not included in equation 7 is a term for errors in measuring the number of chain scissions. The magnitude of this error is probably large, but at this time is unknown. In comparison, the variance contribution from the photodegradation process, λt, is very small, as long the terms used in computing the average number of chain scissions per unit time, λ, are not themselves random variables.

The density function, $f_K(M_n)$, of the number average molecular weights from a population of polymeric components after K chain scissions has yet to be studied. Certain properties of this distribution, however, are known. For example, the expected value of the number average molecular weight after K chain scissions has the form of equation 2. If we define $\overline{F}_K(M_n)$ as the probability that the number average molecular weight has a value greater than the threshold after K chain scissions, where

$$\overline{F}_K(M_n) = \int_{\min M_n}^{\infty} f_K(u)du \qquad (8)$$

then, as the number of chain scissions, K, increases, the fraction of the population having number average molecular weights above this threshold decreases; that is

$$\overline{F}_K(M_n) > \overline{F}_{K+1}(M_n)$$

From equations 7 and 8, a model for the survival fraction, $\overline{H}(t)$, of PMMA films having a number average molecular weight above the critical minimum after exposure can be derived. The total probability that a component or material will survive beyond time t (the shaded area in figure 1) is given by

$$\Pr(M_n > \min M_n) = \sum_{k=0}^{\infty} \Pr(M_n > \min M_n \text{ given k scission have occurred})$$

$$\times \Pr(\text{k chain scissions})$$

or in our case

$$\overline{H}(t) = \int_{-\infty}^{\infty} \overline{F}_k(M_n) \left(\frac{1}{2\pi(\sigma^2 + \lambda t)}\right)^{1/2} \exp\left(- \frac{(k-\beta_T - \alpha_T t - \lambda t)^2}{2(\lambda t + \sigma^2)}\right) dk. \quad (9)$$

Equation 9 does not include a variable term which would explain errors due to measurement or variations within or between sheets. This variation may be large. Equation 9 also requires that the thermal and photodegradation processes act independently of each other and do not change with time.

SUMMARY

A preliminary stochastic model has been proposed and partially validated for predicting the service life of a commercial PMMA film which is subjected to both thermal and photolytic degradation. These exposure conditions simulate those expected for a polymeric cover plate material used in an active solar collector. The service life is defined as that time beyond which an unacceptable portion, 1 - $\overline{H}(t)$, of the population of the film fail. Failure occurs when the number average molecular weight of a film falls below a specified threshold.

Although the model has many attributes making it attractive for service life predictions [7], it has yet to be fully validated. The assumption must be verified, that the thermal and photolytic degradation processes are acting independently of each other; and it must also be determined whether a limiting number of random chain scissions exists. Research is currently being conducted to verify these points.

LITERATURE CITED

1. ASTM E632, Standard Practice for Developing Accelerated Tests to Aid in the Prediction of the Service Life of Building Components and Materials, American Society of Testing and Materials, 1982.
2. Clark, E. J., Roberts, W. E., Grimes, J. W., and Embree, E. J., "Solar Energy Systems -- Standards for Cover

Plates for Flat Plate Solar Collectors," National Bureau of Standards, NBS Tech. Note 1132, 1980.

3. Mann, N. R., Schafer, R. E., Singpurwalla, N. D., "Methods for Statistical Analysis of Reliability and Life Data," Wiley, New York, 1974.
4. Lawless, J. F., "Statistical Models and Methods for Lifetime Data," Wiley, New York, 1982.
5. Nelson, W., "Applied Life Data Analysis," Wiley, New York, 1982.
6. Kusy, R. P. and Turner, D. T., Polymer 17: 161 (1976).
7. Martin, J. W., J. Appl. Polym. Sci. (1984), 3.
8. Dickens, B., Martin, J. W., and Waksman, D., accepted for publication in Polymer.
9. Cathcheside, D. G., in Advances in Genetics, M. Demerec, Ed. Academic, New York, (1948), Vol. 2.
10. Cathcheside, D. G., Lea, D. E., and Thoday, J. M. J. Genetics, 47, 113, (1945).
11. Davenport, W. G. and Root, W. L. "An Introduction to the Theory of Random Signals and Noises, McGraw-Hill, New York, 1958.
12. Rutherford, Chadwick, and Ellis, "Radiation from Radioactive Substances," Cambridge University Press, Cambridge (1920).
13. Rutherford, E. and Geiger, H. Phil Mag, 20, 698 (1910).
14. Haight, F. A. "Handbook of the Poisson Distribution", Wiley, New York, 1967.
15. Koike, M and Tanaka, K. Rep. Research Laboratory Engineer Materials, Tokyo Institute of Technology 5, 143 (1980)
16. MacCallum, J. R. and C. K. Schoff, Trans. Faraday Soc. 1(75), 2372, (1971).
17. MacCallum, J. R., Makromol. Chem. 83: 137 (1963).
18. Cameron, G. G. and Kerr, G. P., Makromol. Chem. 115(2587): 268-274 (1968).
19. Bywater, S., J. Phys. Chem. 57, 879 (1953).
20. Hattori, S., Kobayashi, R., Nakahara, H., and Kamata, T. Tokyo Koggo Shikensho hokoku 78(8): 559-570 (1981).
21. Cameron, G. C., Kerr, G. P., Euro. Polym. J. 6: 423-433 (1970).

22. Oaks, W. G. and R. B. Richards, J.Chem. Soc. 2929 (1949).

23. Mood, A. M., Graybill, F. A., and Boes, D. C., "Introduction to the Theory of Statistics," McGraw-Hill, 3rd ed., San Francisco, 1974.

APPENDIX: THE POISSON PROCESS

(In which some basic facts about random processes of a certain type are considered, in reference to the polymer chain situation.)

The simple (i.e., "homogeneous") Poisson process is said to occur when "events" happen "randomly" in time (or in some other variable like distance). "Randomly" means that: (1) the probability of an event occurring in a small interval of time $(t, t + \Delta t)$ is of the form $\lambda\Delta t + o((\Delta t)^2)$, where λ is a constant, and the probability of more than one event occurring in such an interval is of the form $((\Delta t)^2)$ as Δt approaches zero; and (2) the occurrence of an event in an interval is independent of whether events have occurred in other (nonoverlapping) intervals.

The generalized (or "nonhomogeneous") Poisson process is said to be obtained when λ is not a constant, but rather a function of t.

In the case at hand, consider a short interval from t to $t + \Delta t$. The probability that a photon of wavelength between ν and $\nu + \Delta\nu$ arrives on an element of area ΔA during this interval is approximately $I(t,\nu,x,y)\cdot\Delta\nu\cdot\Delta A\cdot\Delta t$, where $I(t,\nu,x,y)$ is the radiation intensity (photons/sec/unit area/unit wavelength) projected onto the sample at a point (x,y) in the area ΔA. (We assume continuity of I.) Thus, the arrival of photons of this wavelength on this element of area is a (generalized) Poisson process, and by integrating over ν and/or A, the same can be said for the arrival of photons of any energy band onto any area.

To obtain the probability that a photon (of wavelength between ν and $\nu + \Delta\nu$) is absorbed within the element ΔA between t and $t + \Delta t$, we multiply the expression just given by $p(t,\nu,x,y)$; and to obtain the probability that a scission occurs due to a photon of wavelength in the given band, we further multiply by $\phi_{cs}(t,\nu,x,y)$. Thus (to first order in $\Delta\nu,\Delta t$, and ΔA)

$$\begin{aligned}&\Pr(\text{scission in } \Delta A \text{ during } (t,t+\Delta t), \text{ due to a photon of}\\ &\text{wavelength between } \nu \text{ and } \nu+\Delta\nu) =\\ &I(t,\nu,x,y)\cdot p(t,\nu,x,y)\cdot\phi_{cs}(t,\nu,x,y)\cdot\Delta t\Delta\nu\cdot\Delta A\end{aligned}$$

Again we have a Poisson process.

Now if we integrate over the spectrum of incident radiation, we obtain

$$\begin{aligned}\Pr(\text{scission in } \Delta A \text{ during } (t,t+\Delta t) &= [\ \int_{\nu} I\cdot p\cdot\phi_{cs}d\nu\ ]\cdot\Delta t\cdot\Delta A\\ &= \lambda(t,x,y)\cdot\Delta t\cdot\Delta A\end{aligned}$$

(where $\lambda(t,x,y)$ might be called the intensity of chain scissions at time t and location (x,y)).

Next, we can integrate over a specific area A (e.g., the exposed part of the sample) to obtain

$$\Pr(\text{scission somewhere, in } (t,\ t+\Delta t)) = \lambda_A(t)\cdot\Delta t.$$

Again, we have a Poisson process. Finally, as with any Poisson process, if we integrate over a time interval (t_1,t_2), we obtain a Poisson distribution for the total number of scissions, with mean m equal to $\int_{t_1}^{t_2} \lambda_A(t)\ dt$. (And of course, the standard deviation is equal to the square root of the mean.)

Notes and discussion:

A. Independence. We have specifically assumed the independence of occurrences across t; and we have tacitly assumed independence across ΔA and ν. The necessity of independence across t can be seen by noting that if $X(t)$ represents the number of scissions by time t, and if the probability of scission, say, is proportional to the amount of some material remaining, i.e., to N-X(t), then X(t) cannot exceed N; so X(t) cannot have a Poisson distribution. Again, suppose as an extreme but illustrative case that every scission at the point (x,y) were accompanied by another scission at (-x,-y). Then the number of scissions is any half plane is a Poisson process; but the number in a general area need not be Poisson.

Note also that if something tends to get used up, then (randomly) more occurrences in early time tends to result in fewer occurrences in later time; this tends to decrease the variability compared to a Poisson process. If on the other hand, more occurrences early on tend to result in still more later, then there will be more variability than a Poisson process of equal mean would show.

B. Variability, Poisson and otherwise; linearity. Let X(t) be the actual number of events by time t. Then X(t) will have a Poisson distribution, so that even without measurement error, X(t) will not be precisely equal to $m(t) = \int_0^t \lambda_A(t)\,dt$. However, if the mean number of events, m(t), is large (say 10^{16}), then the standard deviation of X(t) is $(m)^{1/2} = 10^8$, or (1×10^{-6}) percent of m(t); i.e., X(t) will be <u>very</u> close to m(t) on a percentage basis. Therefore, if $\lambda_A(t)$ is constant, m(t) is a linear function of t, and (except for measurement error) X(t) will also be essentially linear. However, if we don't keep λ constant, then X(t) will not be linear. Also, if different samples are used to estimate X(t) at different times, there will be variation in some or all of I, p, and ϕ_{cs} from sample to sample; this too will cause apparent deviation from linearity, since the measurements at different times come from different straight lines.

Now suppose the observed values are linear (up to experimental error). Then does it follow that $\lambda(t)$ is constant? Not quite: all we can assert with certainty is that for the sample measured at t_i, whose intensity function is denoted by $\lambda_i(t)$, $\int_0^{t_i} \lambda_i(t)\,dt = Kt_i$ (up to measurement error). One can conceive of a set of $\lambda_i(t)$ which are no constant but each of which just happens to coincide with the line Kt at its point of measurement, t_i. But since this is not likely to happen by chance, the observation of a linear growth in time is usually regarded as justification for the assertion that the Poisson process is homogeneous, i.e., λ is a constant -- the same constant for every sample.

Finally, as an illustration of the possible use of the Poisson process model to investigate scientific phenomena, suppose that (say) p varies appreciably with t; then either I or ϕ_{CS} (or both) must vary in a compensating way if λ is to be constant. One way this might happen is if the change in p is due to a second mechanism of absorption, for which ϕ is zero. Other ways might occur to the scientist, suggested by the need for compensation.

C. Normality and the Poisson distribution. When the mean, m, of a Poisson distribution is large, then the distribution is well-approximated by a Normal distribution. The advantages of going through the Poisson approach is that once we know the mean, we also know the variance; if we assumed the Normal directly, we would have to find some way to estimate the variance.

D. Three-dimensional complications. At least in some circumstances, the rate of scissions varies with depth in the sample, and the variation itself changes with time. This does not necessarily vitiate the Poisson model; again, independence is the key. If the change in absorption for the deeper layers is caused by scission in the surface layers, then there is a lack of independence: the more scissions in the surface layer, the fewer there will likely be in the interior. However, one might be able to say that the process is still close to Poisson, if the variation can be modeled closely in terms of the mean number of scissions (rather than the actual number), since as stated above the actual number is (relatively) very close to the mean.

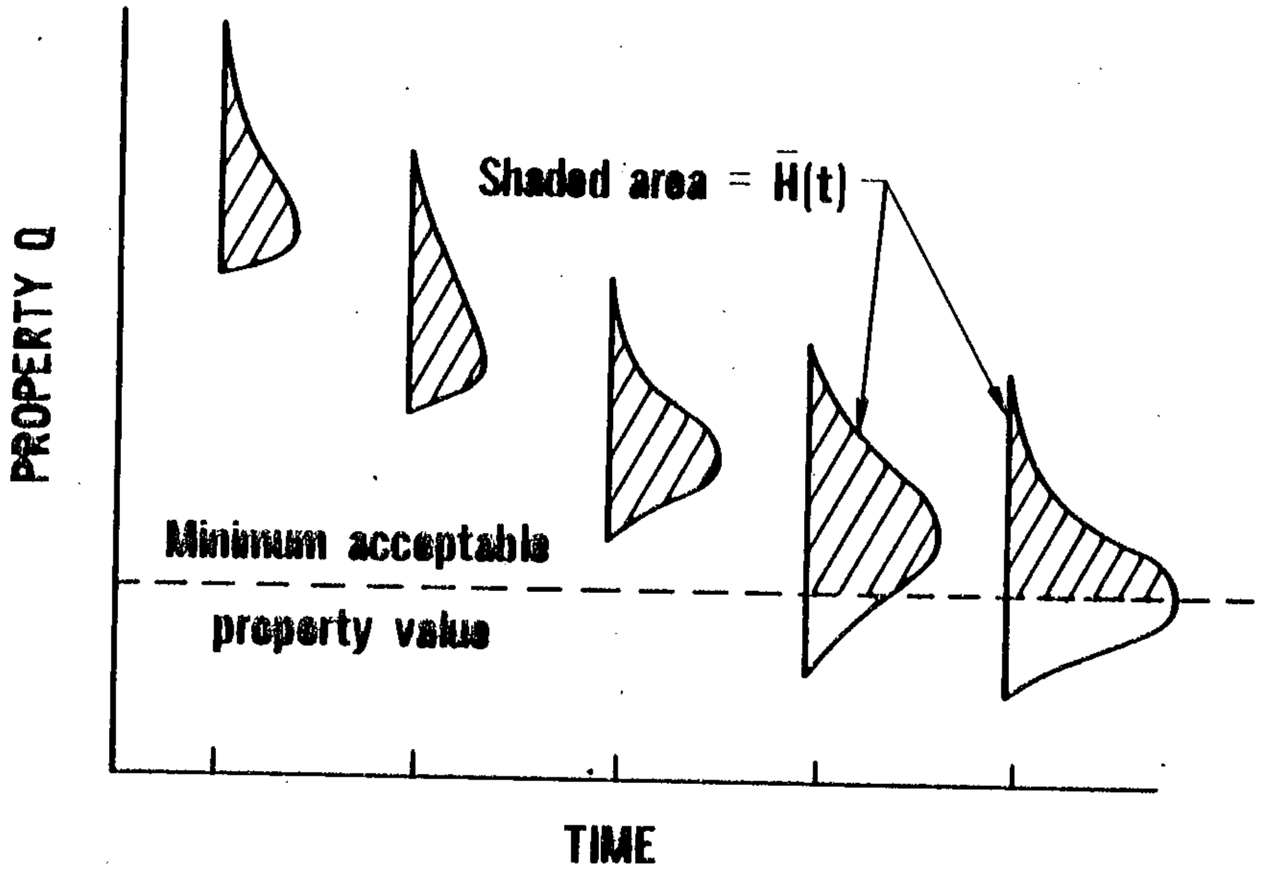


Fig. 1. Schematic depicting a decrease in a property value of a polymeric film with increased exposure time.

