FORSCHUNGSZENTRUM JÜLICH GmbH KFA

Projektträger Biologie, Energie, Ökologie (BEO)
International Energy Agency IEA

Implementing Agreement for a Programme of Research and Development on Wind Energy Conversion Systems – Annex XI

22th Meeting of Experts – Effects of Environment on Wind Turbine Safety and Performance

Wilhelmshaven, June 16, 1992

Organized by:
Project Management Organization Biology, Energy, Ecology BEO
Research Centre Jülich GmbH

On behalf of the
Federal Minister for Research and Technology,
The Fluid Mechanics Department
of the Technical University of Denmark

Scientific Coordination:
M. Pedersen (Techn. Univ. of Denmark)
R. Windheim (BEO-KFA Jülich)

Implementing Agreement for a Programme of Research and Development on Wind Energy Conversion Systems – Annex XI

22th Meeting of Experts – Effects of Environment on Wind Turbine Safety and Performance

Wilhelmshaven, June 16, 1992

Organized by:
Project Management Organization Biology, Energy, Ecology BEO
Research Centre Jülich GmbH

On behalf of the
Federal Minister for Research and Technology,
The Fluid Mechanics Department
of the Technical University of Denmark

Scientific Coordination:
M. Pedersen (Techn. Univ. of Denmark)
R. Windheim (BEO-KFA Jülich)

CONTENTS

22. IEA-Expert Meeting on
Effects of Environment on Wind Turbine Safety and Performance

16 and 17 June 1992 at Wilhelmshaven, Germany

Introductory note prepared by Henry Seifert, Deutsches Windenergie-Institut, Wilhelmshaven

An IEA-Expert Meeting will be held on June 16 and 17 1992 at DEWI in Wilhelmshaven in order to discuss the effects of environment on wind turbine safety and performance.

Wind turbines are designed to operate mostly under normal environmental conditions according to the recommendations for wind turbine design. However, the world wide demand for renewable energy sources to diminish pollution and CO_2 production leads to a wider spread of wind energy application. Thus, more and more sites with extreme environmental conditions are developed for wind turbine operation. Also, the experience of operation of wind turbines all over the world under different meteorological and operational conditions should be assessed. This includes experience from wind turbine accidents and incidents due to environmental impact. To end up in reliable load assumptions and in safe operating wind turbines, all environmental conditions have to be assessed in a proper way.

The items to be discussed are the meteorological and other environmental effects and their influences on wind turbine safety and performance. That means, influences on loads and life time of components, corrosion and erosion of material, power quality and quantity, availability as well as maintenance and inspection procedures.

The meteorological effects are precipitation like rain, snow and hail, reducing the power output or damaging material protection. Icing can occur during standstill and operation, thereby changing the static and dynamic loads of a wind turbine. High and low temperatures as well as moisture will affect e. g. material and control mechanism behaviour. Lightning strokes are known to have a devastating impact on wind turbines. Other environmental effects of concern are earth quakes, acid rain, dust, salt and bugs, and of course effects arising from the grid.

The participants of the meeting are asked to present their experience from one or more of the above mentioned topics as a basis for the discussion. It is the goal of the workshop to improve the knowledge of environmental effects in the field of wind energy, to improve load assumptions, to make wind turbines more reliable and economic and to make wind energy applicable at sites with extreme environmental conditions.

Danish Experience with Environmental Extremes on Wind Turbine Application

Uwe Schmidt Paulsen
The Test Station for Wind Turbines
Risø National Laboratory
Dk-4000 Roskilde
Denmark

During the last decade danish wind turbine industry has gathered world wide experience. Cost effective siting of wind turbines represents for planners one of the major challenges due to the variety of sites and the environmental impact onto the turbine. Risø has been involved in the field of meteorology and wind turbine testing, research and siting and has made contract work for authorities, companies and organizations. Some projects demonstrated that siting areas with a good wind climate involved extreme/aggressive environmental problems for the wind turbine. The paper describes case stories with some aspects of these problems: earthquake impacts and temperature extremes in California/USA; wind turbines exposed to a corrosive air-sea climate in Mogadishu/ Somalia and extreme wind loads combined with local terrain effects on the Faroe Islands. The experiences made confirm sound engineering practice: detailed information on the climate and on external conditions at the site represents a basic knowledge for planners, entrepreneurs, constructors and designers of wind turbine equipment. In case of problems with environmental effects the information provide a proper input for the experts involved.

Experience in United States of America

In the wind turbine area of California a earthquake initiated vibrations and damages on 66 Bonus 65 kW wind turbines on july 8, 1986 [/1/]. During the quake of strength 5.9 on the Richter scale with epicenter 18 km N of Palm Springs the wind turbines were spinning in a 16 m/s wind. Local effects at Painted Hill site intensified the shaking to a equivalent of 6.9 on the Richter scale. However, a inspection report[/1/] concluded that 16 wind turbines did show no visible damages and that 50 units were damaged, of them 25 severe. 7 wind turbines towers were taken off-line: they suffered buckling on the tower and cracks at the inspection door and the concrete base. The bucking zone was limited to the section just above the concentric part of the circular tower at the root of the third tower part, which is 50 % of the tower height. Photos of the wecs are shown in the paper. Minor damaged parts were repaired after inspection.

Another variant of an extreme climate is wind energy systems exposed to high temperatures during summer. Electronic parts have to sustain the local heat capacity built up in cabinets and computer boards. The measurement campaign[/2/] on a Danwin 23 machine demonstrated computer readings listed in table 1. An interview with the designer of the control system revealed that the "design temperature" was specified due to the temperature ranges specified by the wind farmer owner which is 0- 60 °C in this area. The manufacturer reported only one case of higher temperatures, where a air conditioner was required in order to prevent uncontrolled computer stops. The windfarm owner provided information to the subcontractor on the basis of confidence.

Experience in Central Africa

In late 1985 the Wind Engineering Section /Risø was consulted by DANIDA to assist a UNSO wind energy project in Mogadishu/ Somalia[/3/]. The annual average temperature is about 30°C with a monthly variation of 5°C. Temperature extremes of 40°C are common with a relative air humidity of 70 to 90

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.

pct. The site conditions for the four 55 kW Bonus wind turbine units were extremely aggressive due to the strong corrosion from the airborne salt particles of the nearby sea. The corrosion rate is demonstrated with a photo of different stainless and galvanized bolts of different quality, exposed to the open air for a period of one year before installation of the wind turbines. The experiment showed that only a bolt of type A4 according to the Swedish standards resisted the corrosive environment. In view of the climate of the site supplemental anti-corrosion treatment according to danish standards DS/454&DS/464 was initiated at the wind turbine factory. The electronic equipment was moisture protected, the hot dip galvanized towers were additionally epoxy painted and the generators were protected against tropical environment. After installation and after some time of operation, the precautions initially taken showed shortcomings: Severe corrosion were detected on the blade root flange bolts(see Fig.). They were not replaced by the more resistant bolt type A4 at the time of construction. The painting layer of the tower was insufficient thick to resist the injection of condensed water, resulting in a oxidation process with spots as shown in the photos. Authorities like the Danish Corrosion Center advised sets of instructions for the overhaul and maintenance of the steel parts. Some instructions involved highly skilled labor for application of the two-component epoxy painting. The company decided to fix the rotor blades with acid resistant flange bolts and to perform a preparation- and painting program, advised by the corrosion specialists.The Mogadishu experience learned that more rigorous precautions against corrosion, listed as non-mandatory guidelines in the appendix should be employed for wind turbines in extreme environment at the time of production.

Extreme wind climate

The Faroe Islands in the Atlantic Ocean are a collection of several islands rising abruptly from the sea to a typical height of 500 m. The mountainous landscape vary in size and structure. The area has a good wind potential and is frequently exposed to storms. In collaboration with the regional engineering institute of The Faroe Islands/ Thorshavn the meteorologists at Risø perform wind speed measurements[4] at 10 m height since 1987. A number of meteorological stations collect wind speed, wind direction, wind gust and climatic data(see Fig.). The Glyvursnes station with a annual average wind speed of 6.9 m/s is regarded as a reference wind speed station apparently because of the regular local landscape. It has been possible to collect data from stormy days with wind speeds exceeding 20 m/s(see table). A time-trace from the storm 21-22 December 1988 is plotted showing average wind speeds at Glyvursnes and at Nordradalsskard(annual wind speed: 9.6 m/s), which also contains 2-sec gust data. The wind speed difference between the two stations with amplification of 2 indicates local flow(terrain) effects. The plot demonstrates that in spite of the decrease of average wind speed, the local gustiness increased as the wind changed to northern directions. As a result, the gustiness brought down the meteorological tower at about 80 m/s. For wind turbine application areas of good wind as indicated by Nordradalsskard are feasible. However, the wind turbine design should be coordinated with safety standards/codes taking into account the experimental data as a limiting wind speed.

Conclusion

The experience so far confirms sound engineering practice:

- to collect climatic data and conditions relevant for the project
- to identify problems and use experts solving problems on specific items and correlate standards/codes with design and planning

References

1 Bonus documents of the Californian earthquake of July 8, 1986 and photos, provided by E. Kristensen, Bonus Energy A/S. 1992.

2 "Loads for Wind Turbines in Inhomogeneous Terrain Measurement Report". Risø-M-2922. 1991.

3 "A Note on Anticorrosion Design of Wind Turbines for Aggressive Environments". P. Lundsager & J. C. Hansen, Wind Engineering Section, Risø National Lab. 1987.

4 Private communication with N.O. Jensen, Meteorological Section, Risø National Lab. 1992.

List of Tables

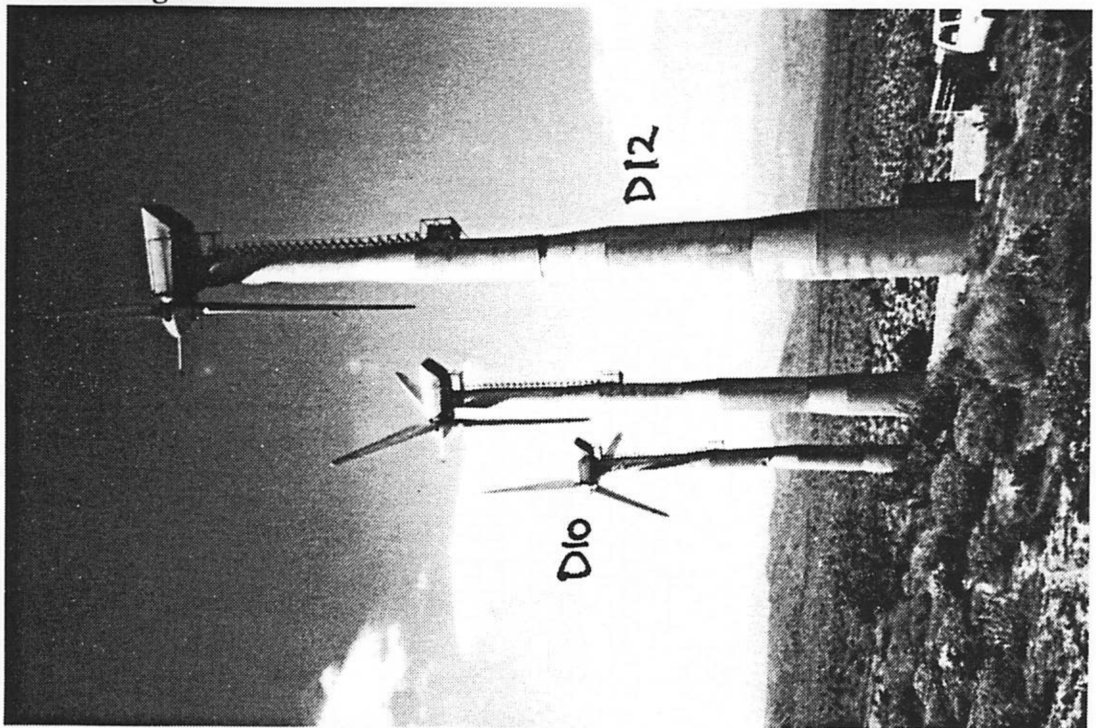
	A08	A09	E33	E34
Total production kWh	878083	857759	235658	245950
Total production hours	8792	8797	2415	2494
Generator cut-in #	1096	1185	327	275
Motor starts #	60	32	9	6
Yawmotor hours	176	173	31	59
Yawings #	80319	80357	14156	22953
Hydraulic motor act.#	62361	33807	7784	12065
Peak value kW/h	247,4	258,0	239,0	233,9
Gearbox temp.°F	147	147	118	123
Cable temp.°F	95	140	98	96
Computer temp.°F	91	89	80	87
Nacelle temp. °F	69	68	69	66