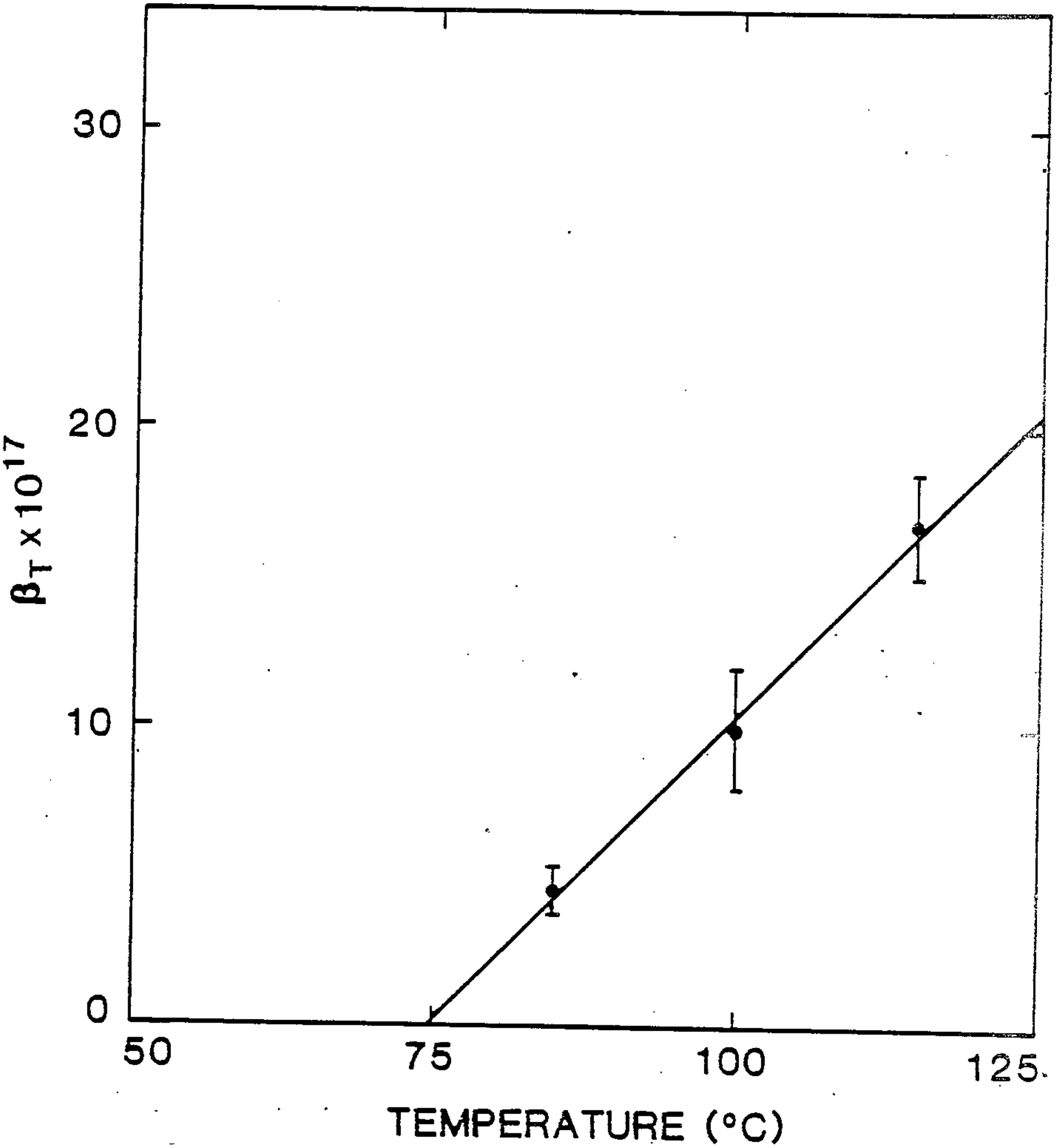


Fig. 2. Thermal degradation intercept parameter versus temperature.

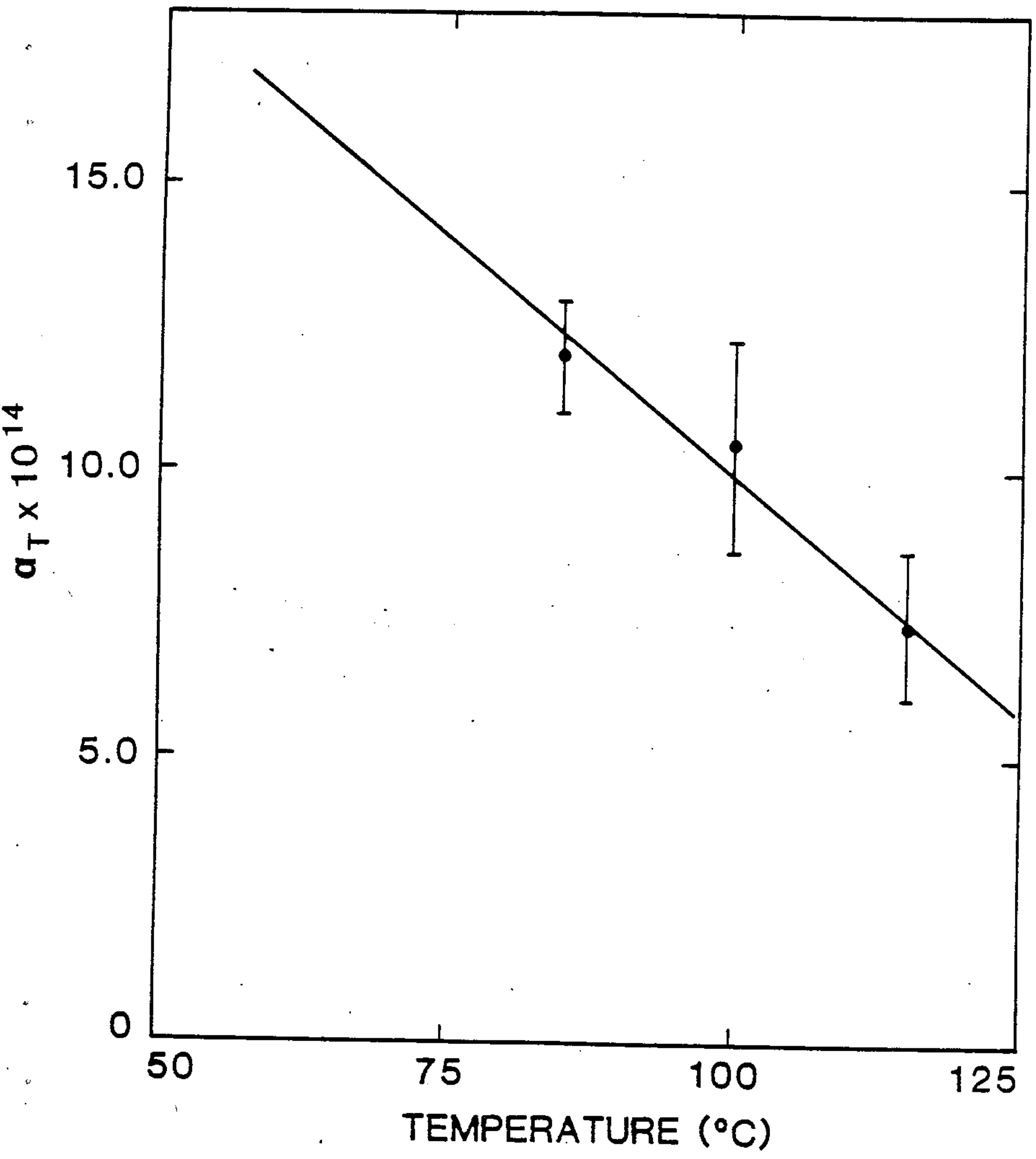


Fig. 3. Thermal degradation slope parameter versus temperature.

OUTDOOR EXPOSURE TRIALS AS INDICATORS OF COLLECTOR DURABILITY

B. J. Brinkworth and B. M. Cross
Solar Energy Unit, University College, Cardiff, U.K.

Presented at the I.E.A. Task III meeting, Copenhagen,
December 6-8. 1983

INTRODUCTION

Improved durability is needed, to enhance the economic attractions of solar energy systems. A life-cycle of about 20 years is probably a reasonable aim, since discounted savings after that time would contribute little to a particular decision to purchase. This workshop should aim to identify a sequence of events that would result in 20-year durability in leading components, particularly solar collectors for DHW and space heating.

It has first to be established what new information is required by designers to enable them to eliminate materials and design features which shorten the service life unduly. It will be a task for researchers to provide this information. However, unless durable products are actually cheaper to produce, manufacturers will not provide them until they are obliged to do so by market forces or mandatory standards designed to protect the customer.

Market forces will come into action when information has been gained to the point at which some manufacturers feel that they can guarantee durability. Standards are basically of two kinds: codes of good practice and qualification tests. A code of practice is an official compendium of the methods used by designers, and derives from the same information. Qualification tests will not ensure durability unless they are certain to bring about in the short time occupied by the test unmistakable signs of the degradation that would occur in service. Hence, they have to accelerate degradation, implying that the mechanisms of failure are understood by those framing the tests. All considerations of durability ultimately come to the question of failure mechanisms.

STAGNATION

As the collector is drained of fluid it becomes subject to extremes of temperature, and of rates of change of temperature, as radiation levels change. This accelerates certain mechanisms of degradation such as creep, thermally induced fatigue, and changes in material properties at high temperature, but may not accelerate the effects of general weathering and corrosion. The stagnation test has been successful as a qualification test to reveal design shortcomings and material faults which lead to catastrophic failure. Usually such faults are evident within one or two years of outdoor exposure. Examples of early failure encountered in a sample of twenty commercial collectors undergoing test at UC Cardiff are as follows: cracking of glass glazings, yellowing of plastic glazings with insufficient UV stabilisation, deterioration of glazing seals causing ingress of rain, discoloration of absorbing surface due to condensation, or galvanic corrosion, etc.

OUTDOOR EXPOSURE TRIALS AS INDICATORS OF COLLECTOR DURABILITY

B. J. Brinkworth and B. M. Cross
Solar Energy Unit, University College, Cardiff, U.K.

Presented at the I.E.A. Task III meeting, Copenhagen,
December 6-8. 1983

INTRODUCTION

Improved durability is needed, to enhance the economic attractions of solar energy systems. A life-cycle of about 20 years is probably a reasonable aim, since discounted savings after that time would contribute little to a particular decision to purchase. This workshop should aim to identify a sequence of events that would result in 20-year durability in leading components, particularly solar collectors for DHW and space heating.

It has first to be established what new information is required by designers to enable them to eliminate materials and design features which shorten the service life unduly. It will be a task for researchers to provide this information. However, unless durable products are actually cheaper to produce, manufacturers will not provide them until they are obliged to do so by market forces or mandatory standards designed to protect the customer.

Market forces will come into action when information has been gained to the point at which some manufacturers feel that they can guarantee durability. Standards are basically of two kinds: codes of good practice and qualification tests. A code of practice is an official compendium of the methods used by designers, and derives from the same information. Qualification tests will not ensure durability unless they are certain to bring about in the short time occupied by the test unmistakable signs of the degradation that would occur in service. Hence, they have to accelerate degradation, implying that the mechanisms of failure are understood by those framing the tests. All considerations of durability ultimately come to the question of failure mechanisms.

STAGNATION

As the collector is drained of fluid it becomes subject to extremes of temperature, and of rates of change of temperature, as radiation levels change. This accelerates certain mechanisms of degradation such as creep, thermally induced fatigue, and changes in material properties at high temperature, but may not accelerate the effects of general weathering and corrosion. The stagnation test has been successful as a qualification test to reveal design shortcomings and material faults which lead to catastrophic failure. Usually such faults are evident within one or two years of outdoor exposure. Examples of early failure encountered in a sample of twenty commercial collectors undergoing test at UC Cardiff are as follows: cracking of glass glazings, yellowing of plastic glazings with insufficient UV stabilisation, deterioration of glazing seals causing ingress of rain, discoloration of absorbing surface due to condensation, or galvanic corrosion, etc.

Most of these failures could have been avoided by effective quality control or by simple and probably cost-free design changes. The accuracy of the outdoor stagnation test as an accelerated ageing test has yet to be evaluated. Collectors were tested for change in thermal performance after two years exposure and little deterioration was observed. (Figs. 1 to 3). Table 1 shows the value of U/η_o (which is an indicator of collector quality) before and after exposure for a sample of four collectors.

TABLE 1

Collector No	U/η_o, W/m²K before exposure	U/η_o, W/m²K after exposure
2	-	-
10	10.96	11.27
19	9.83	11.65
25	-	-
26	8.44	7.67
27	11.72	11.92

This was at first surprising as visual examination had revealed significant discoloration of some absorbers and glazings. To investigate this the collectors were dismantled and the absorptance for the absorbing surface, and transmittance of the glazing were measured. The surface of the absorber and the inner surface of the glazing were then cleaned and the absorptance and transmittance measured again. These results are presented in Tables 2 and 3.

TABLE 2

Collector No	solar transmittance before cleaning	solar transmittance after cleaning
2	0.761	0.787
10	0.737	0.743
19	0.845	0.848
25	0.781	0.789
26	0.714	0.728
27	0.657	0.671

TABLE 3

Collector No	solar absorptance before cleaning	solar absorptance after cleaning
2	0.958	0.960
10	0.965	0.964
19	0.968	0.968
25	0.952	0.971
26	0.933	0.937
27	0.935	0.936

It was found that the measured values of absorptance and transmittance were close to those that would be expected for unexposed materials. The values changed little after cleaning, so it is evident that surface contamination from outgassing, or microbiological growth, was not a significant problem with these collectors.

In conclusion it can be stated that the outdoor stagnation test did not produce significant deterioration of these collectors in a period of two years. It is also concluded that visual deterioration does not necessarily indicate a drop in thermal performance.

FUTURE WORK

If the stagnation test is to be a useful indicator of service life it must reproduce the degradation likely to be experienced in service but in a shorter time period. Work is necessary to identify the conditions likely to be encountered in service, and existing stagnation tests must be continued to gain long-term validation for the method.

Fig. 1

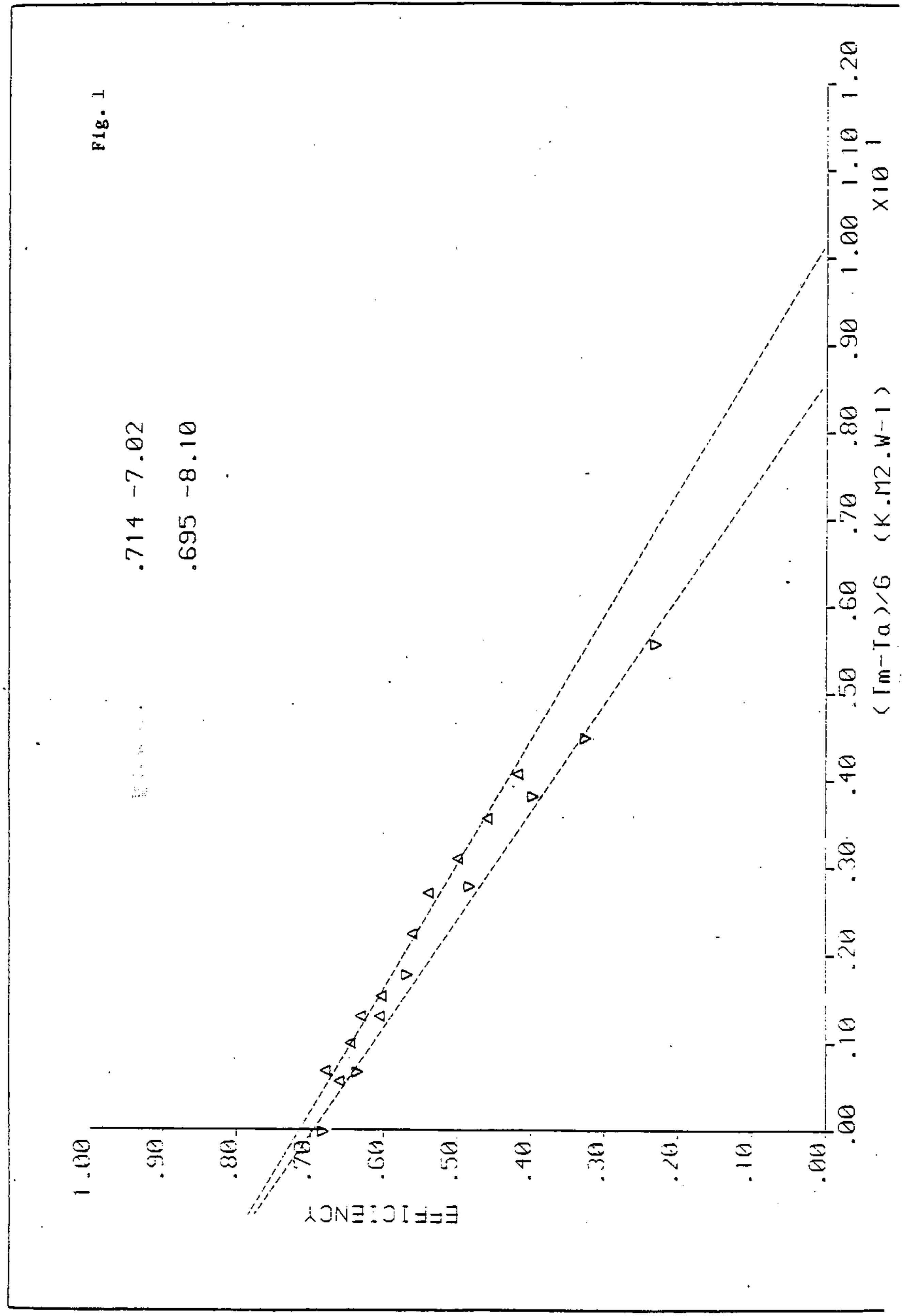

.714 -7.02
.695 -8.10
EFFICIENCY
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
1.10
1.20
X10 1
(Tm-Ta)/G (K.M2.W-1)