Table 1. Computer readings from four wind turbines, 10/6-90 01:00 am

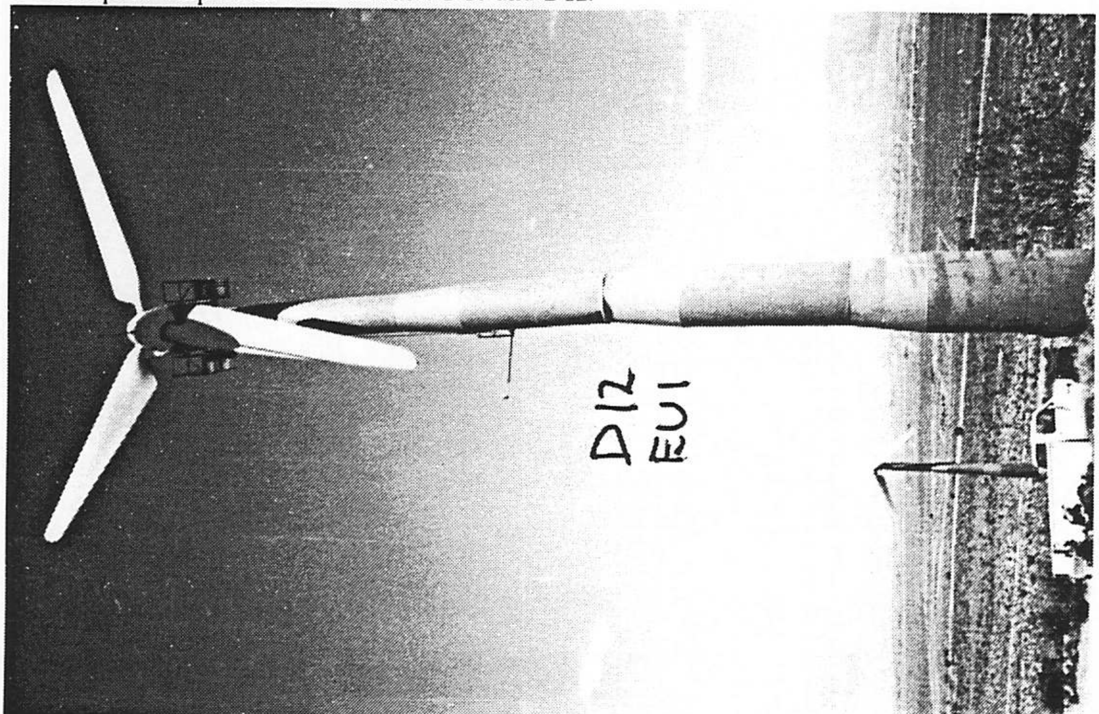
Time		Direction deg.	$\bar{u}$ m/s	$u^{max}_{2\,sec}$ m/s	$u^{max}_{32\,sec}$ m/s
88.01.09	18:35	197	22.2	31.2	
88.02.13	09:35	165	21.1	27.4	
88.03.10	02:25	325	21.4	27.1	
88.12.18	13:45	286	23.0		
88.12.21	23:45	210	30.5		
88.12.22	00:45	259	39.2		
88.12.23	20:05	348	20.2		
89.01.08	11:45	265	21.4		
89.01.13	13:35	143	26.7		
89.01.14	19:15	205	21.8		
89.01.15	03:05	267	26.7		
89.01.27	20:25	226	21.2		
89.01.28	05:35	267	21.0		
89.02.02	18:35	274	20.4		
89.02.11	08:05	189	21.3		
89.02.13	15:45	349	20.1		
89.02.14	21:35	269	24.1		
89.03.06	07:35	218	22.1		
89.09.16	16:35	226	20.6		26.8
89.12.17	17:55	38	20.9	27.1	24.0
89.12.18	02:15	39	21.2	30.9	27.8
90.01.09	04:55	263	20.4	30.6	26.5
90.01.12	09:35	248	21.3	30.3	26.8
90.01.15	01:55	282	21.4	28.7	24.9
90.01.19	22:45	265	21.6	35.4	26.2
90.01.20	00:45	277	20.2	28.7	25.2
90.01.23	06:45	200	22.7	31.2	27.4
90.02.19	23:25	269	24.7	36.6	30.0
90.02.20	01:15	272	22.8	31.2	26.8
90.03.05	02:45	273	22.0	29.3	24.9
90.03.07	16:35	267	21.5	29.3	24.3
90.03.24	04:25	273	23.3	30.3	26.8
90.03.29	04:25	271	21.6	30.6	25.5
90.04.25	22:05	263	20.3	28.1	24.6
90.09.19	09:05	334	23.3	31.9	26.8
90.12.11	14:05	328	23.3	32.8	28.1
90.12.23	14:15	195	20.9	30.6	25.2
90.12.25	04:05	148	21.1	27.4	24.3

Table 2. Stormy days at Glyvursnes with wind speeds exceeding 20 m/s .

List of Figures

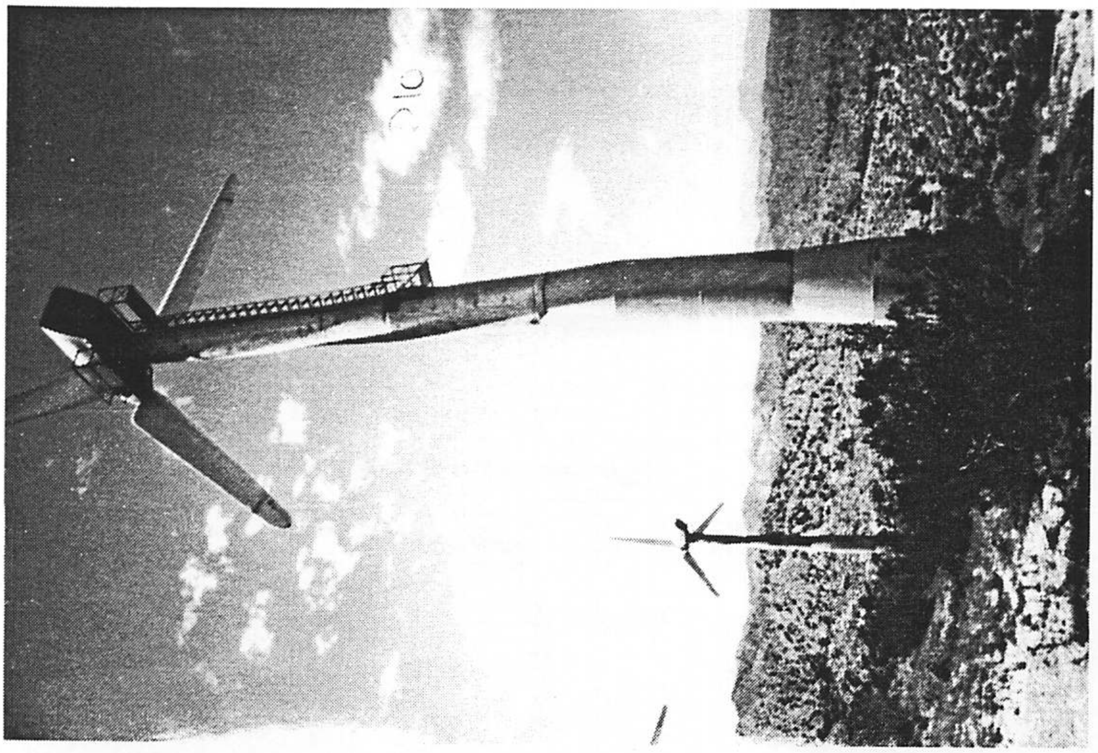


1 Earthquake impact on wind turbines D10 and D12.

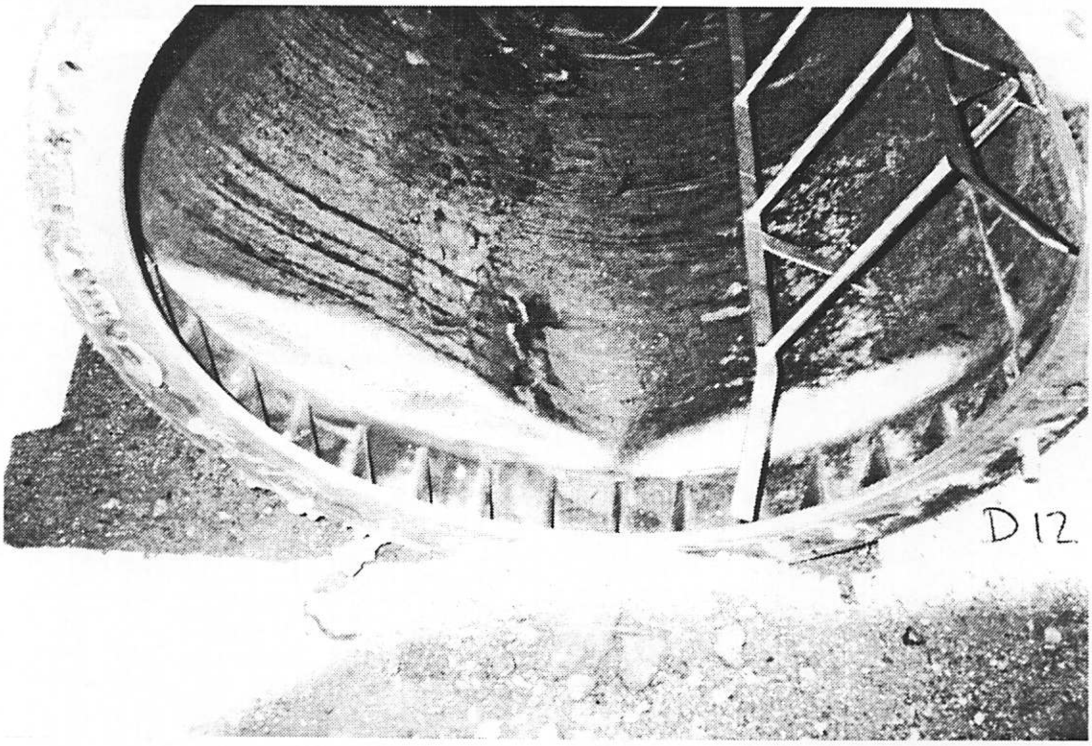


2 Earthquake impact on wind turbines D10 and D12.

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.