Fig 2

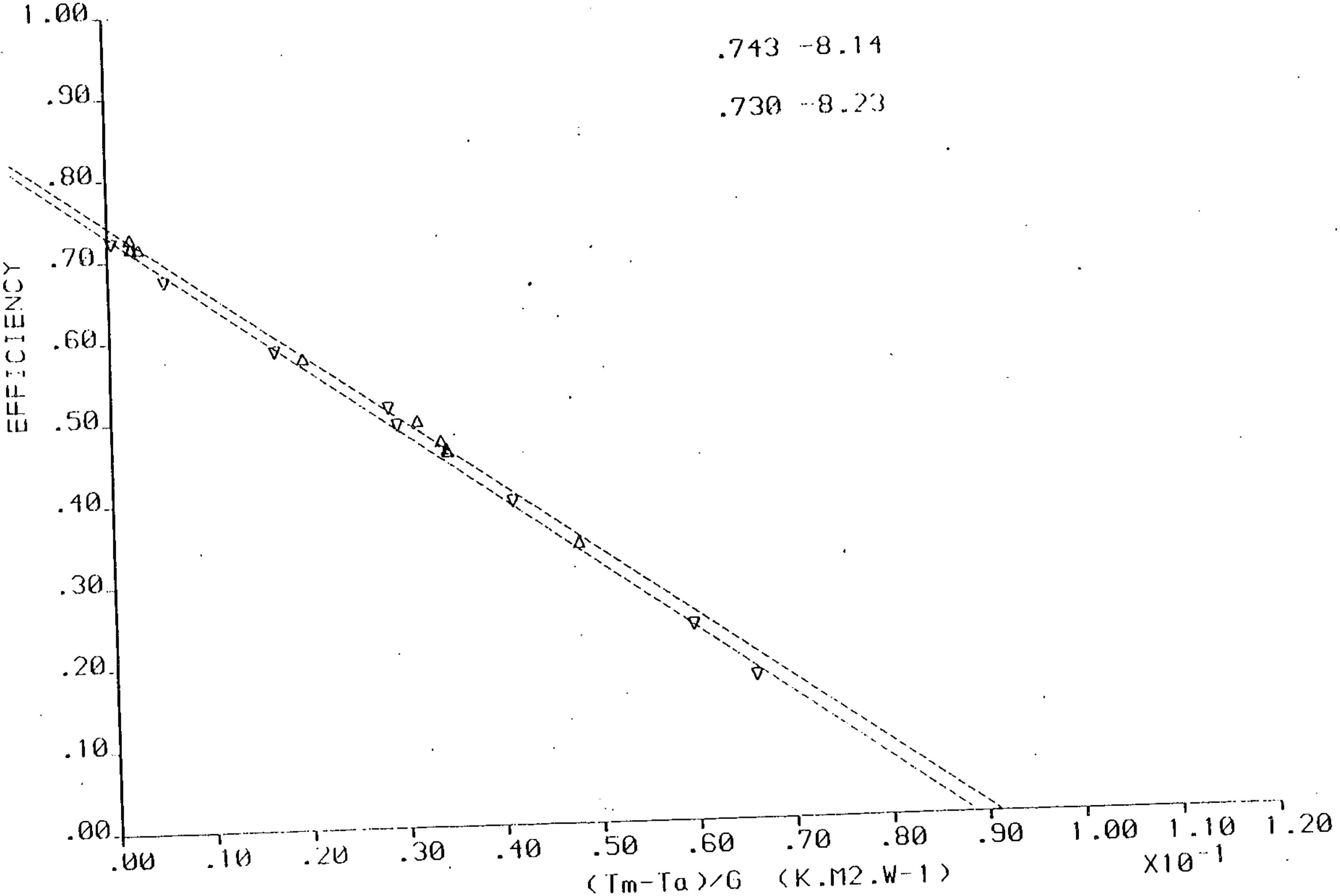
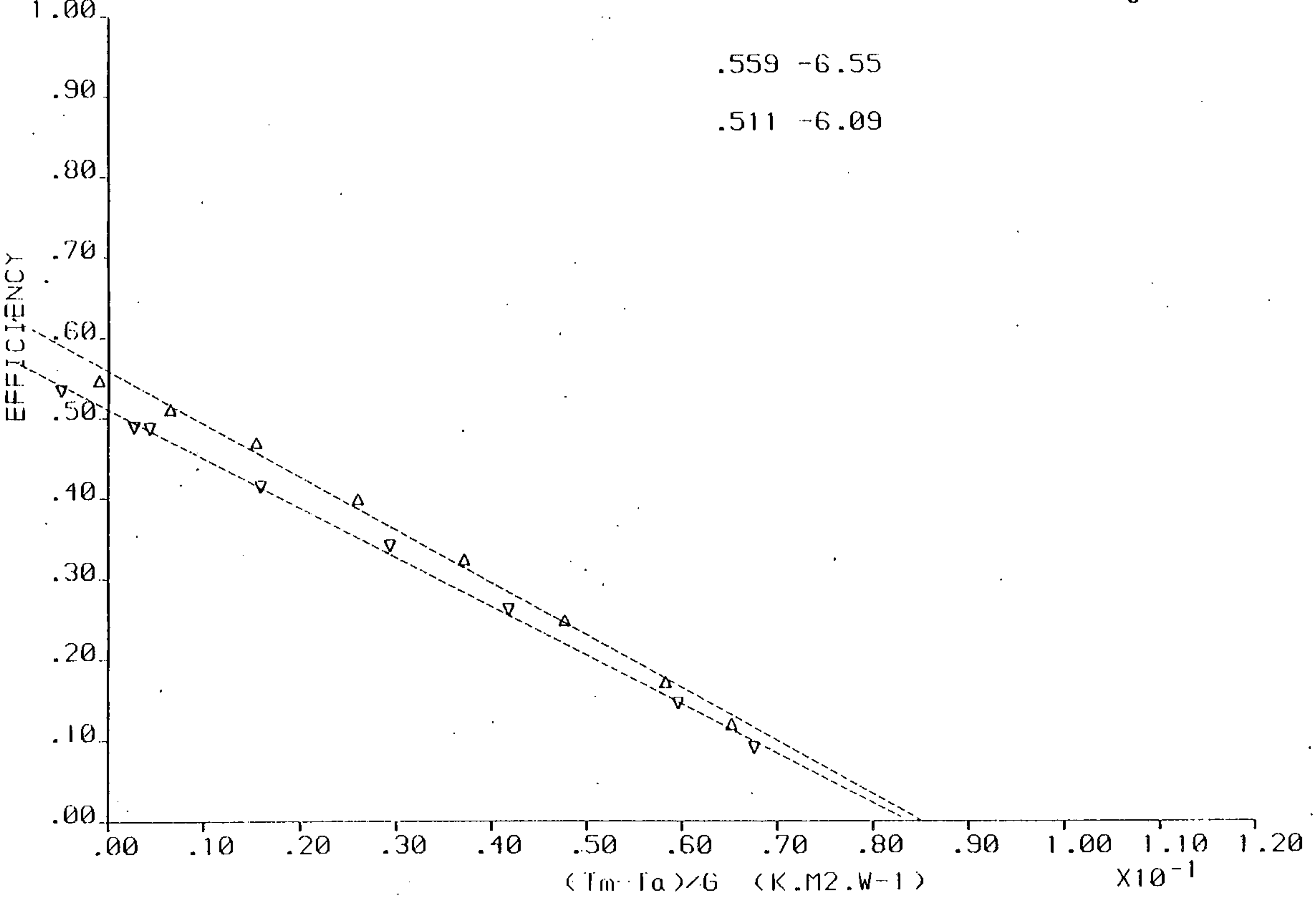

.743 -8.14
.730 -8.23
EFFICIENCY
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
1.10
1.20
X10^-1
(Tm-Ta)/G (K.M2.W-1)

Fig 3


.559 -6.55
.511 -6.09
EFFICIENCY
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
1.10
1.20
(Tm-Ta)/G (K.M2.W-1)
X10^{-1}

Paper presented at the workshop
on Service Life of Solar Collector Components and Materials
Dec. 6 to 7th,1983 Technical University of Denmark,Lyngby.

by Gerhard Riesch, Commission of the European Communities,
Joint Research Centre, Ispra/Va, Italy.

Test Procedures for Thermal Collectors used at the Joint Research Centre, Ispra.

The work at the JRC, Ispra on the durability of thermal collectors comprises tests in the following fields:

-Destructive failures (qualification tests).
-Slow efficiency degradations.
-Outer corrosion.
-Inner corrosion.

The work is mainly executed on complete collectors; studies on samples of materials are only complementary.

The qualification tests can be subdivided in the following items:

--Static pressure test, to check the resistance
  to overpressure and the leak tightness of the absorber.
--Static and dynamic loads on the collector glazing:
  (wind and snow pressure, wind suction).
--Hail resistance (of glazing or of evacuated tubes ecc.).
--Resistance to thermal shocks.

In the field of slow efficiency degradation the following tests are made:

--Test for rain water tightness.
--Exposure to ultraviolet irradiation.
--Exposure to sun and weather in dry conditions
      (outdoor exposure).
--Exposure to simulated sun (indoor exposure).

Experimental investigations on the corrosion of the outer parts of the collector (everything except the inside of the absorber) comprise:

--Treatment in a climatic chamber in corrosive atmosphere
  containing sulphur dioxide, humidity and ozone.
--Normalized corrosion tests in salt mist atmosphere.
--Outdoor correlation exposure in normal operating
  conditions in two (later three) exposure fields.

The inner corrosion finally is studied by means of a test loop permitting to circulate different liquids through three absorbers with variabel parameters such as flow rate or temperature.

Description of tests and results.

Static pressure tests of absorbers (in the AT-5 facility).

Resistance of absorbers to overpressure.
This test is executed normally at an overpressure of 1.5 times the normal operating pressure. For safety reasons the absorbers are pressurized with water, not with air, using a plumbers, hand-operated pressurising device. From 16 tested collector types two (roll bonded aluminium absorbers) were severely deformed by the applied pressure. No bursts of absorbers were encountered.

Leak tightness test.

Several types of collectors and bare absorbers were tested so far for leakage with pressurized air at nominal operating pressure. On one absorber a leak of the order of 10 cubiccentimeters of air per minute at 6 bars pressure was found. This leak corresponds to a pressure drop of 0.02 bar/minute and represents the detection limit of this method. Smaller leaks can be detected with a helium leak detector now available.

These two tests can easily be performed and do not require expensive apparatus. It can be recommended to execute these simple tests on all collectors with roll-bonded absorbers before they are mounted on the roof (or even better before they leave the factory).

Resistance to life loads (AT-3).

For collectors with glass covers the resistance to wind pressure loads (up to 2400 Pa) or to snow loads (up to an additional 3000 Pa) does not seem to be a problem. In fact the glasses are normally 3 to 4 mm thick and are hence sufficiently resistant.

There might be problems on some collector concerning the resistance to negative pressures (wind suction) on the cover glazing. This concerns however the connection of the cover and the body (rigidity of the frame and its connection to the case) and not so much the glass cover itself. These problems would have to be studied with another apparatus.

Also for collectors with plastic glazing of the current design the resistance to mechanical deformation by wind and snow pressure seems to be quite sufficient, as long as the measurements are made at room temperature. Problems may occur , if any, at higher temperatures, where bowing and warping of the plastic glazings is more likely, but this cannot be studied with AT-3 so far.

Hail test. (AT-4).

It has been found experimentally with the hail gun (AT-4), that hail at our standard test condition of 2.5 J of impact energy (27mm diameter (=9.3 g); 23.1 m/s) is unproblematic for thermal collectors. Even ten times higher impact energies that occured in September 1982 at our site in reality (estimated to have been 26 J; 40 mm diameter; 42 m/s) did not damage any flat plate collector.

Hail can hence be considered to be unproblematic for flat plate collectors of current design.

(Eventually hail resistance of plastic covers, after embrittlement due to UV irradiation has to be studied further).

For evacuated tube collectors however hail resistance can be an important criterion: There are samples of one manufacturer that broke already at impact energies of 1 to 2 Joule, there are samples of another manufacturer, that broke at 3 to 4 Joule and there are others that resist still at 12 Joule and more of impact energy.

It is difficult to fix the value of the impact energy to which a solar device must resist, as this depends on the meteorological conditions of a given site. A rather reasonable value for european weather conditions seems to be about 2.5 Joule (our standard impact energy). Devices that break at lower impact energies are probably not apt for longer life.

For details see topical report "Solar Collector Resistance to Simulated Hail" in Solar Energy Programme Progress Report, July-Dec. 1982, page 19).

Thermal shocks.

Two types of thermal shocks are studied at the JRC:

- outer thermal shocks by spraying cold water onto the hot collector
- inner thermal shock by filling the hot collector with cold water.

In both cases the collector is heated up by irradiation from the solar simulator AT-6.

Immediately before the application of the spray the lamps are shut off. Then water is sprayed for 5 minutes onto the hot collector.

This type of thermal shock did not cause any damage to 6 different collectors treated, except some temporary condensation observed in one case.

Also in the case of the thermal shock by filling with cold water the lamps are shut off immediately before the filling. In the first moment of the filling operation the water evaporates and causes hence not only a thermal shock but also a slight, transient overpressure on the absorber, which however remains open to the atmosphere and hence does not get pressurized permanently. The water is then circulated for about five minutes in the absorber.

In one case of six collectors tested so far by this method the absorber was visibly lifted off from the thermal insulation for several centimeters, but this bowing was partially reversible. There remained however a permanent bowing of the absorber plate of about 1 cm in the upper part of the collector.

The results of the slow efficiency degradation tests are described in another paper.

Paper presented at the workshop
on Service Life of Solar Collector Components and Materials
Dec. 6 to 7th,1983 Technical University of Denmark,Lyngby.

by Gerhard Riesch, Commission of the European Communities,
Joint Research Centre, Ispra/Va, Italy.

Results of slow efficiency decrease tests made at the Joint Research Centre,Ispra.

In the field of slow efficiency degradation the following tests are made:

--Test for rain water tightness.
--Exposure to ultraviolet irradiation.
--Exposure to sun and weather in dry conditions (outdoors).
--Exposure to simulated sun (indoor exposure).

1.) Rain water penetration.

Rain water penetration into collectors is a frequently encountered event. It seems to be obvious, that rain water entered into a collector can damage the collector in the long run (corrosion inside of the box, soaking of the thermal insulation) and that it also can reduce its efficiency (condensate on the inside of the glazing.)

Two types of apparatus are used at the JRC to study this effect.

In one apparatus the collector is mounted in a vertical position inside of the pressure chamber AT-3. In front of the collector is installed a spray nozzle system, containing 20 or more nozzles in a square grid of about 30 cm grid distance, allowing to spray rather uniformely on the whole area of the collector. The nozzles are orientable and can be directed also towards selected points, for instance towards the outlets of the absorber connection studs.

Further the collector can be exposed to cyclic air pressure (about 0.1 c/s) of about +-200 Pascal. This treatment causes the collector to "breath", thus increasing the water penetration, as water in slits around the sealings ecc. can be sucked into the collector (as it occurs in reality under the influence of wind).

The other apparatus consists simply of two showers mounted on a rack on which the collector can be fixed in a 45 degrees inclined position.The showers are rather abundant and create a continuous film of water on the glazing of the collector.

The water penetration into the collector is determined by weighing the collector before and after the shower treatment on an accurate balance (precision +-1 g relative).

Ten collectors of recent construction were exposed to the shower during 2 hours on the rack facility. The measured weight increase varied from 7 g to 281 g showing that non of the tested collectors was completely water tight and that two were really very leaky.

Two of the collectors were then treated in the pressure chamber facility during 1 hour with application of +-200 Pa pressure cycles.The weight increase was about the same as in the simple shower facility.

It can be recommended that the aspect of rain water tightness of collectors needs further investigations.

In any case it seems to be preferable that all collectors, which, as it turns out, cannot easily be made water tight should be provided with suitably located drain holes on the bottom.

2.) Exposure to ultraviolet irradiation (AT-2).

For the irradiations three collectors with materials susceptible to uv-damage have been selected. Irradiations to ultraviolet doses equivalent to serveral years of outdoor exposure were applied at temperatures around or somewhat less than the normal operating conditions of the collectors. For details see topical report "Ultraviolet Irradiation of Collectors with the AT-2 Facility of ESTI", in Solar Energy Programme Progress Report, Jan.-June 1982, p. 19.

No significant damage could be observed after the exposure on any one of the three collectors. Based on this very limited statistics one might conclude that thermal collectors of the current design are not sensible to uv-irradiation. This statement seems to be confirmed by the experience gained during many years of operation of collectors, for which no damage due to uv-irradiation is known to have been reported.

Nevertheless the AT-2 facility can be used for screening collectors to identify eventually used non- uv- resistant materials.

UV irradiations should be done in rather severe conditions i.e. at high temperature, with high humidity of the surrounding atmosphere and with intermittent water spray on the samples.

3.) Outside exposure to sun and weather in dry conditions.
(with analysis of the Dry Exposure Temperature).

The efficiency of a flat plate thermal solar collector decreases with its lifetime due to reduction of the transmission of the coverplate, the reduction of the absorption of the absorber and the increase ot the heat losses.

A well established method to test the durability consists in the dry exposure of the collector during several months. During this dry exposure the collector is subject to daily thermal cycles, to general weathering (rain, wind, freeze) and to maximum temperatures, that are higher than the ones reached in normal operation.These higher temperatures of all inner parts of the collector may cause some accelerated aging for instance:

-by outgasing of the insulation and sealant materials and formation of an opaque layer on the inside of the cover;

- by thermal degradation of the optical quality of the absorber surface;

- by thermal degradation of the insulation material.

As an efficiency measurement facility is not always available it is useful to have during the long exposure, which lasts at least 2 months, already some quantitative measure of an eventual efficiency degradation.

This information can be obtained by monitoring during the exposure: the temperature of the collector absorber, the ambient air temperature, the global irradiation and the wind speed.

These data are collected (every 30 seconds) by a data-logger, a computer, that allows also the compacting and analysis of the data.

The analysis of the data is made by calculating heat balances: The integral over time of the incoming global irradiance from the starting time (in the morning) when the absorber has reached a given temperature T until to the end time (in the afternoon) when the absorber has reached again the temperature T. By extending the integral over that specific laps of time one has the same energy content of the collector and hence the total incoming thermal energy must have been lost by heat losses of the collector to the surrounding air. These heat losses (including the radiant heat losses) are proportional to the integral (over the same laps of time) of the temperature difference between the absorber and the surrounding air, which are also measured and calculated. The ratio of the two integrals is a measure of the "quality" of the collector, i.e. its ratio of effectively absorbed thermal energy and of effectively lost thermal energy. If this ratio decreased with time, the collector has degraded.

In reality the heat losses of the collector are not exactly proportional to the temperature difference between absorber and surrounding air, but they depend on the temperature of the absorber (non-linearity; radiation losses !) and other parameters, mainly on wind speed. A better method of analysis is hence more adequate, where only heat balances over small time lapses are considered (while the absorber temperature increases from T1 to T2 in the morning and decreases from T2 to T1 in the afternoon).
Details on the method are described in (Programme Progress Report,July-Dez.82, Rep.4072, p.26.).
Two collectors exposed in dry conditions on the roof of building 45 have been monitored since January 1982 in this way. The simple analysis method described, did reveal no loss of efficiency of the two collectors. This result was confirmed by a measurement of the instantaneaous efficiency in the solar simulator LS-1 at the end of 1982.
The collectors are now remounted on the roof for further

ageing. The more elaborate analysis of the data for temperature dependent heat losses is under way, which requires the time consuming writing and testing of computer programs.First results indicate that the precision of the data is quite sufficient to make such an analysis.

4.) Exposure to simulated sun (AT-6 facility).

The outdoor exposure as described under point 3.) can be substituted by an indoor exposure. If one supposes, that the major effects for the degradation of the efficiency are caused by the high temperatures reached (which is likely) then by increasing the temperatures one would expect an accelerated degradation. The high temperatures of the whole collector are obtained by irradiation under the solar simulator AT-6. In order to check whether during the long term irradiation, which is of the order of 200 hours or more, the efficiency of the collector has decreased, a continuous measurement of the same data as in the outdoor exposure is made, which permit to draw the heat balance of the collector. For a point model of the collector the temperature of the middle of the absorber can be taken to be characteristic. The absorber energy of the collector is then:

Absorbed energy = I * tau * alpha.

where

I= the irradiance of the lamps as measured by solarimeters,

tau = the transmissivity of the cover plate,

alpha = the absorptivity of the absorber.

The energy lost by the collector is:

Lost energy = k * (Tc -Ta).

where

k = a factor characterising the thermal losses,

Tc = the measured temperture of the centre of the absorber,

Ta = the measured temperature of the ambient air.

From the heat balance follows:

I * tau * alpha = k * (Tc -Ta) .

or

(Tc -Ta)/I = (tau *alpha)/k.

The ratio (Tc-Ta)/I is hence characteristic for the quality of the collector, as this quality is defined by a high value of tau and alpha and by a small value of the thermal losses k. If , under the influence of the thermal treatment, the transmissivity tau or the absorptivity alpha should diminish or the thermal losses k should increase, this would be indicated by the measured ratio (Tc -Ta)/I, which would decrease. If the ratio (Tc -Ta)/I remains constant during the irradiation one can deduce, that the efficiency of the collector has not changed.

Two collectors were treated by this method so far but no efficiency decrease has been found. This is in agreement with the outdoors exposure where for the same types of collectors no efficiency decrease was noted either.

The sensibility of the method has been checked however by artificially decreasing the tau of a collector (putting an extra glass pane between the light source and the collector) The ratio (Tc -Ta)/I has decreased in a well detectable way by about 15 %.

Work with this installation does continue.

Heinrich Wenzel
TÜV Bayern e.V.
Westendstr. 199
D-8000 München 21

DEVELOPMENT OF PRACTICAL METHODS FOR THE DETERMINATION OF THE STAGNATION TEMPERATURE AND THE DURABILITY OF SOLAR COLLECTORS

In 1979, a program was initiated to find suitable methods to determine the stagnation temperature of solar collectors. For this purpose, 6 different types of flat plate solar collectors representative of those in use at that time were exposed outdoors in Munich. From September 1979 up to October 1980, the stagnation temperature was measured continuously from 9 a.m. up to 4 p.m.

The findings are shown on picture 1. The result of the winter months is not shown in this picture, because at the beginning of the tests, no important values were expected. The curves below the stagnation temperature represent the ambient air temperature (°C), the monthly hours of sunshine and the monthly rainfall (mm). A correlation between the hours of sunshine and stagnation temperature or ambient air temperature and stagnation temperature was not found. The best correlation was obtained between the rainfall and the stagnation temperature. This surprising result may come from a few measurements which were carried out between the rainy days while the diffuse radiation was extremely low.

The result of these measurements is that there are only few days in the year, for which the same value of stagnation temperature are obtained. If you want to take the stagnation temperature as a scale for the degradation of the collector, then you better take two collectors of the same type, expose one outdoors and one in a room with constant air conditions and protect the cover and the coating by a non-transparent plate.

In picture 2 you find the degradation of the conversion factor and the degradation temperature at a wind velocity of 0 and 4 m/s. It was found, that the degradation of the collector with "black painting" was relatively low (A, C, D). These solar collectors with selective coating, however has a high degradation (E). Collector F has a relatively high degradation in the second year, because the adhesive paste between the two aluminium sheets and the tube degraded.

The hatched areas in picture 2 represent the degradation of the collector at a wind velocity of 0 and 4 m/s. The comparison between these two areas shows the joint losses of some collectors (A, B and D) to be rather high, while the joint losses of other collectors didn't increase (E, F). The degradation of the stagnation temperature of collector C was 0. The absorber of this collector is made of a copper sheet, on which a copper pipe is clamped.

Simultaneously to the measurement of the stagnation temperature the changes of the absorber temperature were measured from September 1979 up to August 1980. In table 1 you will find the changes of the absorber temperature for collector A. The exchanged air (V_{ges}) in one year between the enclosure and the ambient air you may calculate by the following equation:

$$V_{ges} = n \cdot V_1 \left(\frac{T_1 + \Delta \vartheta}{T_1} - 1 \right)$$

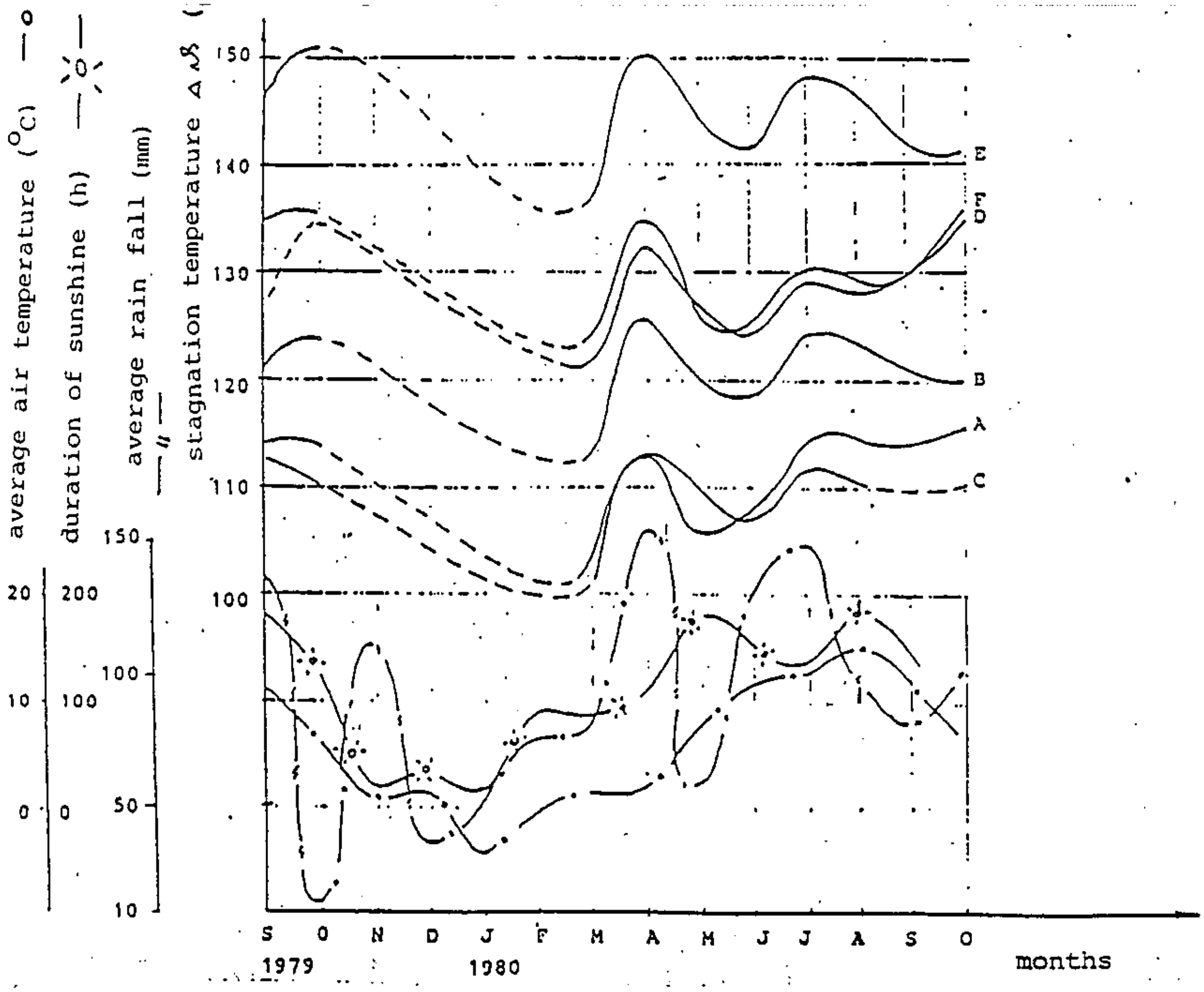
It means:
V_1 = air volume in the enclosure
T_1 = temperature of the ambient air
n = number of temperature changes according to table 1
$\Delta \vartheta$ = Difference of absorber temperature and temperature of the ambient air (table 1)

According to this equation and table 1 you will receive, that the air volume V_{ges} of the enclosure will be changed in one year about 49 times. By replacing $\Delta\vartheta$ by a bigger amount, which is interesting for the simulation in a laboratory, you have to heat an absorber 89 times to a $\Delta\vartheta$ of 150 K. If you don't take stagnation conditions but cycling conditions the absorber temperature change $\Delta\vartheta$ will not exceed about 40 K. This means, that the number of heat cyclings "n" will reduce from 89 to 36 times. For a life time of 15 years you than get about 550 cycles.

The result of another method to accellerate the ageing process is shown in picture 3. The collectors were put in a climatic chamber with a tropical climate (for example the first 3 days 40 °C and 95 % humidity). The absorber were cooled by water with a temperature of about 12 °C. Before and after each measurement period the collectors were weighed. Picture 3 shows the amount of water each collector absorbed by water diffusion. The result was, that the enclosures made of glass and metall were almost completely tight against water diffusion (A, B). The enclosures of the other collectors (D, C, E and F) were partially made of plastic, with a much higher water diffusion.

The tightness of the sealing does not appear to be that important for this test method. The method mentioned could be further improved by using additives like SO_2, CO_2, H_2S and NO_x.

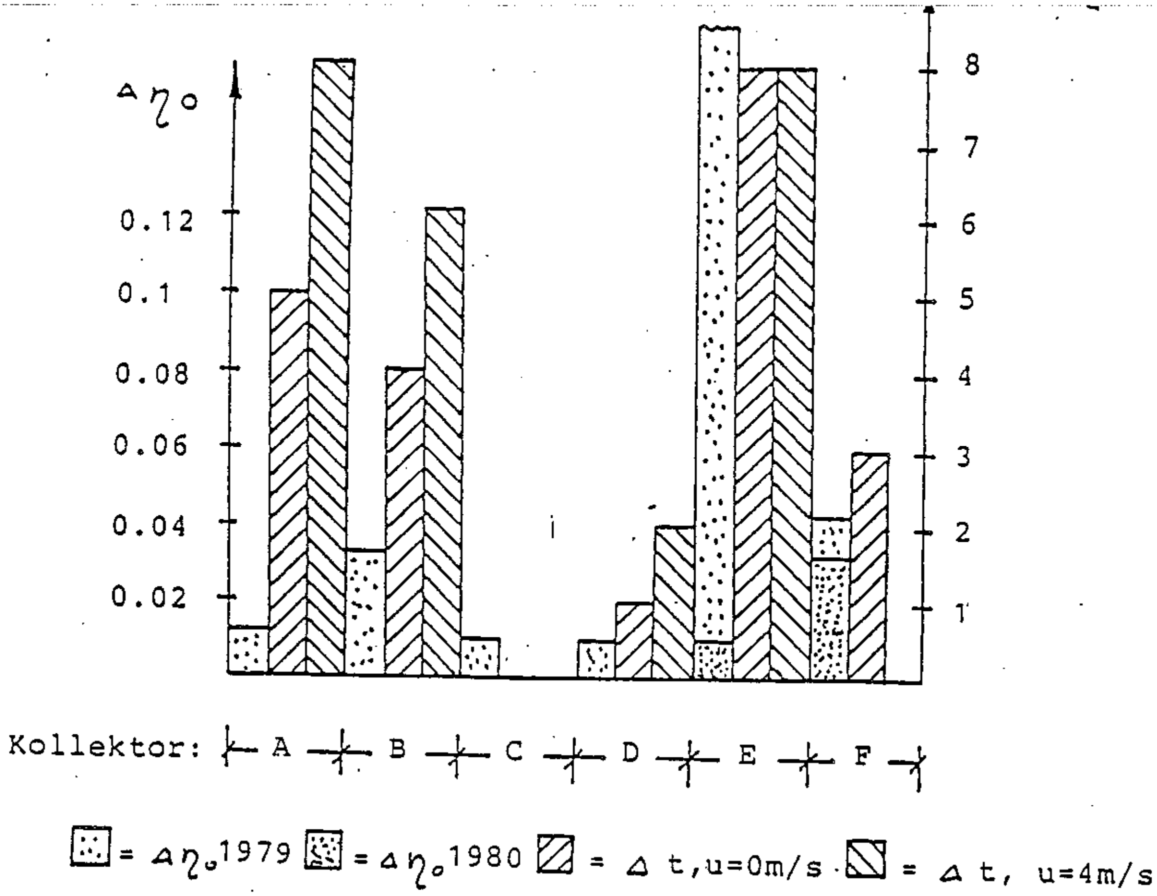
To determine the partial pressure required, a chemical analysis of the condensed water of these collectors which are build in closed systems should be made. Besides the chemical analyses the number of hours should be registred as soon as condensed water develops in a system. An accellerating process will be reached by decreasing artificially the pH-value to an estimated amount of 5 to 4 or less.