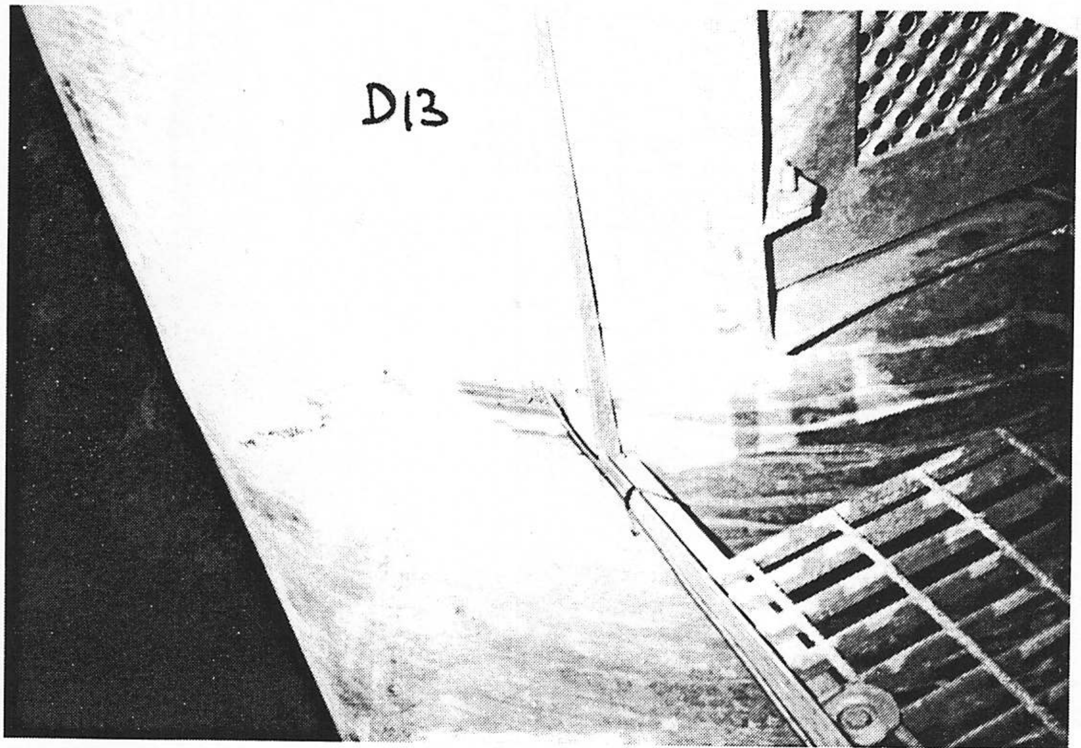


3 Earthquake impact on wind turbines D10 and D12.



4 Buckling zone of wind turbines D12.

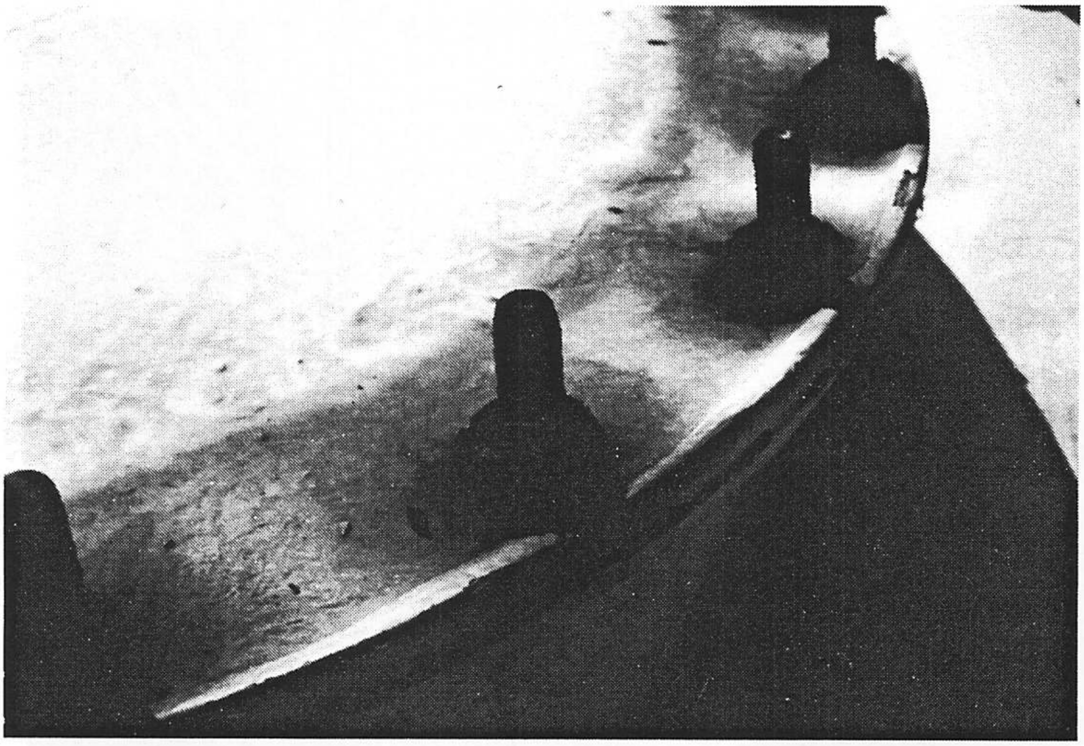
IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.



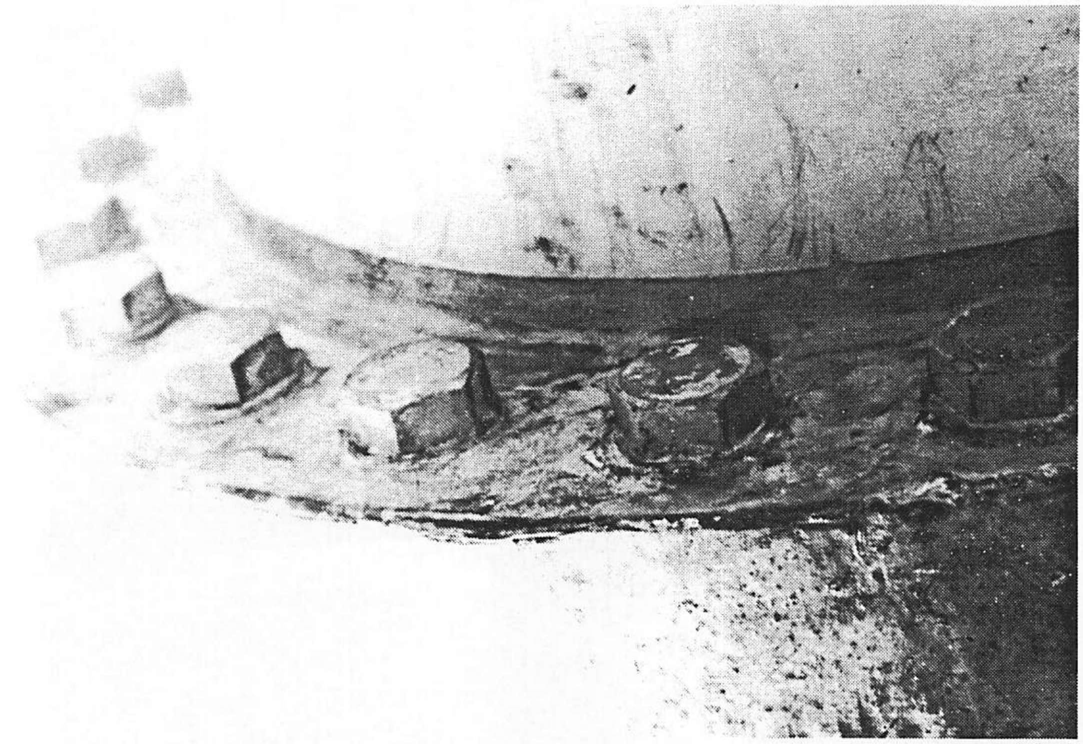
5 Cracks at the inspection door of wind turbine D13.

6 Wind turbines near the sea/Somalia

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.

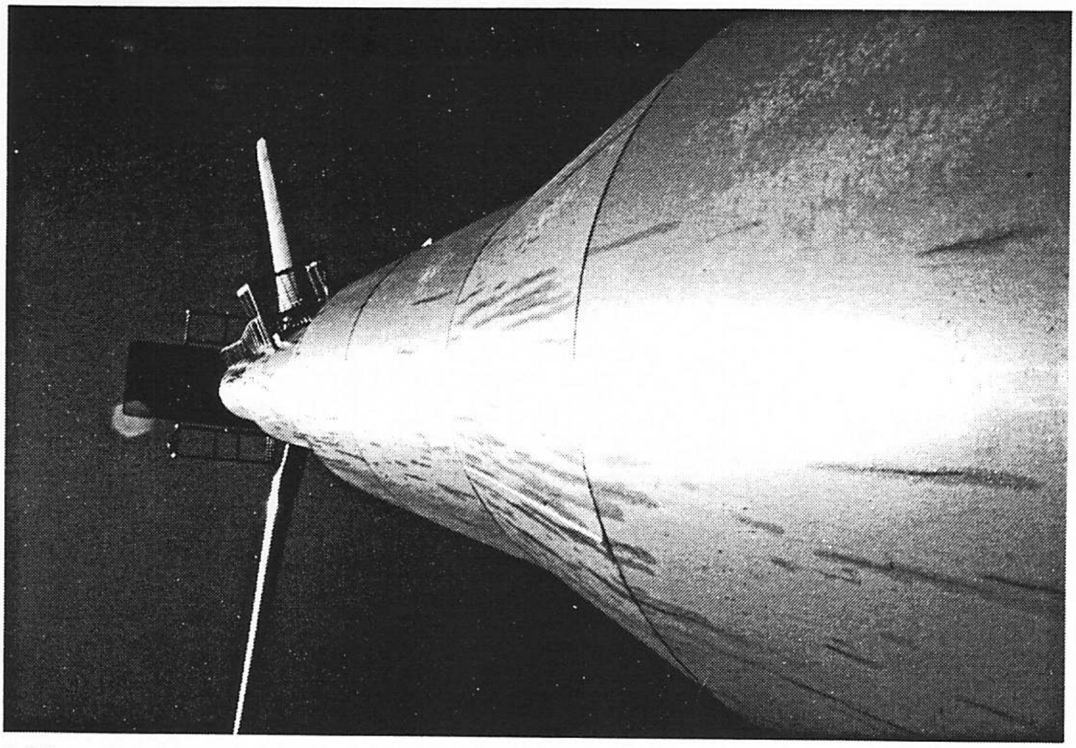


7 Test sample of different stainless steel bolts/Somalia.

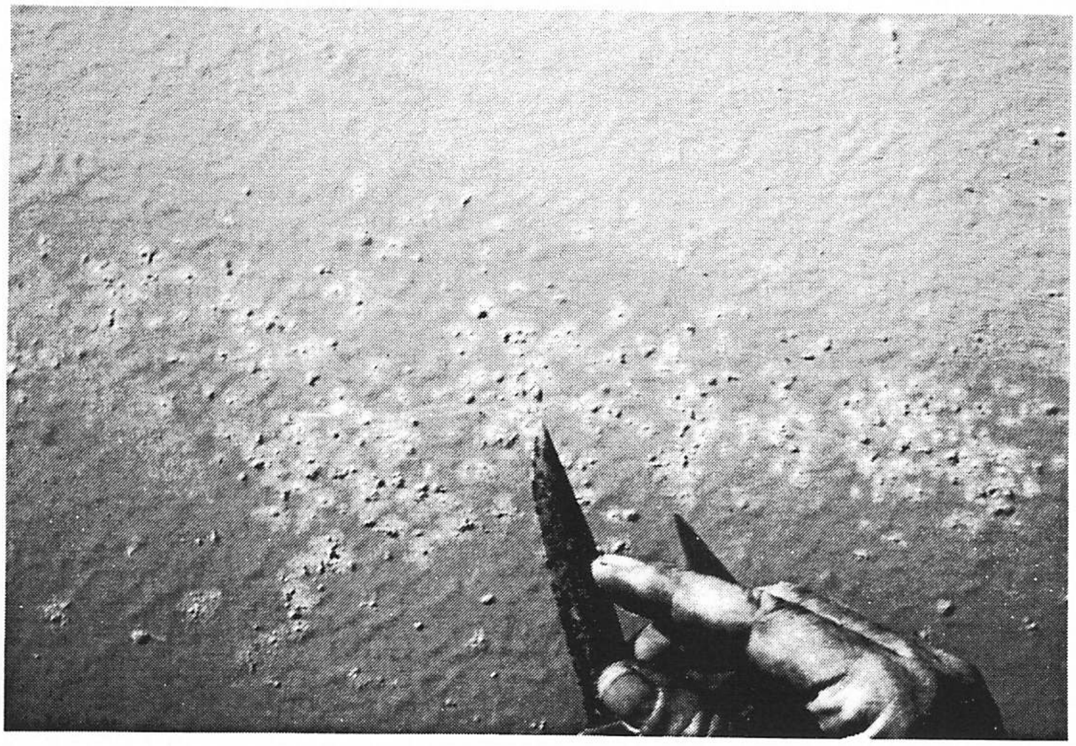


8 Flange bolts on wind turbine blade/Somalia.

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.