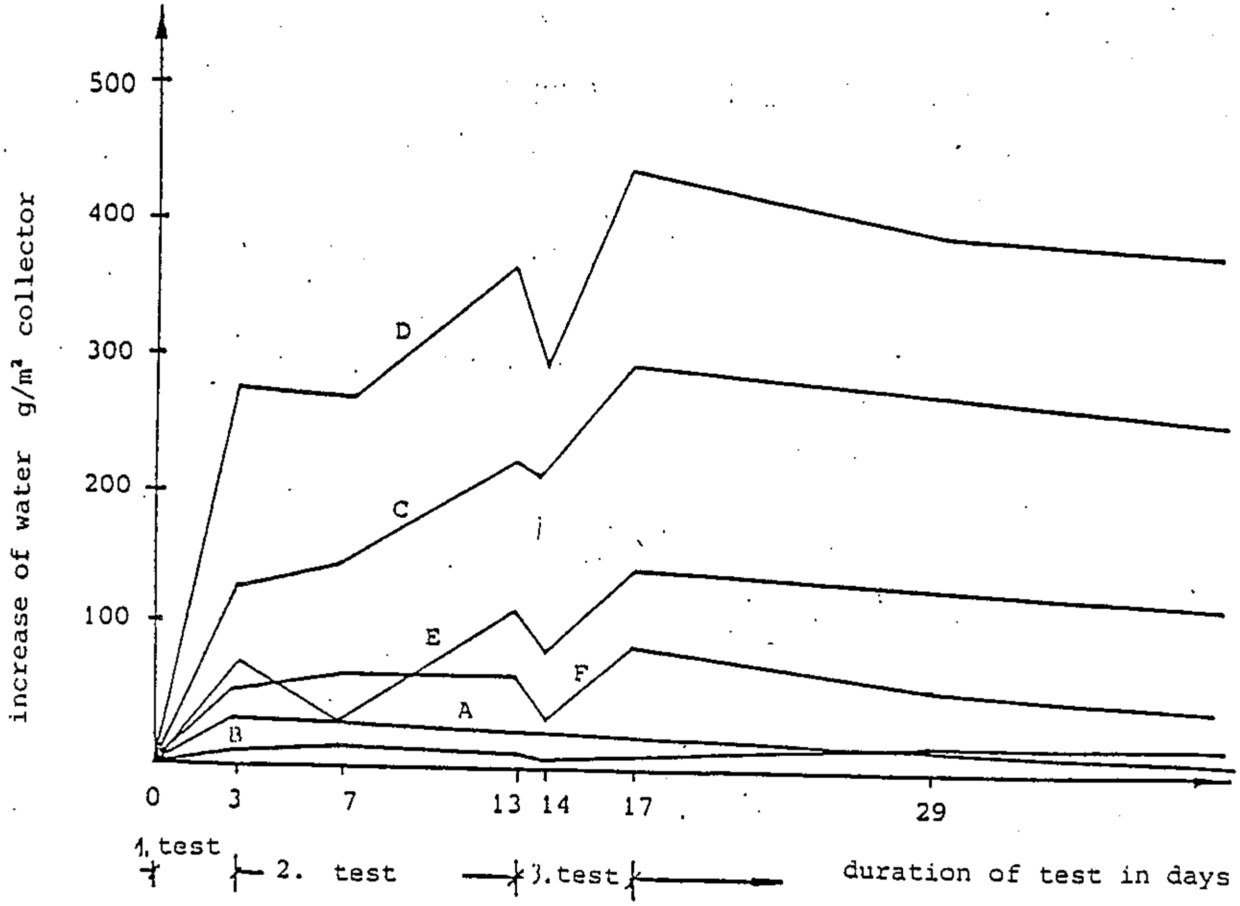
picture 1: seasonal oscillation of the difference between the stagnation temperature and the ambient air temperature of the collector A-F at an irradiation of 1ooo W/m²

table 1: number n of the absorber temperature changes Δϑ for collector A

Δϑ °C	5	10	15	20	25	40	60	80	100	120	140
September 1979	9	5	3	2	7	6	0	4	3	1	1
October 1979	35	20	11	8	8	8	7	5			
November 1979	20	7	5	4	4	4	2	1			
December 1979	4	6	3	1	3	2	2	1			
January 1980	12	2	3	1	2	2	0	3	5		
February 1980	33	8	2	3	5	4	2	8	7		
March 1980	43	27	16	15	7	5	3	7			
April 1980	21	20	13	10	6	6	2	4	2		
May 1980	38	27	20	9	8	4	2	7	1		
June 1980	54	40	28	22	17	10	4	5	3		
July 1980	51	32	14	15	3	2	2	5	2		
August 1980	64	21	10	13	7	4	7	8	8		
Sumary	384	215	128	103	77	57	33	58	31	1	1



picture 2: Degradation of η_0 and of the stagnation temperatures at the wind velocity of 0 and 4 m/s



picture 3: increase of water of the collectors A-F in the climatic chamber

PRESENTATION AND EVALUATION OF INDOOR TEST PROCEDURES FOR THE DURABILITY OF SOLAR COLLECTORS, AS PRESENTLY USED IN THE NETHERLANDS

A. Koelimij, I.B.B.C. - TNO, The Netherlands.

1. INTRODUCTION

Since 1982 IBBC-TNO and TPD-TH are involved in the development of durability tests for solar collectors. The functional durability of a solar collector in operations depends on the decrease of the efficiency through the years.
The efficiency of a solar collector in operation partly depends on the performance of the joints in the collector case.
As a result of the penetration of water into the collector, the efficiency will decrease and corrosion of the collector will be stimulated.
The efficiency may also decrease as a result of airleakage.
A collector, in operation or in stagnation conditions, is exposed to various termal loads which can affect the joints.
With the testprogramme the influence of several thermal loads on the efficiency (as measured in the laboratory), the airleakage and the raintightness of the solar collector is to be determined.

T.N.O.	Netherlands Organisation for Applied Scientific Research
I.B.B.C.	Institute for Buildingmaterials and Buildingstructures
T.P.D.	Institute for Applied Physics
T.H.	Technical University

2. TEST PROGRAMME

The testprogramme starts with the determination of the following properties of the solar collector:

A
1. Measurement of the airleakage through the collector.
2. Determination of the efficiency curve of the collector.
3. Test of raintightness of the collector.

The following thermal loading tests are then carried out:

B
1. Stagnation test followed by test of resistance of the collector to temperature shock *.
2. Test of resistance of the collector to thermal cycling at high temperatures.
3. Test of the resistance of the cover to temperature shock.
4. Exposure to frost and thaw cycles.

The properties of the collector, as mentioned before, are determined again.

---

* For practical reasons, this test has been carried out directly after the efficiency test, this in contradiction with the testprogramme.

3. DESCRIPTION OF THE TESTS

A 1. Measurement of the airleakage through the collector.

The lower half of the solar collector is enclosed in an airtight case in which the airpressure is raised from 50 N/m^2 to 750 N/m^2 overpressure, with increments of 50 N/m^2. At each step the airleakage through the collector is measured

A 2. Determination of the efficiency curve of the collector

A solar collector is characterized by the efficiency curve. The determination of this efficiency curve takes place at the T.P.D. under the solar simulator according to an internationally agreed test method: at fixed weather conditions (solar insulation, ambient temperature, wind speed etc.) the ratio between heat output and heat input is measured at several temperature levels.

A 3. Test of raintightness of the collector.

The solar collector (tilted 40°) is exposed to both rain (100 mm/h) and wind (8 m/s and 20 m/s) from 3 different directions.
The collector is checked visually for penetrated water.
A collector which has been developed to be place in a roof construction is tested within such a simulated roof.
After that the collector is placed into an airtight case and sprayed with water (approx. 100 mm/h) while the airpressure in the case is changed 20.000 times from 10 N/m^2 to 200 N/m^2 overpressure.
After the test the collector is checked visually for penetrated water.

B 1. Stagnation test followed by testing the resistance of the collector to a temperature shock

This thermal load may occur in practice when an installation is put into operation after a period of stagnation.

In this test the collector is placed under a "sun"-simulater while the absorberplate is empty. Due to radiation the temperature of the absorberplate increases to the stagnation temperature (100 °C-200 °C).
When the stagnation temperature is reached, the absorberplate is filled with cold water (approx. 10 °C), while radiation continues.
During this test the temperature of the absorberplate is recorded continuously and the collector is inspected visually.

B 2. Test of the resistance of the collector to thermal cycling at high temperatures

This test imitates the effects of a long period of stagnation.

Hot oil (120 °C) is pumped through the absorberplate for 3 hours.
The pumping is then stopped and the absorberplate empties itself. For a period of 3 hours, the collector can cool down at an airtemperature of 20 °C.
After the test the collector is inspected visually.

B 3. Test of the resistance of the collector cover to temperature shock

This test imitates sudden rainfall on a solar collector which is under stagnation conditions.

The collector is heated by pumping hot oil (120 °C) through the absorber plate.
When the temperature on the cover has stabilized, the cover is sprayed with water of 8 °C until the temperature of the cover has stabilized again.
The cover is then inspected visually.

B 4. Exposure to frost and thaw cycles

This test imitates the effect of ice on solar collectors.

The collector is placed into a box, insulated to minimize thermic heatlosses.
The air in the box is cooled to -15 °C. When the temperature of the collectorcover is -2 °C, the collector is sprayed with water for a short period of time, afterwhich the collector gets frozen.
When the cover temperature reaches - 10°C the cooling is stopped, the air is heated and water with a temperature of 40 °C is
pumped through the absorberplate, until the cover temperature is 5 °C.
The cooling then commences again.
This cycle is repeated 19 times.
After the test the collector is inspected visually.

4. RESULTS

Until now 6 flat plate solar collectors from 3 different manufactures have been tested.
Now follows a summary of the results of the tests.

The airleakage through the collectors of different manufactures varied from $2,7 \times 10^{-4}$ m^3/s at 50 N/m^2 overpressure to $4,5 \times 10^{-3}$ m^3/s at 50 N/m^2, overpressure.
The airleakage through some solar collectors increased as a result of the thermal tests.

Rain penetrated into the solar collectors of two manufactures in the first and the second test.

The efficiency of the collectors of two manufactures decreased 2-3% as a result of the tests.

On one solar collector, the adhesion of the sealant to the collector case had been a little damaged by the frost-thaw test.

5. EVALUTATION

Air leakage through a solar collector in operation may cause decrease of the efficiency and must therefore be limited.

Waterpenetration may also decrease the efficiency.
This must be avoided by making a raintight collector case. Moreover, it is advisable to make drainage holes in the collector case.

The effects of the thermal tests on the performance of the solar collectors were limited.

The results of the indoor tests will be compared with the results of outdoor stagnation tests which are now in operation.

Institute for Buildingmaterials and Buildingstructures T.N.O.

PREVENTION OF CORROSION-, SCALE-FORMATION AND FOULING-DAMAGE IN LOW- AND MEDIUM TEMPERATURE CLOSED LOOP COLLECTOR SYSTEMS

M. Bruck, Austrian Solar and Space Agency.

1. INTRODUCTION

The following report essentially gives a short overview of the state of the art of the ongoing "corrosion activities" of the "solar group" of the Austrian Standards Institution (Österreichisches Normungsinstitut).

2. CHARACTERISTICS OF LOW AND MEDIUM TEMPERATURE CLOSED LOOP COLLECTOR SYSTEMS

The basic elements of the collector loop are the collector array, piping, heat exchangers, circulation pumps, valves, control-elements, sealing materials and the heat transport medium. If water or water/antifreeze mixtures are used as a heat transport medium, the following "boundary conditions" are typical:

- water velocity: 0,05 - 1 m/s
- maximum operating temperature: ≤ 80 °C
- minimum operating temperature: ≥ 10 °C
  In case of uncovered "absorbers" serving as low temperature heat sources of heat pump systems the minimum operating temperature is ≥- 15 °C
- stagnation temperatures: 80 °C (uncovered absorbers) to 230 °C (vacuum tubes)
- inlet-outlet temperature difference under operating conditons: 4 K - 10 K
- Leakage (evaporation losses etc.): 0,05 % - 0,1 % of the total water content per day
- collector loop
- most commonly the closed loop consists of one or a combination of the following materials: steel, galvanized steel, stainless steel, cast iron, copper, aluminium, various types of brass and bronze.

Dipl.-Ing. Dr. M. BRUCK, Austrian Solar and Space Agency (ASSA), Vienna

The important properties of the circulating water are:

- o pH
  which gives an indication on the relative acidity or basicity of the water
- o Hardness
  which refers to the amount of calcium and magnesium minerals present in water
- o Alcalinity
  For the water most commonly used in solar collector systems the carbonate (CO_3) and bicarbonate (HCO_3) alcalinity play a dominant role.
- o Conductivity
  which indicates the amount of dissolved minerals and gases in water.

3. PROBLEMS

In the closed loop of the system one or more than one of the followin problems may occur leading to an often considerably reduced service life of the total system.

3.1. Corrosion

Corrosion is an electrochemical process; metal ions dissolve into the electrolyte (water) at the anode. The electrons - left behind - flow through the metal to the cathodic region where electron consuming reactions occur. The result is the loss of metal at the anodic area and often the formation of a deposit. Mostly corrosion appears as general attack when the corrosion is uniformly distributed over the metal surface, as pitting attack, when only small areas are affected or as galvanic attack, when one of two different metals which are in contact, corrodes.

Corrosion is mainly caused by one of the following effects:

- Different metals in galvanic contact
  In this case the more active metal can corrode rapidly (aluminium/steel, steel/brass etc.).
- Different oxygen concentrations within the loop
  Due to small leakages, fresh water addition and oxygen diffusion the amount of oxygen dissolved in water can be considerable even in closed systems.
- Different electrolyte concentrations within the loop.

Furthermore corrosion effects can be increased by

- pH
  Acidic and (slightly) alcaline water can dissolve metals and also the protective oxide layers on metal surfaces.
- Temperature effects
  In the temperature range below ~ 70 °C approx. every 20 K increase in temperature causes corrosion rates to double.
- Dissolved metallic solids increase the electrical conductivity and therefore the probability of corrosion. Suspended solids can influence corrosion by erosive and/or abrasive action.
- Water velocity
  In case of high velocities corrosion can be increased by increased transportation rates of oxygen or corrosion products. In case of low water velocities localized corrosion elements can be established (deposition of suspended solids).

3.2. Scale

Theoretically, in closed systems, scale formation (calciumcarbonate, calciumphosphate, magnesium salts, silica etc.) should be negligible, because the amout of scale forming materials in the water volume is negligible, but due to the leakage induced need of fresh water considerable amounts of scales can be deposited in the system within a period of two or three years.

3.3. Fouling

The deposition of solid materials - others than scale - such as

- o corrosion products
- o dirt and silt
- o lubricants
- o sand etc.
- o sealing material

can cause serious damages in the system.