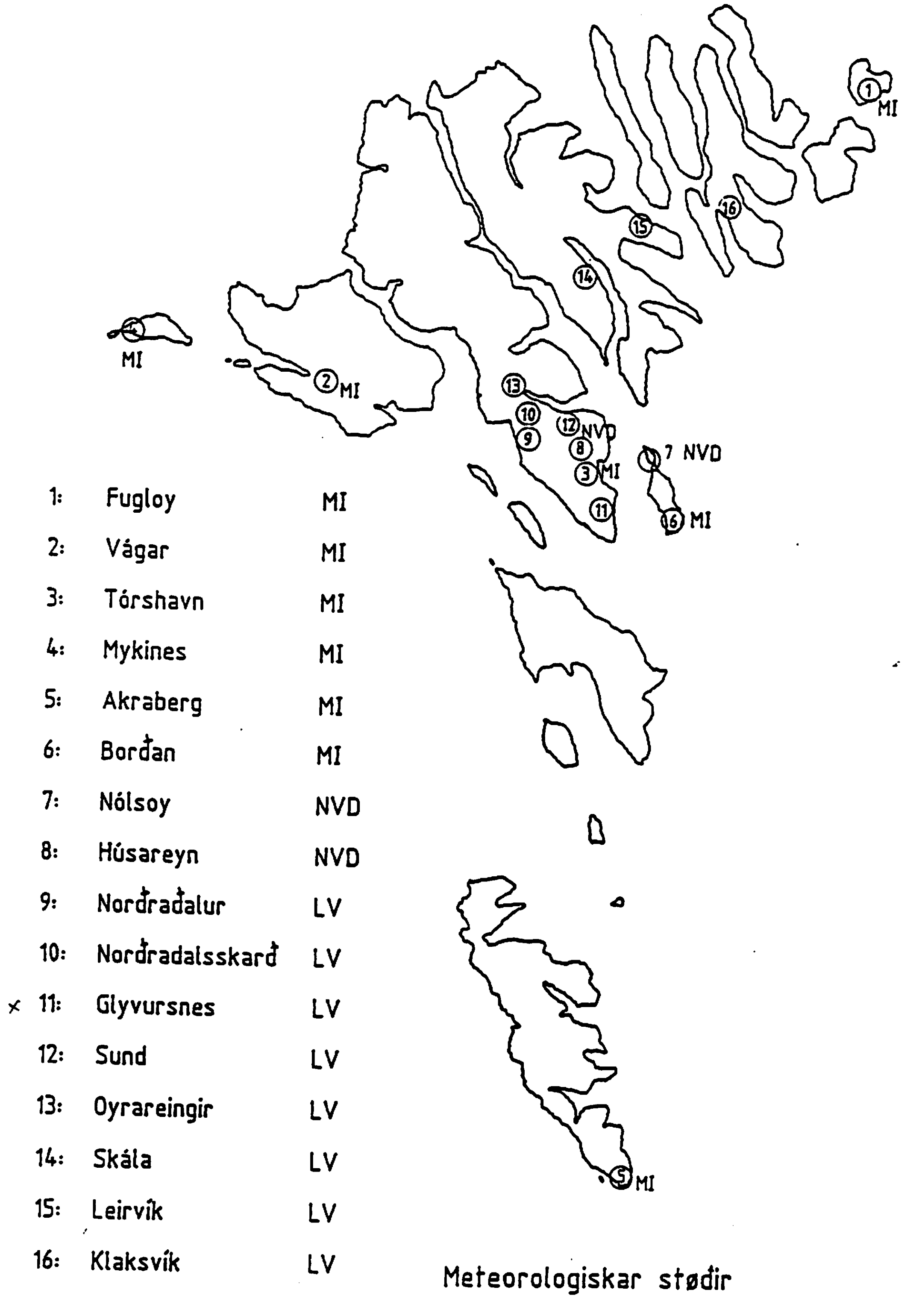


9 Wet spots on the leeward tower side/Somalia.



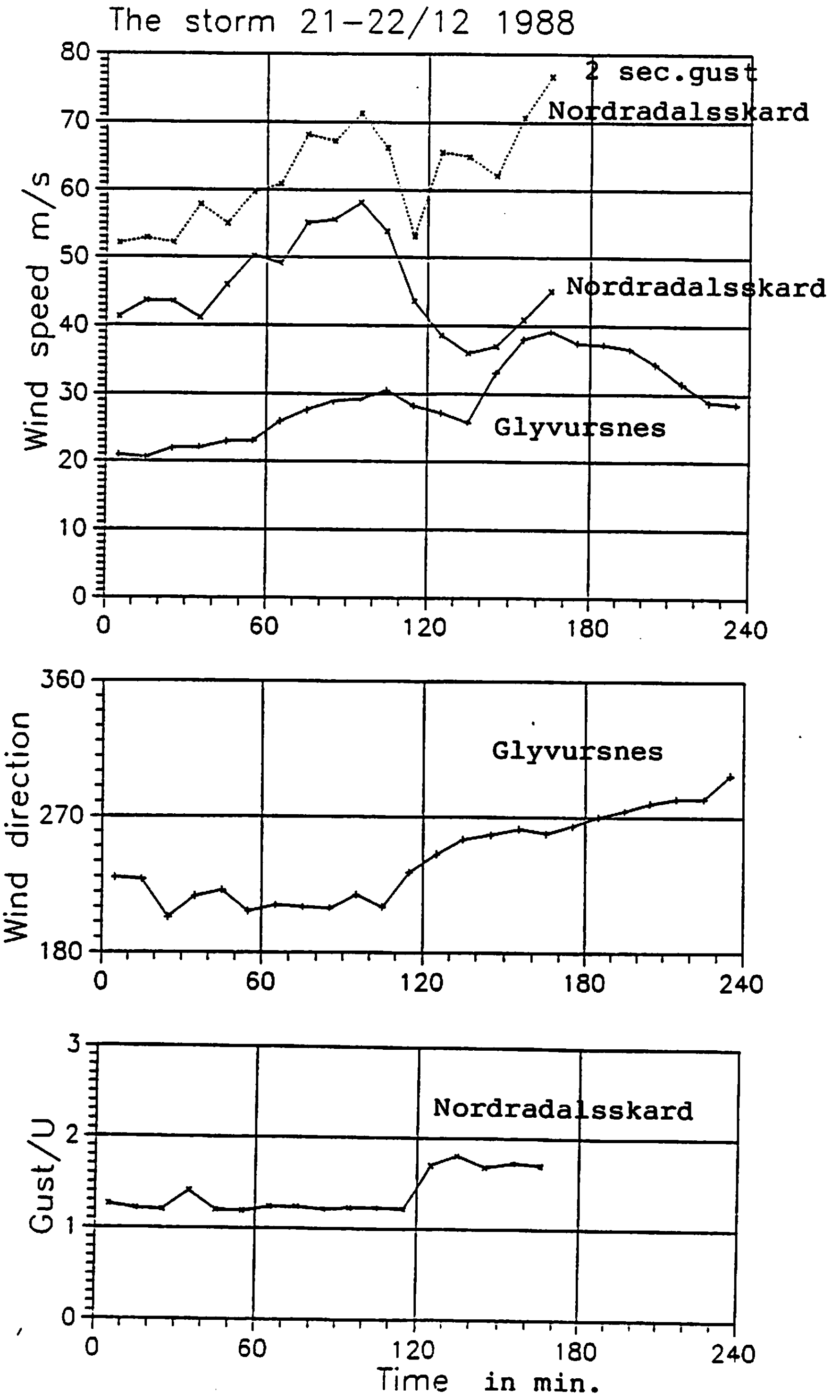
10 Oxide spots on the tower surface/Somalia.

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.



11 Wind speed measurement stations on The Faroe Islands[4].

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.



12 Wind speed measurement results from Faroe Islands[4]. Time in minutes.

IEA R&D WIND ANNEX XI
Effects of Environment on Wind Turbine Safety and Performance.
DEWI Wilhelmshaven, FRG 16-17/6 1992.

Non-mandatory guidelines for the anticorrossion design of wecs[3]

Item	Precautions
Blades	Standard blades of GRP material, metallic parts: Blade Roots: Corrosion resistance corresponding to cast SG-iron with epoxy coating. A built-up root should be moisture-sealed. The surface against the hub should be milled, and it should be moisture sealed when mounted to the hub. Blade Root Bolts: Corrosion resistance corresponding to stainless steel bolts and nuts. If the above corrosion resistance is reached by means of galvanized bolts and nuts these should be moisture-sealed, and special precautions should taken in case of oval holes in the hub. Airbrake Mechanisms: All metal parts exposed to open air should be stainless steel or bronze.
Hub	Corrosion resistance corresponding to cast SG-iron, epoxy-coated at the factory. If the hub is bolted on a flange on the main shaft, precautions are as stated for blade root bolts. If not, special precautions should be taken to avoid corrosion of the surfaces of joined parts (pasrust).
Main shaft	A special surface treatment should be prescribed.

Main bearings	Should be comparable to VR 33 spherical bearings with centre lubrication. Grease nipples should be provided with caps for moisture sealing. The bearings should be provided with lip gaskets, and a throw-off ring (slyngring) should be placed in front of the front bearing for protection against water.
Main brake	Methods of preventing damage from corrosion of the brake disc should be developed. For example, the disc could be equipped with holes or grooves to absorb rust from the disc. Alternatively, frequent exchange of disc should be foreseen.
Gearbox	Shaft sealings should be comparable in reliability to labyrinth sealings with a rubber grease guard. Protection and inspection against oil deterioration caused by the excessive moisture should be comparable to that obtained by the application of a bottom plug with moisture absorbant (silicagel), synthetic oil and viewing glass.
Generator(s)	Should be comparable to IP 54 generators with a bottom drain hole and/or heating coils to prevent moisture in the generator(s) during standstill. It should be possible to regrease the generator bearings; grease bearings should be equipped with caps for moisture sealing.

Nacelle

<u>Bottom Frame</u>: Comparable to a galvanized steel frame with the following features:

(1) Drain holes where needed in order to keep the nacelle dry.

(2) Anticorrosion treatment of all cavities.

(3) All surfaces epoxy-coated.

(4) Welded details instead of bolted ones where possible.

(5) All bolts and nuts moisture-sealed.

<u>Sides and Top Cover</u>: Comparable to a GRP design with a minimum of metal parts. Metal parts protected as specified for the bottom frame.

<u>Yaw Drive</u>: Comparable to a bearing (kugledreje-skive) with forced lubrication. The effective greasing of the sprockets needs special attention. In a king-pin design the king-pin should be cast SG-iron bolted to the bottom frame, bolts and nuts moisture-sealed. Oversized fibre blocks should be used, and holes/grooves for rust removal should be provided for.

Tower

All galvanized steel surfaces should be epoxy-painted. All connections should be moisture-sealed. Precautions for bolts and nuts are the same as for blade root bolts and nuts.

Electronic equipment

Designed in accordance with experienced or specifically performed accelerated environmental testing for environments similar to that of Sta. Caterina, as described in DS/IEC 68.

Energieonderzoek Centrum Nederland
Netherlands Energy Research Foundation ECN

Renewable Energies

Environmental Effects on Wind Turbines in The Netherlands.

a contribution to the
22. IEA-Expert Meeting on
Effects of Environment on Wind Turbine Safety and Performance
by
Servaas Ramakers, Petten
13th May 1992

Environ.net.revision

Postbus 1, 1755 ZG Petten
Bezoekadres: Westerduinweg 3, Petten
Telefoon: 02246-4949 Fax: 02246-4480 Telex: 57211 REACP NL

P.O. Box 1, 1755 ZG Petten, The Netherlands
Visiting address: Westerduinweg 3, Petten, The Netherlands
Phone: (+31)2246-4949 Fax: (+31)2246-4480 Telex: 57211 REACP NL

ECN is ingeschreven bij de Kamer van Koophandel te 's-Gravenhage, nr. S 151233

ECN is registered with the Chamber of Commerce at The Hague, No. S 151233

Introduction:

Environmental conditions always affect wind turbines. Every area on earth has its own impact on loads and life time. The temperate coastal area of The Netherlands does not have extreme conditions. In The Netherlands the demands for these external conditions are laid down in the "Regulations for the Type-Certification of Wind Turbines : Technical Criteria".

In the Netherlands except for wind loads and operational loads the influence of the following effects have to be considered: rain, fog, salt (aerosols), air pollution, hail, snow, ice, sand, UV-radiation and lightning discharges.

Hereafter a brief view is given of the possible consequences of these influences.

Phenomenon	:	RAIN
Occurrence NL	:	often and much
Direct damage	:	none
Long term damage	:	acting on mechanical parts by corrosion and on electrical parts by spark over
Consequence	:	loss of production due to defects
Precautions	:	recognized environmental protection system and edging, enclosing and draining, stand still heating
Maintenance	:	scheduled inspection and maintenance
Investigation	:	long term influence on GFRP and wood-epoxy blades

---

Phenomenon	:	FOG
Occurrence NL	:	regular
Direct damage	:	none
Long term damage	:	acting on mechanical parts by corrosion and on electrical parts by spark over (condensate)
Consequence	:	loss of production due to defects
Precautions	:	recognized environmental protection system and edging, enclosing and draining, stand still heating, filtered cooling air
Maintenance	:	scheduled inspection and maintenance

Phenomenon	:	SALT (aerosols)
Occurrence NL	:	coastal areas
Direct damage	:	none
Long term damage	:	acting on mechanical parts by corrosion and on electrical parts by spark over
Consequence	:	loss of production due to defects
Precautions	:	recognized environmental protection system and edging, hot dip galvanized structure parts, filtered cooling air and thermal controlled flaps for open generators
Maintenance	:	scheduled inspection and cleaning (external deposition washes of by rain)

Phenomenon	:	AIR POLLUTION
Occurrence NL	:	industrial areas
Direct damage	:	none
Long term damage	:	acting on mechanical parts by corrosion and on electrical parts by spark over
Consequence	:	decrease of performance by dirty blades, loss of production due to defects
Precautions	:	selection of surface layer
Maintenance	:	scheduled cleaning
Investigation	:	non-adhering surface layers

Phenomenon	:	HAIL
Occurrence NL	:	now and then
Direct damage	:	surface failures
Long term damage	:	abrasion of leading edge
Consequence	:	influence of moisture and frost on blade construction, decrease of performance
Precautions	:	coating
Maintenance	:	inspection/renewing coating

Phenomenon	:	SNOW
Occurrence NL	:	now and then
Direct damage	:	none (additional loads)
Long term damage	:	obstruction of cooling air supply, penetration of melting water and spark over
Consequence	:	turbine shut down due to overheating or short circuit
Precautions	:	filtered cooling air, draining
Maintenance	:	none

Phenomenon	:	ICE (glazed frost)
Occurrence NL	:	now and then, short time
Direct damage	:	blocking of wind speed and -direction sensors, blocking of flaps and tips,(cars and cattle)
Long term damage	:	extra loads, frost influence on blade
Consequence	:	wrong control info, oblique inflow, incorrect working safety devices, imbalance, turbine shut down
Precautions	:	check of wind speed and -direction against power and rev. number
Maintenance	:	none

Phenomenon	:	ICE (white frost)
Occurrence NL	:	now and then, short time, thin layer
Direct damage	:	blocking of wind speed and -direction sensors
Long term damage	:	additional fatique loads
Consequence	:	wrong control info, oblique inflow, incorrect working safety devices, changing of profile, noise, decrease of performance, turbine shut down
Precautions	:	check of wind speed and -direction against power and rev. number
Maintenance	:	none

Phenomenon	:	SAND (coarse)
Occurrence NL	:	coastal dune areas
Direct damage	:	none
Long term damage	:	abrasion of conservation layer on lower construction parts
Consequence	:	corrosion of lower structural parts
Precautions	:	recognized environmental protection system
Maintenance	:	scheduled inspection and repair

Phenomenon	:	UV-radiation
Occurrence NL	:	normal latitudinal
Direct damage	:	none
Long term damage	:	ageing of conservation and blades
Consequence	:	corrosion and loss of strength
Precautions	:	recognized environmental protection system
Maintenance	:	scheduled inspection and repair

Phenomenon	:	LIGHTNING
Occurrence NL	:	regular
Direct damage	:	electric and electronic installation, non-ferro blades, bearings
Long term damage	:	none
Consequence	:	turbine shut down, safety
Precautions	:	structure earth connections; conducting of discharges from rotor, nacelle and external conducting parts; over voltage protection on at least: grid connection, all out going elect. cables, all external elect. cables;
Maintenance	:	scheduled inspection and repair

General remarks:

Prevention of damage is important because of:
- high repairing costs
- production drop out

Extra provisions on top of the basic equipment depend on the demand of the investors.

Environmental effects on wind turbines have an influence on:

- **SAFETY**	- direct, when hit by lightning discharge. The danger is small when protected correctly.
	- indirect, by affecting of the construction by corrosion
- **PRODUCTION**	- by damaging of electric components (short term),
	- by damaging of mechanical parts (long term)
- **PERFORMANCE**	- by pollution (long term), by ice (short term)

RESEARCH should be done on the long term influence of moisture on (G)FRP and wood-epoxy blades and on non adhering surface layers.

Contribution to the 22nd IEA Expert Meeting in Wilhelmshaven June 16 1992

EFFECTS OF A VERY LARGE OBSTACLE UPON THE WIND FIELD AND COMMENTS ON WEATHER INFLUENCES

by

Heiner Schmidt

Abstract

Helgoland is a rocky island in the German Bight, about 50 km off shore. It is more than 50 m high, flat on top, and has steep sides all around. From the measurements of an 80 m meteorogical mast 700 m southeast of the rock a strong leeward turbulence can be shown, which reaches up higher than 80 m. A case study shows a broad band spectral peak around periods of 100 sec.

The combination of wind and weather conditions is discussed. At sea thunderstorms are mostly connected with higher average wind speeds (other than inland, where average speeds then are generally low). Off shore buildings (e.g. wind converters) will therefore often be covered by salty sea spray during thunderstorms which makes them a good target for lightning strokes.

Introduction

There are many different environmental influences on wind converters. Only a few of them will be discussed here using meteorological data from the island Helgoland. It is situated in the Inner German Bight, about 50 km off shore, open to the North Sea. About half of the island is a table rock ("Oberland", dark shading in fig 1) with steep sides and more than 50 m height. The rest (east and south) is flat and low land ("Unterland"), 4 m above sea level, as can be seen from fig. 1 and 2.

In the south harbour ("Südhafen", see fig. 2) a 1.5 MW wind energy converter ("WKA60") was erected with 50 m hub height and a three-blade windward rotor of 30 m radius. 100 m northwest of it an 80 m mast ("Hauptmast") with meteorological equipment in 8 levels existed for nearly three years (the project was funded by the German Research Ministry, BMFT) from July 1989 to April 1992. The WKA60 was erected later and was in operation about half of this time. Nearby, also on the low land, is the weather station Helgoland ("Wetterstation") of the German Weather Service.

Measuring strategy

On the 80 m mast the wind was continuously measured as 2 sec averages of wind speed and direction at 8 levels with 3 cup anemometers and 1 wind vane per level. Normally these values were reduced on line in a PC resulting in 1 min average, standard deviation and extreme values for each sensor. During special campaigns the original time series were stored over a couple of hours. Later, off line, in Hamburg a further data reduction was performed to remove the remaining (small) mast influence upon the measurements, resulting in only one corrected wind speed and direction per level. From all different records a continuous time series of hourly averages, standard deviation and extremes was calcutated.

The nearby weather station records ten min averages of wind speed and direction from a 15 m mast. Every hour the weather state is observed and coded according to the international rules of WMO (World Meteorological Organization). Both are sent away in a standard telegram ("SYNOP") together with other meteorological information (temperature, humidity, cloudiness...). From both the 80 m mast measurements and the observations of the weather station a relatively complete set of the meteorological ground information is given.

Island influence on wind speed and turbulence intensity

The above mentioned time series of hourly wind speed and direction in the 8 height levels were the basis for the following evaluation. In order to avoid any confusion we state here, that in meteorology the wind direction is the direction where **the wind comes from.** Further the directional angle starts with 0^{o} at North and counts clockwise. East thus is 90^{o}, South 180^{o}, and West is 270^{o}.

The "Turbulence Intensity" **I** is a dimensionless measure of the turbulence of the atmospheric motion, and is defined as

$$I = s/F$$

where **F** is the average and **s** is the standard deviation of the momentary wind speeds (here 2 sec averages) within a certain time interval (here 1 hour).

Figure 3 gives a 2-dimensional plot of the normalized wind speed as a function of height and wind direction, averaged over the whole time of almost 3 years. For each direction all speeds are normalized with the wind speed at 78 m height. All wind speeds in the vertical profile were excluded, when the speed in the 78 m level was less than 5 m/s. Generally the wind at 50 m is about 95%, and at 20 m is about 80% of the wind speed in the top level of 78 m.

Two dominant features can be seen. One hump is at 340^{o}, which is wind from the island rock (see fig. 1). The speed is reduced by 10% up to a level of 60 m, when compared to the open sea direction $300\text{-}320^{o}$, and the vertical profile is quite different. The second hump is at 140^{o}, where the air comes from the wind converter. The core of it with relative speeds less than 85% goes up to the hub height of 50 m. Comparison with the adjacent wind direction shows that the reduction is greater than 10%. Considering further, that the wind converter only worked for about half of the time, it can be concluded, that the wind converter takes much more energy out of the wind than the island rock (relatively).

Now look at figure 4, which is the corresponding plot of the turbulence intensities (which is given here in percent). Here you find a quite contrary behaviour of the two obstacles. The wind converter (at 140^{o}) does not produce much turbulence (maximum 13% at 50 m as compared to the adjacent directions with 7%), but the island rock (at 340^{o}) produces much turbulence. Even at 78 m still 17% are found on the average, which is very high. Larger values at this height will only be found over rough urban areas (in flat terrain).

Power spectra from a case study

Turbulence intensity is a bulk integral measure of the wind variability. A more detailed information can be gained from power spectra. For a case study a time series of 2 sec wind values was chosen, where the wind first comes from the open sea (310^{o}) and then gradually turns to the island rock (340^{o}). This data set was split in two parts (series 1 and series 2), where the wind turned to the border of the rock. Both series are 2 hours long.

For both series the power spectra of wind speed and wind direction were calculated for all 8 height levels. Only a part of the spectrum (from periods of 40 to 340 sec) is displayed in 3-D-plots, where the left axis is height, and the right axis is the period.