4. RECOMMENDATIONS TO PREVENT CORROSION-, SCALE- AND FOULING INDUCED DAMAGE

4.1. Material Requirements

- o The use of galvanized steel pipes and aluminium/copper combinations should be avoided.
- o Aluminium and aluminium compounds, steel/copper and steel/aluminium combinations can be used provided that $pH \leq 9$ and oxygen content $\leq 0{,}05\ g/m^3$.

4.2. Water Requirements

- o pH
  In general the pH of water resp. water/antifreeze solutions must be in the range of $8 \leq pH \leq 9{,}5$.
- o Hardness
  small systems: $\leq 2\ mol/m^3$ (11,2 ° dH)
  large systems: $\leq 0{,}1\ mol/m^3$ (0,6 ° dH)
- o Chloride content $\leq 60\ g/m^3$
  In case of systems consisting of different metallic materials inhibitors should be applied if the chloride content exceeds $30\ g/m^3$.

- Oxygen content ≤ 0,1 g/m³ for steel and cast iron systems
  ≤ 0,05 g/m³ for systems consisting of different metallic materials (see 4.1)

4.3. Inhibitors

o Phosphates (P_2O_5)	5 - 30 g/m³
o Polysilicates (SiO_2)	20 - 60 g/m³
o Hydrazine (N_2H_4)	1 - 5 g/m³
o Sulphite (SO_3)	20 - 40 g/m³

$NaSO_3$ can be used provided that the total hardness of the water does not exceed 1,8 mol/m³ (10 °dH).

For steel/copper systems phosphates and hydrazine should not be used.

For small (normally fresh water filled) systems only polysilicates or silicate-based multi-component products should be used. For large (softed water filled) systems phospates, polysilicates or silicate-based multi-component products are recommended. Sulphite should be used for oxygen absorption.

4.4. Antifreezing Agents

Glycol-based agents are recommended; the use of agents based on esters should be avoided. Below the boiling temperature of pure water no dissociation of the water/antifreezing agent mixture should occur.

4.5. Pretreatment

The following preparations and start-up-proceedures are recommended:

- system cleaning
- application of pretreatment chemicals
- Initial high dose application of corrosion inhibitors.

4.6. Control

The inhibitor level should be checked at regular intervals. Also the amounts of dissolved substances, heavy metal ions and the pH of water/

antifreeze solutions should be checked at least once a year.

LITERATURE

ÖNORM M 7545 (Entwurf)	Verhütung von Schäden durch Korrosion und Steinbildung in Warmwasserheizungen bis 120 °C
ÖNORM M 7702 (Entwurf)	Sonnentechnische Anlagen Flachkollektor-Sonnenheizungsanlagen zur Warmwasserbereitung "Anforderungen"
B.J. Kelly	Korrosionsschutz in geschlossenen Heißwasser- oder Kaltwasser-Umlaufsystemen Deutsche Nalco Chemie GmbH Sonderdruck 134
K. O. Lagerkvist, H. Wannerholm	The Durability of Solar Collectors Swedish Council for Building Research, 1982
M. Bruck	Alterungserscheinungen bei Flachkollektoren Solarheizungssysteme 1980 Austrian Solar and Space Agency (ASSA), Wien 1980

EIDG. INSTITUT FÜR REAKTORFORSCHUNG
INSTITUT FÉDÉRAL DE RECHERCHES EN MATIÈRE DE RÉACTEURS
5303 WÜRENLINGEN (Schweiz)

SONNEN-
ENERGIE

REPRINT OF A
CONTRIBUTION TO THE
IEA Task III Workshop on

SERVICE LIFE OF SOLAR COLLECTOR COMPONENTS AND MATERIALS

December 6 - 7, 1983

Technical University of Denmark

Lyngby, Denmark

EIR SOLAR HEATING PLANT

CORROSION SURVEILLANCE PROGRAM

K.H. Wiedemann

Corrosion surveillance of the EIR solar heating plant OASE

K.H. Wiedemann, Swiss Federal Institute for Reactor Research,
CH-5303 Würenlingen, Switzerland

Abstract

For a corrosion surveillance program of the EIR solar heating unit OASE, the coolant of the flat collector circuit has been controlled and material samples mounted in a circuit by-pass have been tested periodically. The results of the first 13 months are published in the EIR-Report No. 457. This report presents the results of the coolant tests as well as the material samples tests after 25.5 or 33 months of surveillance, respectively.

At the start of the program the composition of the coolant was 65 Vol. % deionized water, 35 Vol. % ethylenglycol, and 15 g/l inhibitor. This composition remained practically constant.

The metal contents of the coolant samples show large differences, because of deposits of metal containing precipitates, the amount of them being temporal and locally different; p_H and electrical conductivity remained practically constant. Therefore, corrosion in the circuit cannot be recorded by p_H or electrical conductivity readings or by chemical analysis of coolant samples.

The metal losses at the material samples in the by-pass have been determined after two years:

aluminium	ca. 70 µm;
mild steel St 37	ca. 0.3 µm;
red brass RG-5	ca. 0.4 µm;
stainless steel Cr Ni 18 10	ca. 0.1 µm.

The greatest quantity of the metal loss occured during the first year and increased only slightly during the second year. Pitting corrosion has not been observed on any material.

EIR SOLAR HEATING PLANT
CORROSION SURVEILLANCE PROGRAM

K.H. Wiedemann

Swiss Federal Institute for Reactor Research (EIR)
CH-5303 Würenlingen, Switzerland

1. INTRODUCTION

The EIR solar heating plant "OASE" was the largest of its kind when it was started up in 1978. With this unit, the warm water supply of the institute's personnel restaurant - about 5000 liters at 80° C per day - is prepared mostly by solar energy. The design of the plant allows the obtention of practical experience, and also facilitates several investigations to be carried out, e.g. the corrosion behaviour of materials in the coolant circuit under service conditions.

The reliability and the durability of a solar heating system is essentially dependent on the corrosion resistance of the materials used in the coolant circuit. A knowledge of the corrosion behaviour of the materials in the coolant is a precondition for the design of a coolant circuit as well as for an optimization of the working conditions.

A corrosion surveillance program has been commenced for the EIR solar heating unit. The program includes two sub-programs:

- Surveillance of the circuit coolant
- Testing of circuit material samples, mounted in a circuit by-pass.

The results of this program are available for the program "Durability and Reliability of Solar Heating Plants", which is a sub-project of the "Program to Develop and Test Solar Heating and Cooling Systems", run by the International Energy Agency (IEA).

2. SURVEILLANCE OF THE CIRCUIT COOLANT

The goal of this part of the program was to find out whether corrosion in the circuit could be recorded by p_H or electrical conductivity readings.

At the start of the surveillance program the composition of the coolant was about 65 vol.% deionized water, 35 vol.% ethyleneglycol, and 15 g/l inhibitor (9.5 g/l borax, $Na_2B_4O_7 \cdot 10\ H_2O$; 5 g/l sodium benzoate; 0.5 g/l benzotriazole*).

Fig. 1, which originates from laboratory tests, shows that

- p_H depends only on the glycol content of the coolant, while the inhibitor concentration does not influence p_H;
- the electrical conductivity decreases with increasing glycol content, but increases with increasing inhibitor concentration.

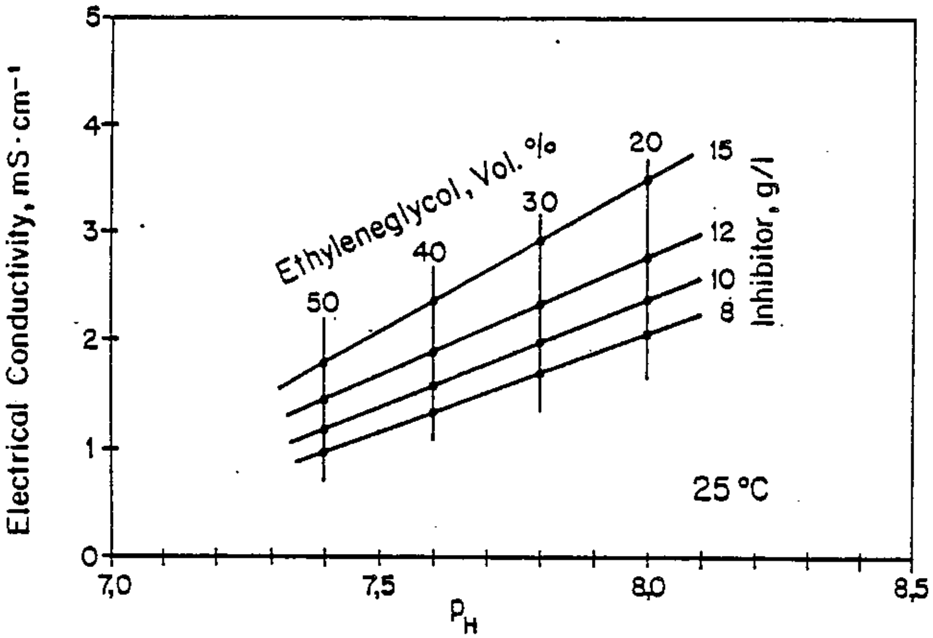


Fig. 1. p_H-value and electrical conductivity of water-ethyleneglycol mixtures with different concentrations of a given inhibitor.

Note that the diagram given in Fig. 1 is only valid for a certain inhibitor composition at a given temperature; for other inhibitors and temperatures, one has to develop corresponding diagrams by laboratory tests.

---

* This inhibitor composition has been recommended from another source after the occurence of a leak caused by corrosion in an aluminium rollbond absorber plate.

At certain intervals, a sample of the coolant is taken from the circuit for p_H and electrical conductivity tests and for analysis of the ethylene-glycol, inhibitor and dissolved metals originating eventually from possible corrosion processes on the circuit materials. During the period before the surveillance program was started, limestone containing water was used in the coolant. Due to this a limestone layer was built up on the inner surface of the circuit. As a consequence of this the calcium content of the coolant samples has now also been determined.

Fig. 2 shows the results of the first 35 months of the circuit coolant surveillance.

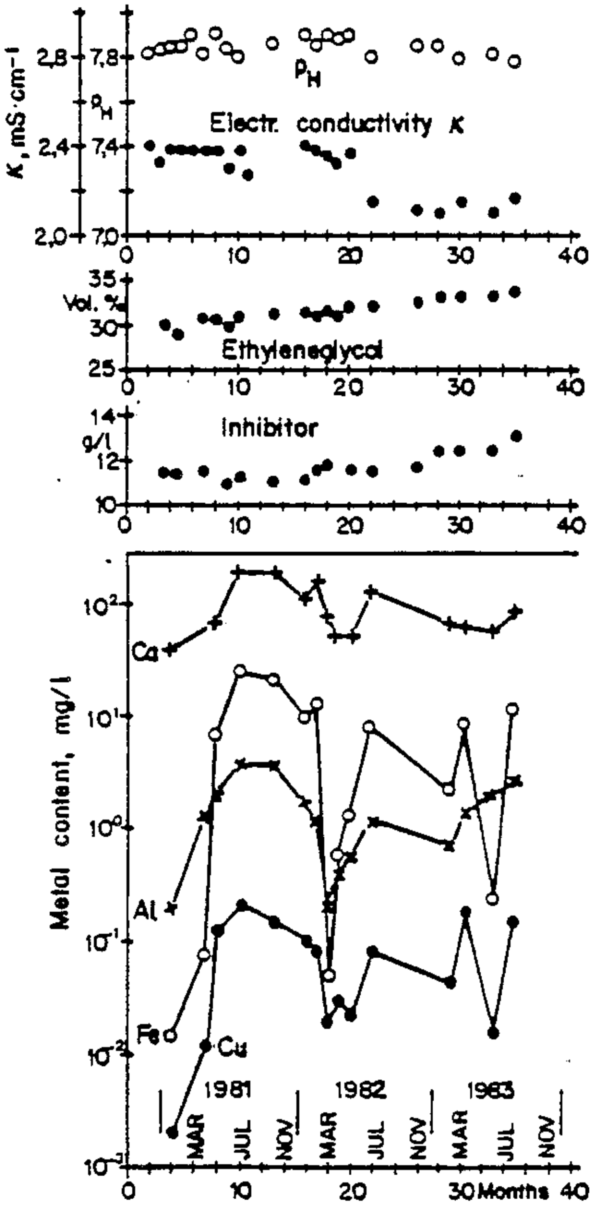


Fig. 2 Coolant Samples.
p_H, electrical conductivity, composition, and metal content during the time in service.

Table 1: Corrosion in the EIR Solar Heating Plant Coolant (65 vol.% deionized water; 35 vol.% ethyleneglycol; 15 g/l inhibitor*).

	Metal Loss			
	After 1 year		After 2 years	
	mg/cm^2	µm	mg/cm^2	µm
Aluminium	16	58	16.5	60
Red Brass (RG-5)	0.25	0.3	0.3	0.35
Mild Steel (DIN 2440)	0.15	0.2	0.2	0.25
Stainless Steel (AISI 304; CrNi 18 10)	0.08	0.1	0.08	0.1

* Inhibitor

Borax, $Na_2B_4O_7 \cdot 10\ H_2O$	9.5 g/l
Sodium Benzoate	5.0 g/l
Benzotriazole	0.5 g/l
	15.0 g/l

present in the circuit system will not be changed unless there is severe corrosion damage; this is to study the corrosion behaviour of the mentioned materials in a given coolant composition over a long period of service.

REFERENCES

K.H. Wiedemann
EIR Solar Heating Plant OASE - Investigations on the Circuit Coolant and on the Corrosion Behaviour of Flat Collector Circuit Materials.
EIR-Report Nr. 457, March 1982 (in German).

K.H. Wiedemann
EIR Solar Heating Plant OASE - Corrosion Surveillance, Part II
EIR-Report Nr. 462, August 1983 (in German).

INPROVEMENT OF RELIABILITY, DURABILITY AND EXPECTED LIFETIME FOR SOLAR COLLECTOR SYSTEMS.

P. V. Pedersen
Thermal Insulation Laboratory
Technical University of Denmark
Lyngby. Denmark

1. The IEA cooperative work

The work to improve reliability, durability and expected lifetime of collector systems in Denmark has a strong connection to the collaborative work within the Solar Heating and Cooling Programme of the International Energy Agency (IEA), Task III, subtask B and F. The aim here is to achieve knowledge of operating solar collector systems with respect to reliability and durability, to be able to identify performance requirements and to make qualified predictions of expected lifetime of solar collector materials and components.

Untill now there have been 3 different important activities:

1. Compilation and analysis of operational experience with solar collector systems
2. Development of accelerated material tests and service life testing
3. Development of complete collector tests.

A database of failures with reliability and durability and also good design features of solar collector systems will be developed.

Degradation factors and degradation mechanisms (corrosion, ageing, etc.) will be identified and investigated as basis to develop useful accelerated test procecures, and results from accelerated tests should be compared to reality.

When you want to identify degradation factors for solar collector components and materials, it is especially the outdoor climate, the climate inside the solar collector, the operation of the solar system, and condensation and outgassing that are of importance. The use of corrosion classes, could be a useful tool. Measurements of temperatures and humidity inside collectors under different circumstances can be used as an indicator of the corrosivity here. The "inside" collector climate can for example be expressed in different corrosion classes 1, 2, 3 or 4., which an absorber surface treatment should be able to cope with.

It is also the aim to try to identify optimal ventilation rates of solar collectors which can reduce condensation without allowing rain penetration.

2. Useful lifetime of solar collector systems

The useful lifetime of a solar collector system can be estimated from an estimation of the following items:

- the expected lifetime of the cover material - the expected lifetime of the necessary tightening systems, cover/enclosure assembly, connection holes, enclosure assembly and flashing system.
- the expected lifetime of the absorber (depending on the climate inside the collector = corrosion class).
- the expected lifetime of heat exchanger, connections and the piping system (considering knowledge of system operation, fluid and materials).
- the influence of condensation and outgassing for the actual collector. (Is there for example a satisfatory ventilation rate ?).
- the possibility for maintenance and repair (can the collector cover or the absorber for example be changed or repaired ?).

Here it is important to note that we have not limited ourselves only to look at the collector alone, but include connections, piping system and heat exchanger or storage tank, which all are part of what one would call the solar collector system.

It is also very important to investigate to which extent a solar collector system is or can be integrated in the building it is supposed to be used for. In the long run, the ideal lifetime of a building integrated solar collector system, which is regularely maintained as other builing components, should be the same as the normal lifetime for buildings.

3. Some results from 52 IEA solar collector system inspections

To be able to evaluate the reliability and durability of operating solar collector systems in the IEA participating countries, inspections of 52 solar collector systems in 11 different IEA countries have taken place since 1982 as a collaborative effort. A special inspection format was developed for this purpose in order to obtain important information on materials, components, system operation, etc. Researchers at the Thermal Insulation Laboratory have compiled and analysed the reports. A final report with all results is expected to be finished during 1984.

All in all, 6975 m^2 of solar collectors were represented in this investigation. Participating countries were Sweden, United Kingdom, Denmark, Belgium, Austria, Australia, The Netherlands, Germany, Switzerland, the USA and Japan.

19 solar collector installations had more than 50 m^2 of solar collectors. 16 installations had between 10 and 50 m^2 of collectors. And 17 installations had less than 10 m^2 of collectors. 36 out of the 52 inspected solar collector systems were domestic hot water systems, while the rest were combined systems either for heating or cooling of houses or for swimming pool heating.

11 of the solar collector systems were less than 2 years old. 29 were between 2 and 5 years old. 10 were between 5 and 10 years old. 1 was 16 years old and 1 was 20 years old. The two last mentioned installations were from Australia and are interesting because of their age, since 20 years is considered to be the wanted and expected lifetime of a solar collector system. The two old Australian solar collector systems were of a relatively good quality and have operated without serious problems. There is still observed condensation in the collectors and there is a slight galvanic corrosion at the connections. It is clear that it has especially been the outer parts, i.e. the enclosure, the attachment, the connections and the piping system which have suffered from the 20 years of operation. These problems can to a large extent be referred to as quality problems of the mounting and the installation.

The lifetime of the 52 inspected solar collector systems was also estimated in the inspection reports. For most of the inspected solar collector systems a lifetime of 15-20 years was expected, and several examples of good design features was reported.

The installations which were between 2 and 5 years old had a lower expected liftetime. The reason could be a lower quality of the systems installed in the years 1975-1978, when the solar market expanded very quickly. It was also interesting to see that the installations which were less than 2 years old seemed to be of a much better quality.

As a part of the evaluation of problems and failures, the inspected solar collector systems were divided into 3 different groups. Group no. 3 was used for solar collectors which had serious failures or problems with reliability and durability. Failures and problems which could be referred to the construction or materials used and which would lead to an unacceptably low lifetime.

Group 2 was used for solar collectors which had failures or problems which could be easily mended without completely changing the construction. And group 1 was used for solar collectors without failures or problems. 16

solar collectors were placed in group 1 with an expected lifetime of at least 20 years. 17 solar collectors were placed in group 2 and 12 solar collectors were placed in group 3. A few collectors were not possible to place in any of the groups.

4. Indoor and outdoor tests of 22 solar collectors in Denmark

The reported failures and problems for solar collectors in the inspection reports were very similar to what was seen in Denmark in connection to indoor and outdoor reliability and durability tests performed from 1980 to 1983 of 22 different solar collectors.

Here it was concluded that especially solar collectors which are not raintight or which have problems with condensation over long periods cannot be expected to have a long lifetime.

For this reason it is a very necessary and important demand to the construction of solar collectors in the wet northern European climates that they are raintight and are well ventilated with outside air.

Failures at the cover/enclosure assembly, the piping holes or at the corners are normally the reason for collector leaks.

Ventilation shall be made in such a way that condensation in the morning can be evaporated into the solar heated ventilation air inside the solar collector and can get out near the top without leaving condensed water in unwanted places.

The very effective selective solar collectors which are used now can reach temperatures of 180-200 C on the absorber. This means that you will have to choose materials which do not deteoriate at high temperatures. Plast foam insulation materials, for example, will meet heavy degradation at temperatures exceeding 130 C. Outgassing from insulation and gaskets can reduce the transmission and can also have a corrosive effect. Plast covers can collapse at stagnation because of a combination of a high stretching coefficient and a low heat transmittance. This can be prevented by a profilation of the cover.

Almost all of the 22 tested collectors had several good details and gave many examples of good use of materials.

On the other hand many collectors had one or more failures in the construction and were not designed to meet all the demands a solar collector should be able to meet. Most of the collectors were 1. generation products whose development were not yet adapted for the experience from many years of practice.

Since the tests were performed, the development in Denmark towards more efficient collectors with less durability problems has succeeded very well.

5. Description of the tests

The test programme started with indoor tests of reliability and short-time durability of solar collectors (see table 1). Here it has been possible to detect collector failures, which also have been observed under operation conditions. (1)

TABLE 1 The indoor Reliability and Durability Test Programme includes the following tests:

1. Test of air leakage in the collector.
2. Stagnation of collector followed by absorber shock.
3. Dryboiling of collector followed by cover shock.
4. Thermal cycling at high temperatures.
5. Rain leakage test with and without simulated wind load.
6. Wind load test.

Examples are covers which break or collapse at stagnation, insulation material wich bulges, expands, gets brown or cracks at stagnation, collectors with a very high rate of air leakages and collectors which are not raintight. High temperatures also lead to outgassing for nearly all collectors. When outgassing is observed, separate temperature tests of different materials are made.

The indoor test are very useful because they can be made in only 3 days in connection to the established solar simulator efficiency test. They can give the necessary indication of the ability of collectors to withstand high temperatures, rain- and wind loads. Other failure modes for collectors connected to flashing, connections, piping- system and installation, and problems with longtime durability, e.g. corrosion, ageing, degradation, dirt, frost and condensation should be identified by other tests and inspections of collectors in operation.

The indoor tests of reliability and short-term durability of solar collectors are supposed to be included as a part of the necessary system evaluation which is required in Denmark by law before a State Subsidy of 30% is granted.

An important part of the test programme of solar collectors at the Thermal Insulation Laboratory is the test of collectors under stagnation conditions outdoors. This is also a cheap test. Changes of collectors because of high temperatures can quickly be identified under summer conditions, while water penetration can be identified in rainy periods. Problems connected to longtime durability of collectors can often be identified in the outdoor stagnation test after 1-2 years.

For five years we have made inspections on 14 different solar collectors placed on an outdoor stand where they are exposed to natural weather conditions. Many failure modes have been identified in this simple and inexpensive test (4).

From the middle of 1981 twenty solar collectors of equal manufacturing as the indoor testes were placed on an outdoor stand (see fig. 1). Continuous measurements of stagnation temperatures and climatic parameters were made for two years to see if changes of collector durability could be identified by use of the method proposed by Birnbreier (5) and a method where $\Delta T/I$ registered around noon is used as an indicator of the collector quality. Comparisons were made for equal months of 1982 and 1983. (See fig. 2).

Good results with building integrated solar collector designs

At the Thermal Insulation Laboratory we have achieved several good results in the recent years in connection to the work to develop solar collector designs for building integration. In figure 3 a cross section of the south facing wall of the so-called IEA-solar-low energy house are shown. This house design is used in 55 new houses being built during 1984, a little north of Copenhagen in Snekkersten. The figures shows how a compact solar water heater with natural circulation is integrated in the wall, next to a window which uses the same glazing system as the solar collector, with the exception that there is only one glass layer here.

There is a 3.2 m^2 selective solar collector in front of and connected to a merely 16 cm thick storage tank of 150 liter for domestic hot water made of stainless steel. This one is placed in a compact unit box with all necessary insulation and technics for a complete natural circulation solar hot water heater. An electric heater is placed in the top of the storage tank as back up (8).

The compact solar water heater was developed after good results were obtained with a compact research system where a one way valve without pressure loss was used and a system efficiency of about 40% on a yearly basis was achieved. A rather high temperature rise over the collector of 25-40 °C on sunny days means that you can have a nearly constant stratification in the storage.

Interesting results have also been obtained in connection with research in roof integrated solar collector designs. A site built solar collector which is easy to repair and maintain has been developed. Here the glazing is installed in the roof together with the rest of the roof construction, and absorbers with insulation are placed behind the glazing from the inside of the loft room. Calculations have shown that system built roof-integrated collectors can be made at a very low cost in new-built houses.

A new and promising roof integrated solar collector design which has been developed in Sweden is during 1984 being tested in a solar domestic hot water system with a 170 m^2 of collector as a part of a building project with 150 appartments near Copenhagen. This collector has an under roof of trapez aluminium plates. On this is placed aluminium bars, and 6-8 m long absorbers are placed between the bars on a mineral wool insulation. After this 1 x 1 m vacuum-formed acryllic plates are placed on the bars, connected in the same way as ordinary roof tiles. All the piping to the absorbers is placed at the top making the installation as easy as possible. This solar collector can be installed very quickly, in the actual case in one week. And the cost of the collector is only about 80 $ more per m^2 than the cost of the normal roof, making a 5-year pay back of the whole solar installation possible.

The collector seems to be both raintight and well ventilated, which should help to ensure a long lifetime.

It has been possible to convince architects and engineers that this solar collector system is a good quality 2. generation product, which can function as an attractive building component. And as something new, the projecting engineers and architects are here allowed to choose the absorbers, insulations materials, under roof, piping and flashing system they want.

REFERENCES

(1) Pedersen, Peder Vejsig (1980). Reliability and durability of solar collectors. - Equipment and procedures for indoor test of reliability and durability of complete solar collectors. Report no 80-16.

(2) Pedersen, Peder Vejsig (1981). Failure modes of solar collectors. IEA - Task III Report.

(3) Pedersen, Peder Vejsig (1981). IEA-Inspection Format -Reliability and Durability of flatplate solar collectors.

(4) Pedersen, Peder Vejsig (1980). Reliability and Durability of solar collectors. - Outdoor test of

reliability and durability of complete solar collectors. Report no 80-17.
(5) Birnbreier, H. (1980). Procedure for long-term tests with solar collectors. Technical note. Brown & Cie. AG., Heidelberg, Germany.
(6) Hansen, T.V., G. Madsen and E. Mikkelsen (1980). Long term durability of solar collectors. - Experience with solar collectors under controlled operation for 3 years. (in Danish). Dept. of Heating & Insstallation, Technological Institute, Denmark.
(7) Pedersen, Peder Vejsig (1982). - Experience from testing reliability and durability of 22 solar collectors in Denmark. Report no 82-2, Thermal Insulation Laboratory, Technical University of Denmark.
(8) Pedersen, Peder Vejsig (1984). - A 2nd generation thermosiphon solar water heater. Paper presented at the first EEC/Congress on Solar Heating in Amsterdam, May 1984.

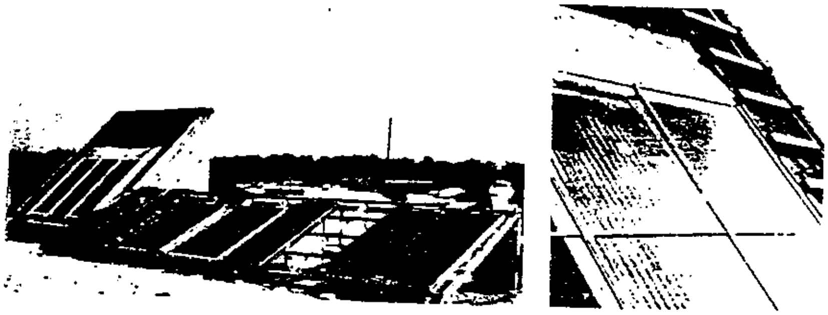
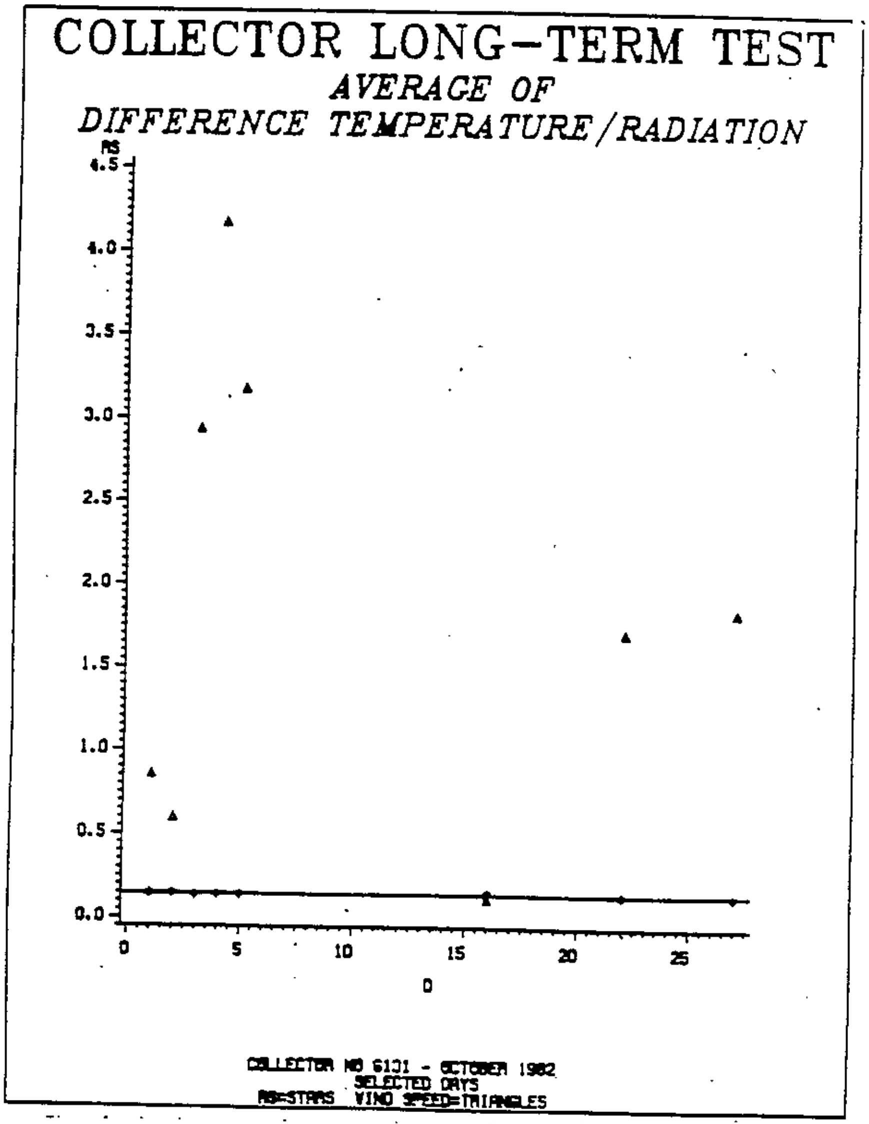


Fig. 1. Stagnation temperatures and climate parameters are measured for collectors exposed to stagnation conditions at the Thermal Insulation Laboratory. The roof-integrated site-built collector had the absorber installed after the glazing and flashing.



Figur 2: Result from outdoor stagnation test of solar collector in 1982. Clear day values of $\eta_0/U_L = \int \Delta T/ \int I$ are shown by (*) and are rather constant. The integration are made from one hour before noon until the same absorber temperature as here is reached again after noon. Windspeed is indicated by (Δ). Comparison between 1982 and 1983 has also been made.


(Courtesy O. Jørgensen)

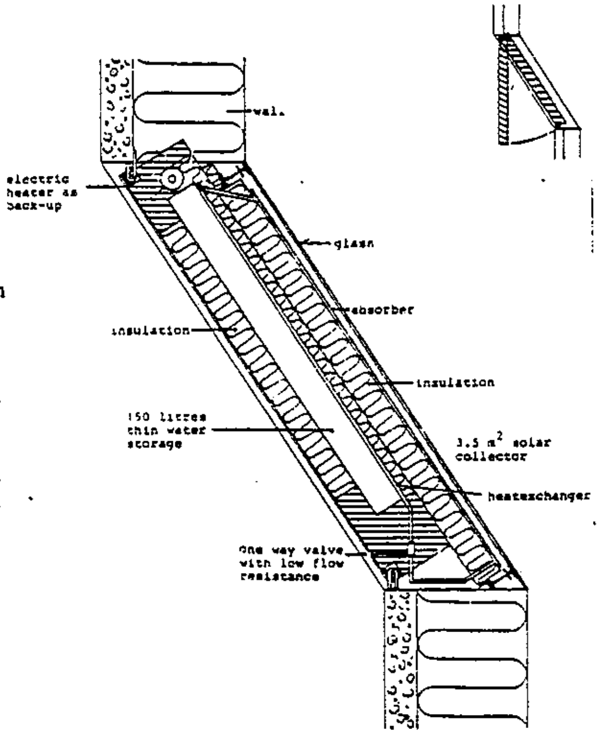
View of the south facade of the innovative Danish IEA Solar Low Energy House.