Figure 5 shows the spectra of wind speed. Series 1 (wind from the open sea) is quite calm. The spectral energy (vertical axis) is low. Series 2 (wind from island rock) shows much higher energy in the spectral range of 40-150 sec. The scaling of the vertical axis is the same for series 1 and 2. The same differences can be found in the spectra of the wind direction (fig. 6).

The dominant frequency of turbulence **f** generated on the leeward side of an obstacle of diameter **d** can be calculated from

$$f = (v * S) / d$$

where S is the dimensionless Strouhal number, and **v** is the average wind speed. If for the Helgoland island rock (at a wind direction of 340°, see fig. 1) we now take d = 350 m, v = 7 m/s (series 2, 50 m), and S = 0.4 (which is typical for large flat buildings) a frequency **f** = 0.01 s^{-1} results, which is a period of T = 100 s. This is well in the enhanced spectral range for series 2 in figures 5 and 6. The dominant frequency under these conditions always is a broad spectral band.

Comments on weather influences

As was explained above the weather station Helgoland measures wind speeds at a height of 15 m nearby. Here the speed units are "knots" (kn, nautical miles per hour), 1 kn = 0.5 m/s. The observed weather state is coded numerically in two digits, thus ranging from 0 to 99. The code will be explained below.

Table 1 gives the two-dimensional distribution of wind speed (ordinate, in classes of 5 kn) versus weather code (abszissa, in classes of 10 code numbers). The lowest line of table 1 is the average wind speed in kn for each code group. In total 24,683 hourly weather observations are availible during our measuring campaign (July 1989 - April 1992). The weather code is more or less ordered in decades, an rough explanation will now be given together with comments on the influences upon wind converters.

Code 0-9: Insignificant weather (only concerning cloud formation and visibility). Average wind speed similar to overall average, see below right column). This is the most frequent weather type (15,526 occurrences = 63%). No influence.

Code 10-19: Similar to code 0-9. No influence.

Code 20-29: Significant weather (codes 30-99) during the last hour, but not at the time of the observation. Complicated group, cannot be explained here, but: no influence.

Code 30-39: Dust and sand storm, drifting snow. Does not occur at sea.

Code 40-49: Fog of various kinds. Occurrence about 2%, but generally combined with very low wind speeds (average only 10.9 kn). Additionally temperatures at sea are seldom below freezing. Therefore hoar frost formation, which may change the aerodynamics of rotor blades, is a very rare event at sea and along the coasts of the north sea. This differs very much from the conditions in mountainous areas, where fog (i.e. clouds) in winter is rather often combined with stronger wind.

Code 50-59: Drizzle. No influence.

Code 60-69: Rainfall. No severe influence.

Code 70-79: Snowfall. No severe influence.

Code 80-89: Rain and snow showers. Average wind speed relatively high, always connected to enhanced gustiness. May have a certain influence.

Code 90-99: Thunderstorm of different severity. Partly connected with hail, and almost always connected with strong gusts. (Occurrence about 0.2%, typical for most of northern Germany). Hail may cause mechanical damages, but large hail stones are rarely found at sea. But lighning strokes may be a severe danger for off shore and even coastal wind converters, as the wind speed during thunderstorms is often high (the average speed is the highest for all weather code groups; quite different to inland conditions, where the average speed generally is low, but strong gusts may occur). With speeds greater than 25 kn (12.5 m/s) a sufficient amount of sea salt spray is present, which covers everything within a short time. Thus even rotor blades without any metal parts may get a high conductivity. The WKA60 in Helgoland lost one of three rotor blades due to a lightning stroke only after about 1.5 years of operation, which means (deduced from the thunderstorm probability of 0.2%) after about 25 thunderstorm hours. Our meteorogical equipment of the 80 m mast was lightly damaged by lightning twice in 3 years, although we had a thorough protection and grounding.

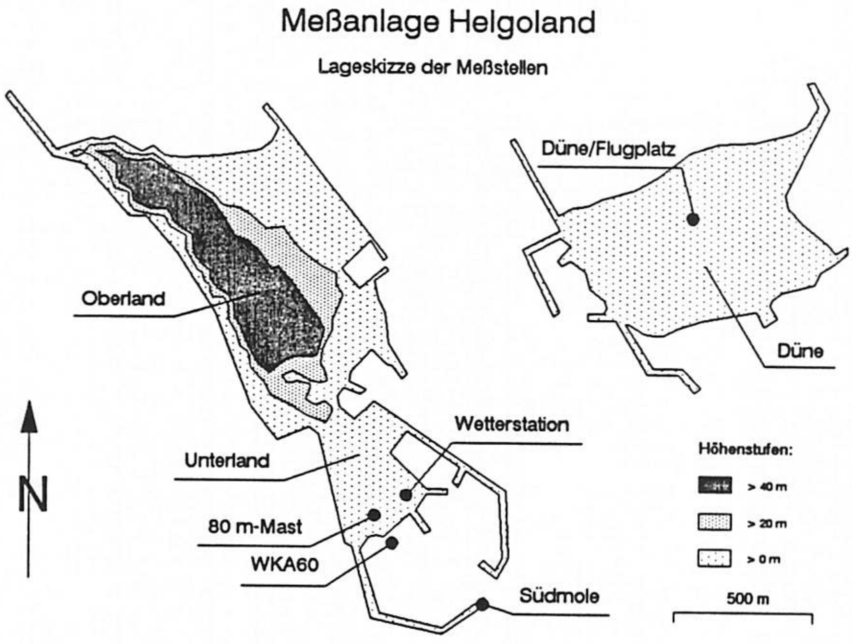


Figure 1: Sketch of measuring points. Island rock shaded dark.

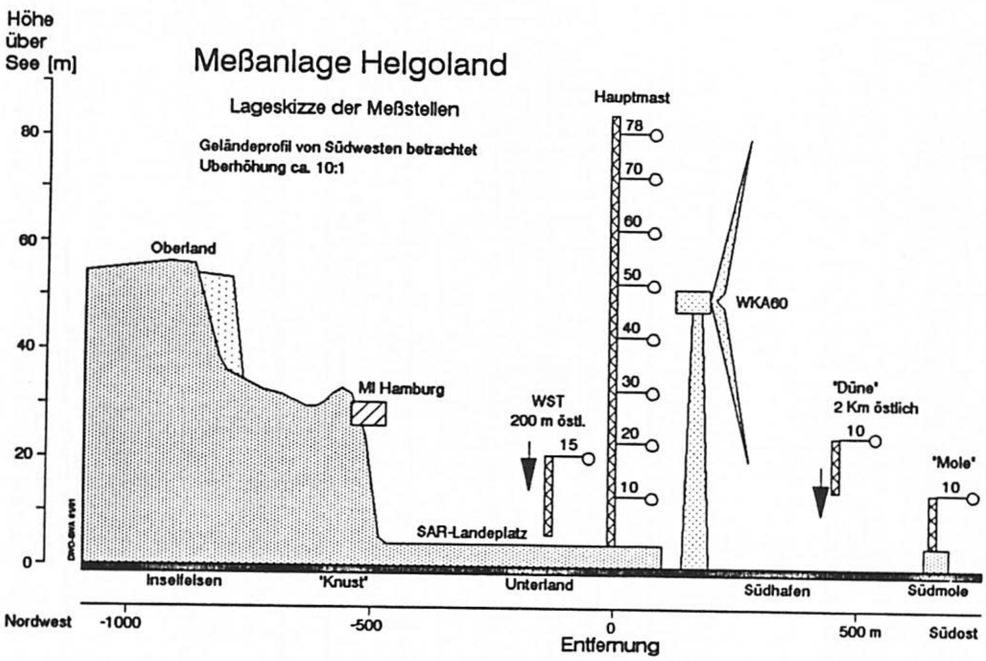


Figure 2: Vertical cross section northwest - southeast.