WALL INTEGRATED SOLAR WATER HEATER FOR 55 PASSIVE LOW ENERGY HOUSES IN DENMARK

Figur 3:

In a building project for 55 houses in Denmark which is finished by the end of 1984, the compact thermosiphon solar water heater has been integrated as part of a south facing wall with a tilt of 52°. The solar collector has a 3.5 m^2 selective stainless steel absorber and the 16 cm thick wall integrated storage tank has a volume of 15o liter: This solar system will only represent an extra investment of lo.ooo D.Crs. or looo $ compared to a normal electrical water heater which was the alternative for the houses. The savings in Denmark will be about 14oo D.Crs. pr.year, so a decrease of the total costs of living in the houses is achived already from the first year.

WALL INTEGRATED COMPACT SOLAR HOT WATER UNIT WITH NATURAL CIRCULATION.



Peder Vejsig Pedersen
Thermal Insulation Laboratory, Building 118
Technical University of Denmark,
2800 Lyngby, Denmark

Condensation problems with roofintegrated solar collectors in climates in nothern countries

Condensation on the inside of the glasscover in solar collectors is a well known problem in northern humid climates. Radiation of heat from the glasscover to the sky during nighttime results in a temperature decrease of a few centigrates from the ambient temperature. In humid and cold climates this will often lead to condensation on the inside of the glasscover.

A built-in possibility of ventilation for a solar collector can often remove the condensate in a few hours when the absorber temperature is increased due to the solar insolation. We know from experience that many solar collectors, as a sign of a humid atmosphere in the collector itself will show heavy condensation over long periods expecially in the winter. Three important reasons for this should be mentioned. Rainwater might have penetrated the collector if it is not raintight, or the collector construction is not protected adequately against humid air coming from the interior of the house to which the collectors are mounted, or perhabs the collector construction has not been provided with nessecary ventilation openings to the outside air. Under some circumstances the result has been a complete degradation of the solar absorber surface treatment after only few years of operation.

As part of the Danish Department of Energy's Solar Energy Research Programme, work has been initiated at the Thermal Insulation Laboratory to look at different aspects in connection with the general problem of condensation in solar collectors. Continous inspection of solar collectors in stagnation and operation and measurements of temperatures and humidity of solar collectors have been carried out at the laboratory's research area.

From experience gained until now we list below some important aspects to be aware of if serious problems with condensation in solar collectors are to be avoided:

- First of all a raintight solar collector construction is necessary. Condensation over long periods in a collector is often a useful symptom for water being trapped in the collector enclosure or the insulation material.

- A solar collector construction should always have a built-in possibility of ventilaton made in such a way that a combination between ventilation forced by the "chimney effect" and ventilation driven by the wind can evaporate the amount of condensation formed at the inside of the cover during nighttime. One can allow quite high ventilation rates for a solar collector without any notable decrease in collector efficiency. A ventilation rate of 10 times per hour will f.ex. only mean an increase of the heat loss coefficient for the collector of about 1%.

- Solar collectors which are built into the roof should always be ventilated with only outside air, unless the collector is mounted to a well ventilated loftroom guaranteeing that air is not coming in from the house. An airtight membrane is necessary to ensure this. Ventilation by outside air will mean a slightly colder solar collector during night where condensation occurs. A higher ventilation rate than necessary would then lead to more condensation. This should be the reason for an upper limit for the ventilation rate.

- Ventilation holes only at the bottom of the solar collector construction is not enough if one wants to make use of the chimney effect.
  To achieve a satisfactory ventilation of the collector, ventilation holes at the top of the collector construction are necessary. The holes must be protected against rain penetration. The ventilation holes provide that warm and relatively humid air can get out without condensing inside the collector.

- It is necessary that penetrated rainwater or condensate can leave the solar collector if it has once appeared. This should be possible with built-in drain holes in the solar collector. These will often function as bottom ventilation holes as well.

- The above is valid for all catagories of solar collectors built into the roof. For both site-built collectors and built-in collector modules you can use a construction with an airtight membrane placed on plywood at the bottom of the construction. The manufacturer of the collector modules should always provide the necessary ventilation holes as a part of the collector module design. Here the ventilation holes at the top of the collector could f.ex. have openings to the inside of the flashing system and could in this way be protected against rain.

The problems with formation and removal of condensation in solar collectors can be illustrated by an example:

Imagine a solar collector with ventilation holes in the bottom and condensation on the inside of the glasscover in the morning. The absorber is now heated by the sun. Outside air with a low water content comes in through the ventilation holes in the bottom of the collector mostly because of the chimney effect. The air inside the collector is at the same time forced out through small airleakage holes in the top of the collector. The outside air which is introduced is heated first near the absorber and moves afterwards to the glasscover where condensate is evaporated to the air, while the air moves downward near the cover. The water content is thus increasing in the air at the same time as the temperature rises. Thus there will be only a slight increase of the relative humidity. For a solar collector with a rather low ventilation rate of for example 5 times per hour, an increase of the water content in the air between the absorber and cover of 30 grams of water per kilo air during 4 hours in the morning, means that the total amount of ventilated air of 0.8 m^3 will receive approx. 30 grams of water per m^2 of collector. This amount of water is near to what is common amounts of condensate of the inside of the glasscover, when only some parts of the glasscover have condensation. Fig. 1 shows the tendency for the development of measured temperatures and humidity in a stagnant solar collector and illustrates the above.

It can be concluded that a low ventilation rate or no ventilation at all might be the only reason why you will see condensation in solar collectors over long periods. The problem will of course be increased seriously if there is water not only on the inside of the glasscover but also in the collector enclosure itself. The need for a high ventilation rate will be increased if you also want condensation to disappear quickly on days with only little sunshine. Also the wind will effect the ventilation because of the variations in pressures it creates around the collector. However, in very humid periods even rather high ventilation rates will not be sufficient for dissolving all condensation. In this case it is an advantage to have a high efficiency collector which can use even very small amounts of solar insolation to rise the absorber temperature.

The problem with an unsatisfactory ventilation in the top of solar collectors, where hot humid air on its way out leaves

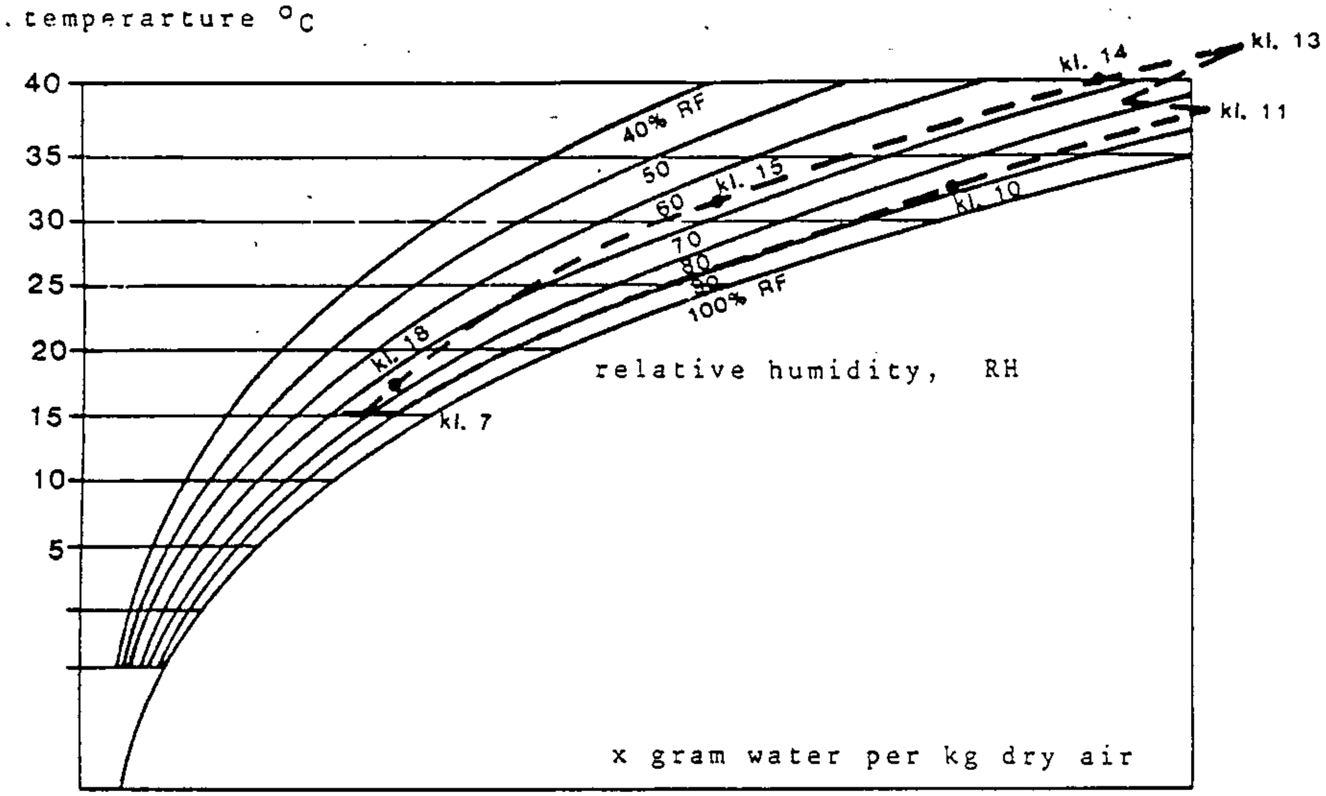


Fig. 1. The figure shows the changes of temperatures and humidity in a solar collector during the day. The ventilation air in a solar collector can dissolve condensate on the inside of the glasscover when the absorber temperature raises because of increased solar insolation. This means strong requirements to the ventilation of the solar collector so hot humid air on its way out of the collctor will not condensate and leave water in the collector enclosure. Ventilation holes near the top of the collector protected against rain could be a mean for this.

condensation inside the collector enclosure or in the insulation material will often lead to a characteristic condensation near the corners of the collector cover in the afternoon. The reason is that the ventilation air in the wet collector is still humid in the afternoon where the cover temperature decreases and then leads to condensation.

It is as indicated an important rule that ventilation of solar collectors should be provided by outside air. Unfortunately many problems with permanent condensation in roof-integrated solar collectors during the winter have been identified as a result of ventilation air from the houses being lead partly through the collector construction. It must be noted that even though the collector is in connection with a non-occupied loftroom, moisture from the house might anyway be introduced to the loftroom.

Thus, it is only heavy ventilated loftrooms, with an airtight membrane as separation to the house, which are reliable.

As problems with rain penetration into solar collectors and condensation are often very closely connected, it is difficult to judge what is the reason and what is the result. Condensation during long periods is often a sympton for the collector construction not being raintight, but condensation in a raintight solar collector, which is not satisfactory ventilated, can under some circumstances be just as serious as from rainwater penetrated into the collector. During long periods more condenced water can be produced than is ventilated away. This can in the long run lead to a permanently wet solar collector resulting in a very limited useful lifetime of the absorber.

LIST OF PARTICIPANTS

IEA-WORKSHOP ON SERVICE LIFE OF SOLAR COMPONENTS AND MATERIALS

TECHNICAL UNIVERSITY OF DENMARK
December 6 - 7, 1983

Name	Institute, Country, tel.
Peder Vejsig Pedersen	Thermal Insulation Laboratory Technical University of Denmark Bldg. 118, DK 2800 Lyngby, Denmark
Hans Koelemy	I.B.B.C.-TNO The Netherlands Tel 015-138222
Bruce Cross	Solar Energy Unit Dept. of Mechanical Engineering University College Newport Road Cardiff, U.K.
Roy S. Yamasaki	Division of Building Research National Research Council of Canada Montreal Rd. Ottawa, Ontario, Canada KIA OR6
Jonathan W. Martin	Building 226, Room B344 Center for Building Technology National Bureau of Standards Washington, D.C. 20234, USA
David Waksman	Building 226, Room B350 Conter for Building Technology National Bureau of Standards Gaithersburg, MD 20899, USA
Pauli Andersen	Technological Institute Dept. of Surface Coatings Technology P.O. Box 141 DK-2630 Taastrup Denmark
Hans Wennerholm	National Testing Institute Laboratory for Surface Protection and Corrosion Box 857, S-50115 Borås Sweden
Riesch, Gerhard	J.R.C., Comm. of Europ. Comm. Ispra, Italy 0039,332,789111
Bruck, Manfred	Austrian Solar and Space Agency Vienna, Austria, 222/438631/

LIST OF PARTICIPANTS

Name	Institute, Country, tel.
Wenzel, Heinrich	TUV, Bayern, Munich W-Germany 089/5791/1868
Sakae Tanemura	Solar Res. Lab. Government Research Institute Nagoya AIST/MITI, Japan Hirate-cho 1, Kita-ku, Nagoya 462, Japan
Keller Johannes	Swiss Federal Institute for Reactor Research, CH-5303 Wärenlingen Switzerland
Svendsen, Svend	Thermal Insulation Laboratory Technical University of Denmark Bldg. 118, DK 2800 Lyngby, Denmark
Andersson, Hans E.B.	Swedish Council for Building Research Sct. Göransgatan 66, S-11233 Stockholm, Sweden tel 46-8-540640. tlx 10398 BFR-S

Methodology for predictive service life tests proposed at the meeting

Performance requirements for materials in solar collector systems of different expected lifetimes could be identified as a function of the environments they are exposed to. This is again a function of the actual climate and used collector construction and design.

Absorber
cover
casing

Sealants
gaskets
insulation

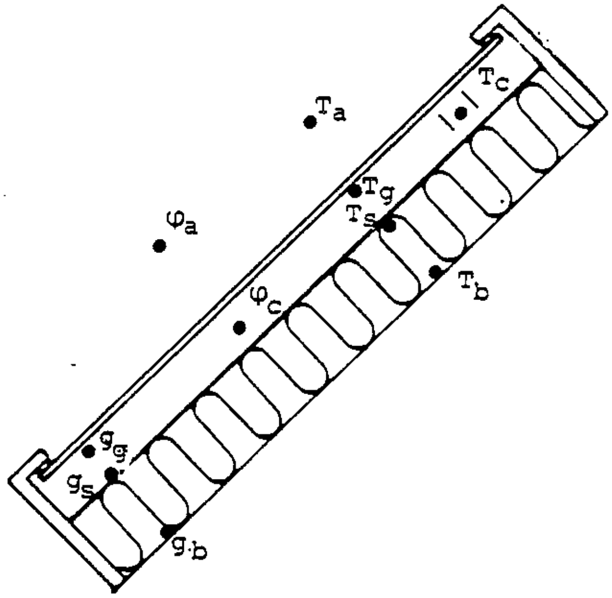
Connections
piping system
flashing system

Lifetime / Environment	5 years	10 years	15 years	20 years	30 years
environment 1.	performance requirements				
environment 2.					
environment 3.					
environment 4.					

Figure 1.

Figure 2.

PROPOSAL FOR A COMMON EXPERIMENT OF HOW TO MEASURE ENVIRONMENT AND THE INFLUENCE ON ABSORBER DEGRADATION IN A SOLAR COLLECTOR



Nomenclature:

g_b : moisture content near the backside of the collector near the bottom (hours of wetness)

g_g : moisture content at the inside of the glass cover near the bottom of the collector (hours of wetness)

g_s : moisture content on absorber surface near the bottom of the collector (hours of wetness)

T_a : ambient temperature (C)

T_b : backside temperature (C)

T_c : collector - air space temperature (C)

T_g : glass temperature, in the middle 1/3 from top of collector (C)

T_s : absorber surface temperature in the middle, 1/3 from top of collector (C)

φ_a : relative humidity of ambient air (% RH)

φ_c : relative humidity of air space near 1/3 from bottom (% RH)

φ_i : relative humidity in insulation (% RH)

Five temperature sensors, three moisture sensors and three relative humidity sensors can be used to tell about the environment inside and outside two experimental solar collectors, which can be separated and are raintight and have a changeable ventilation rate. One is in stagnation, and the other in operation in a small thermosyphon system.

Based on measurements of several collector pairs with different materials combinations in different IEA-countries it should be possible to get knowledge of, e.g. the number of hours, the cover, absorber and insulation are wet at different ventilation rates, and number of hours at certain temperatures and relative humidities, and the effect of these parameters on degradation. Based on this, one should be able to establish a system of climate classes which allows different performance requirements of materials and components.

Peder Vejsig Pedersen