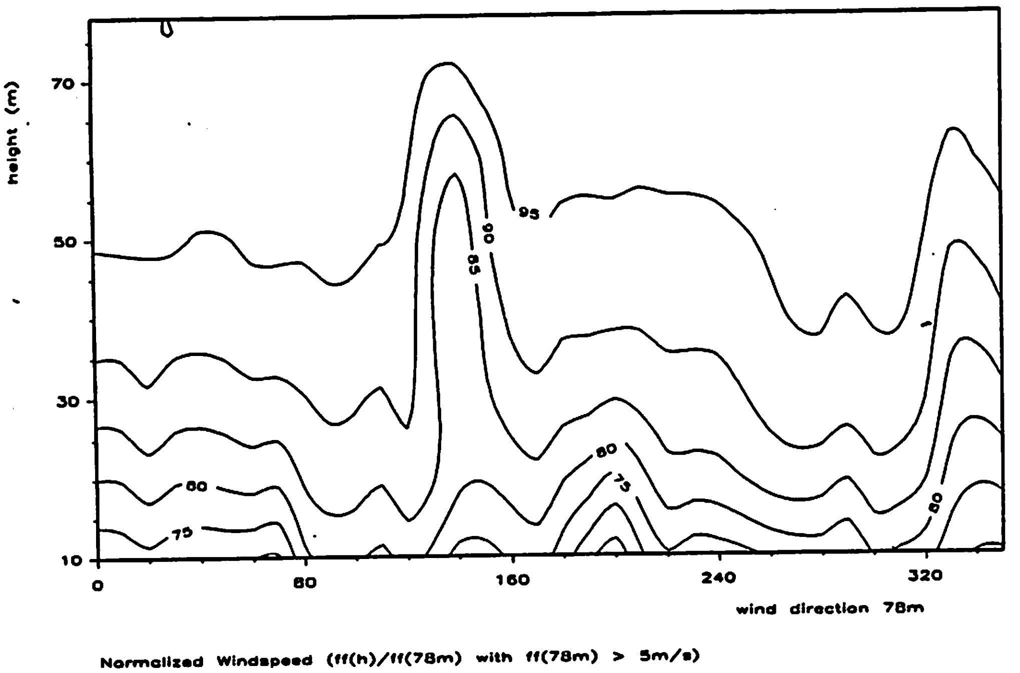


Figure 3: Wind speed normalized with 78 m speed versus wind direction and height

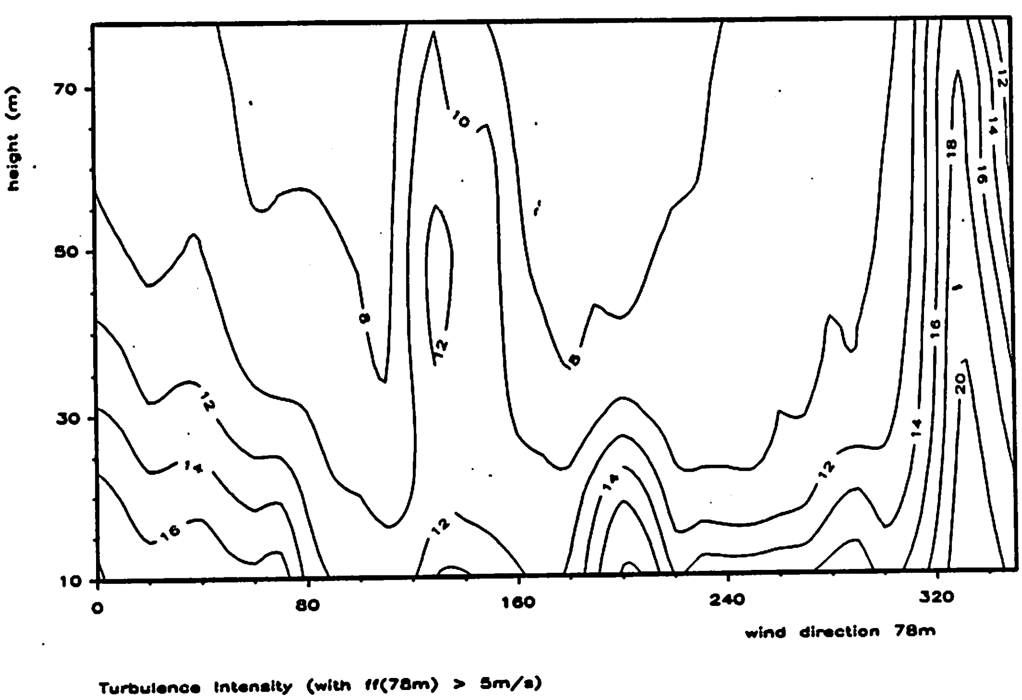


Figure 4: Turbulence intensity versus wind direction and height

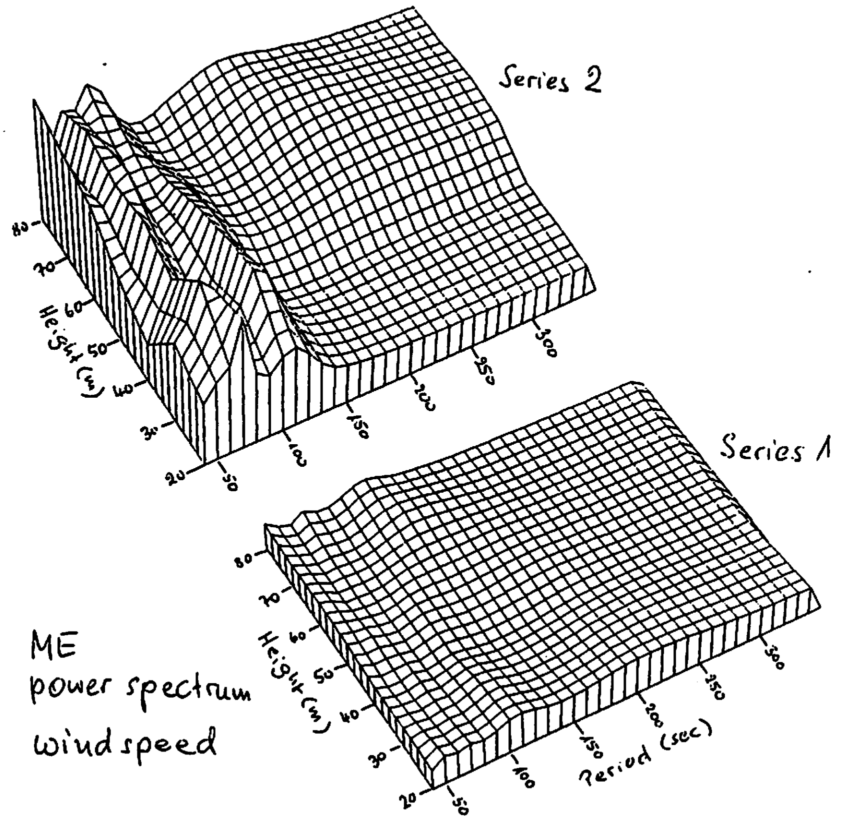


Figure 5: Power spectra of wind speed. Series 1: 25/07/90 0600-0800 UTC
Series 2: 25/07/90 0800-1000 UTC

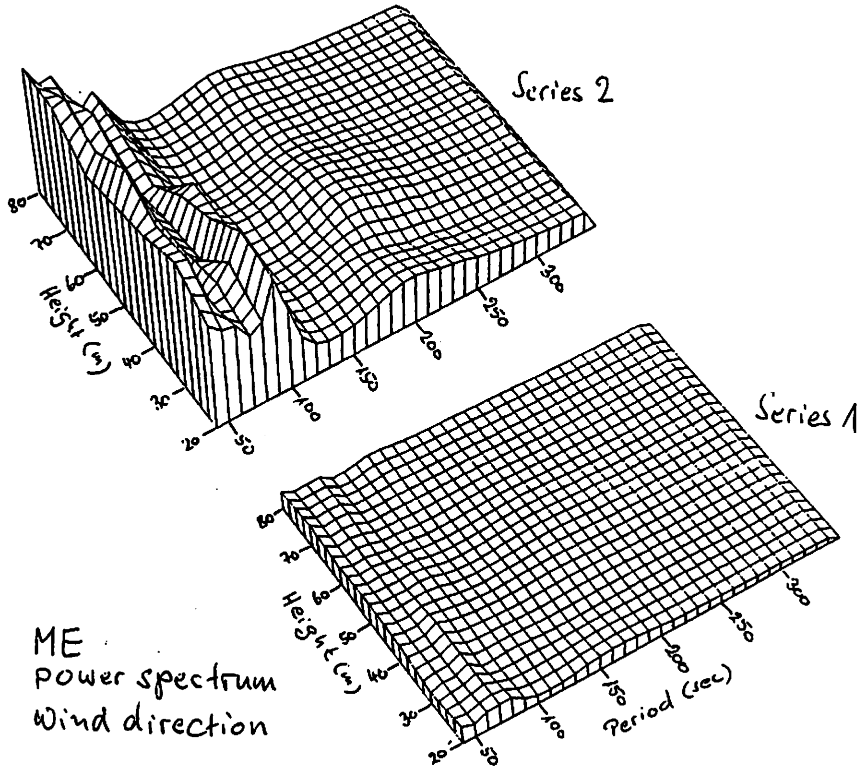


Figure 6: Power spectra of wind direction. Same times as fig. 5.

DEUTSCHER WETTERDIENST, SWA, WAM20 02/06/92

S T A T I O N: Helgoland (01/07/89-30/04/92)

ABSZISSA: WEATHER (CODE)
ORDINATE: WIND (KN)

ABSOLUTE FREQUENCIES

CLASSES FROM	0	10	20	30	40	50	60	70	80	90	
TO	9	19	29	39	49	59	69	79	89	99	ALL
FROM/TO											
0.0/ 4.9	883	207	60		45	9	49	2	3	4	1262
5.0/ 9.9	2992	808	259		156	68	150	17	19	5	4474
10.0/ 14.9	4189	907	488		150	118	261	23	40	6	6182
15.0/ 19.9	3535	772	645		72	232	313	19	65	10	5663
20.0/ 24.9	2358	403	658		17	125	339	8	77	8	3993
25.0/ 29.9	997	168	343			70	189	7	53	10	1837
30.0/ 34.9	464	35	205			31	139	6	43	8	931
35.0/ 39.9	95	19	76			10	58		5	2	265
40.0/ 44.9	10	2	19			2	20		3	3	59
45.0/ 49.9	2		4			1	5		2		14
50.0/ 54.9									1		1
55.0/ OPEN							1				1
ALL	15526	3321	2757		440	666	1524	82	311	56	24683
SPEED AVG.	15.3	14.1	19.6		10.9	18.2	20.1	16.0	21.8	22.3	16.0

Table 1: Frequencies of windspeed and weather code

DLR

Environmental Effects on Gl-Ep of Wind Turbine Rotor Blades

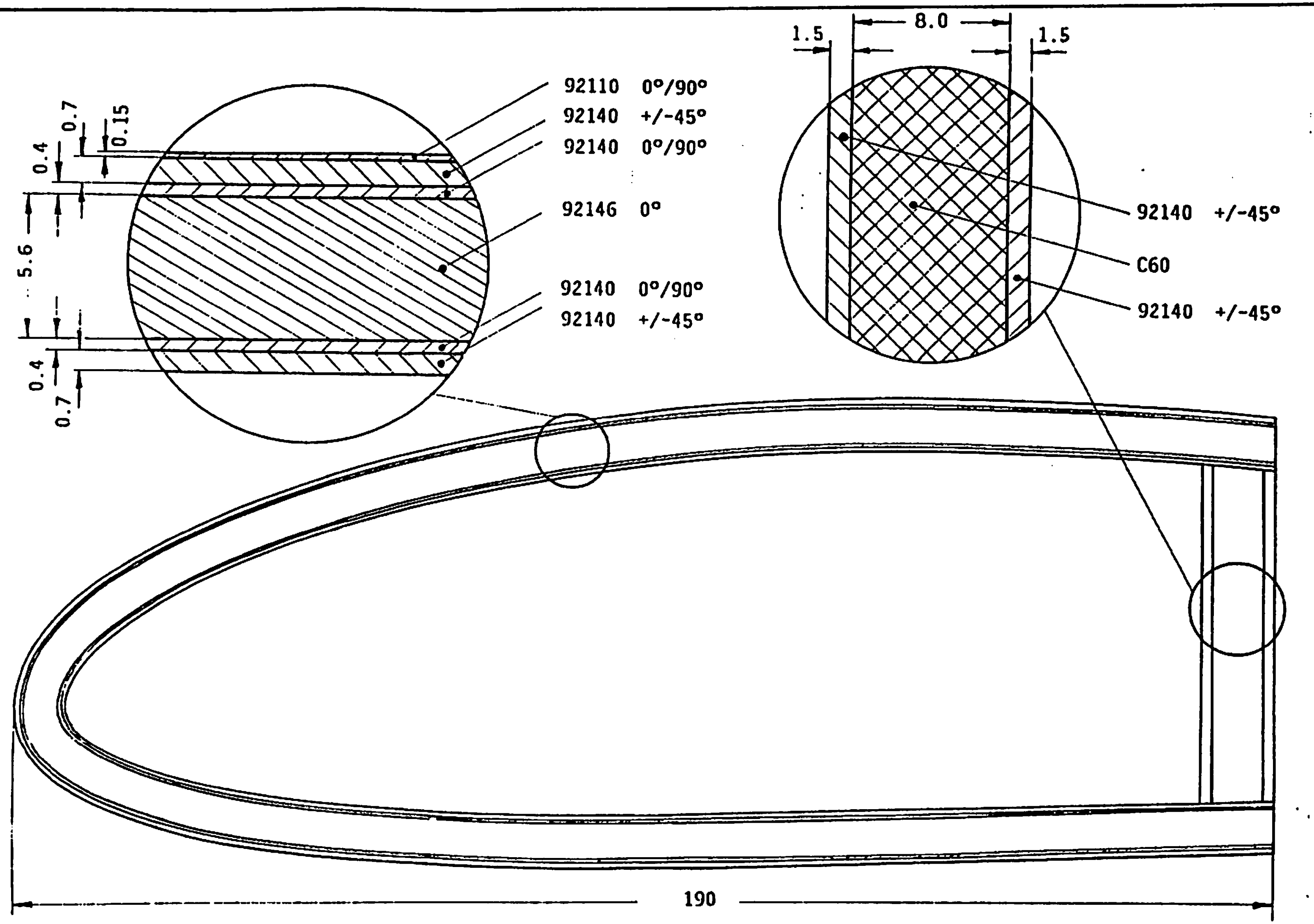
Chr. Kensche
DLR German Aerospace Research Establishment
Institute for Structures and Design
D-7000 Stuttgart 80, Pfaffenwaldring 38-40
FRG

IEA - Workshop on
Effects of Environment on Wind Turbine Safety and Performance
Deutsches Windenergie-Institut
Wilhelmshaven
16/17 June 1992

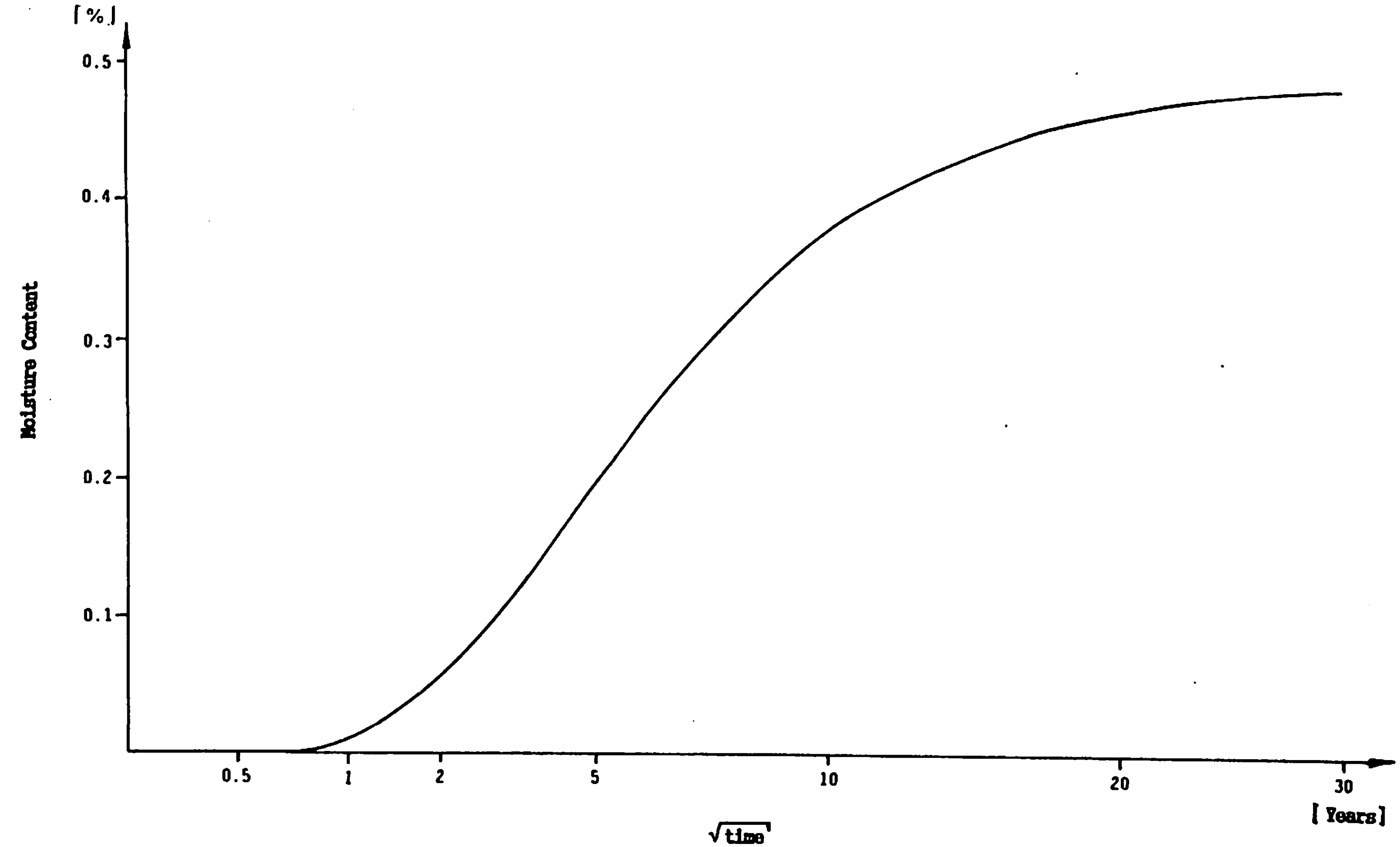
DLR

Objectives

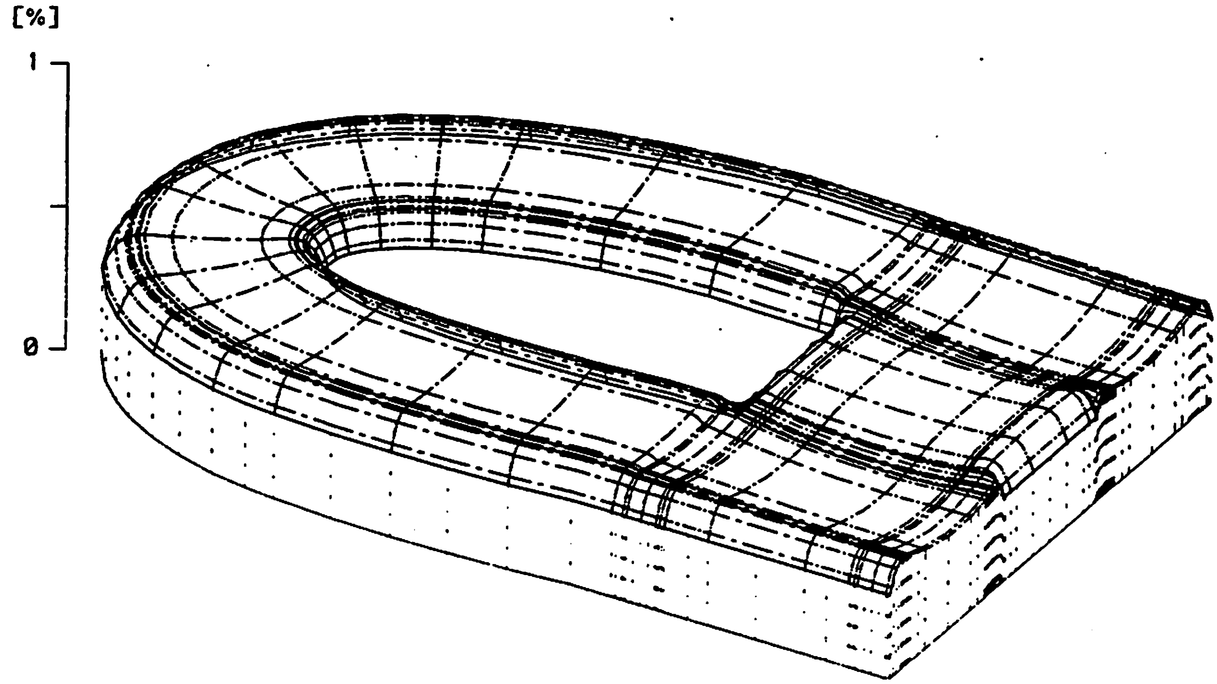
- o Moisture Absorption
- o Hailstone Impact
- o Testing Results
  - Static Compression Performance
  - Fatigue
- o Conclusions



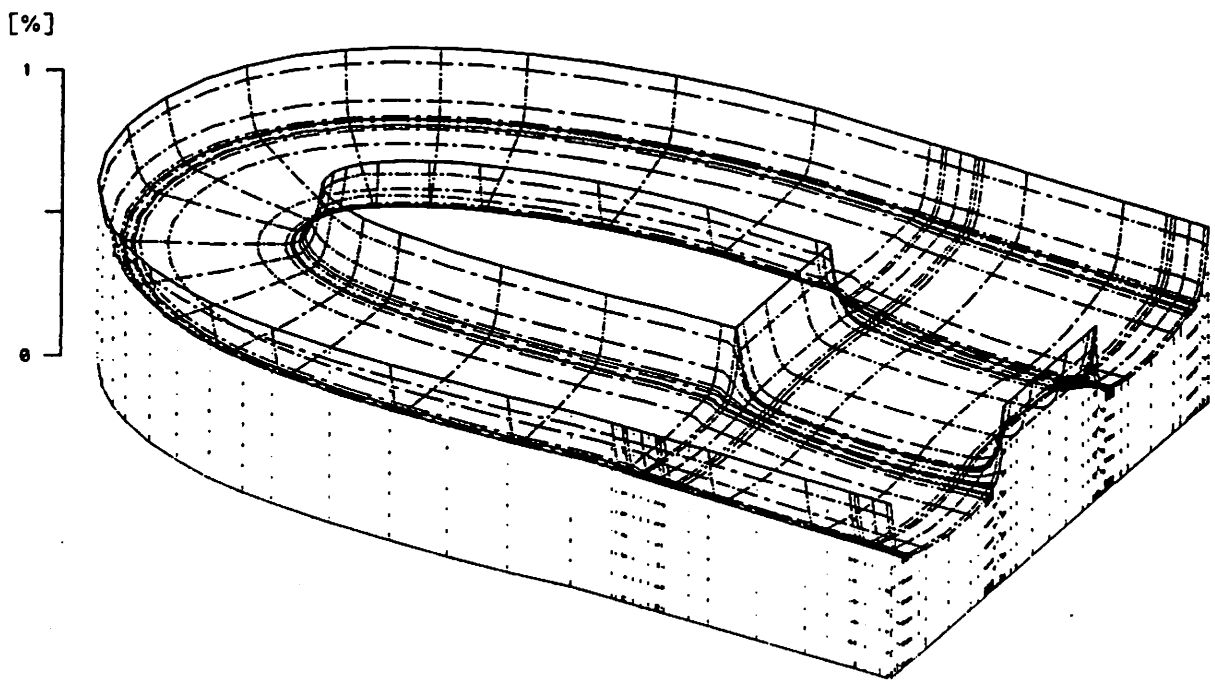
Cross Section through Spar of Rotor Blade



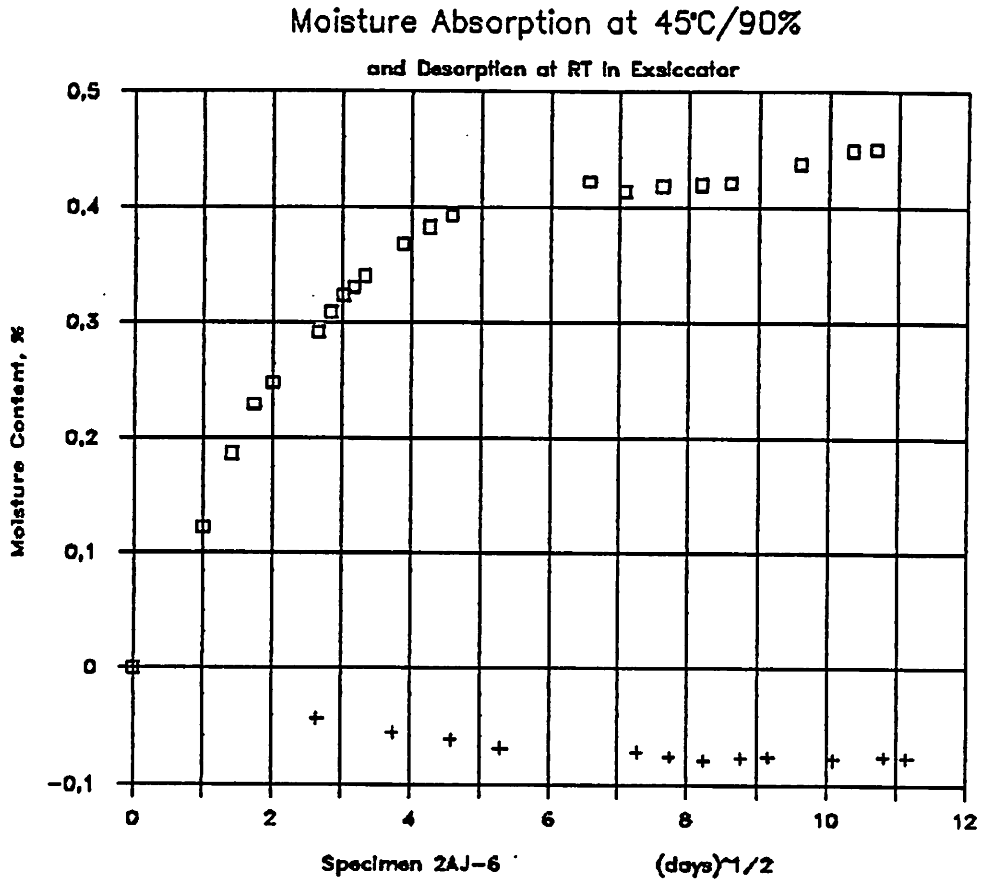
Moisture Content in Wall Centre of Spar versus Time (Years)



Moisture Distribution after 20 Years, Dry/Warm Phase



Moisture Distribution after 20 Years, Wet/Cold Phase

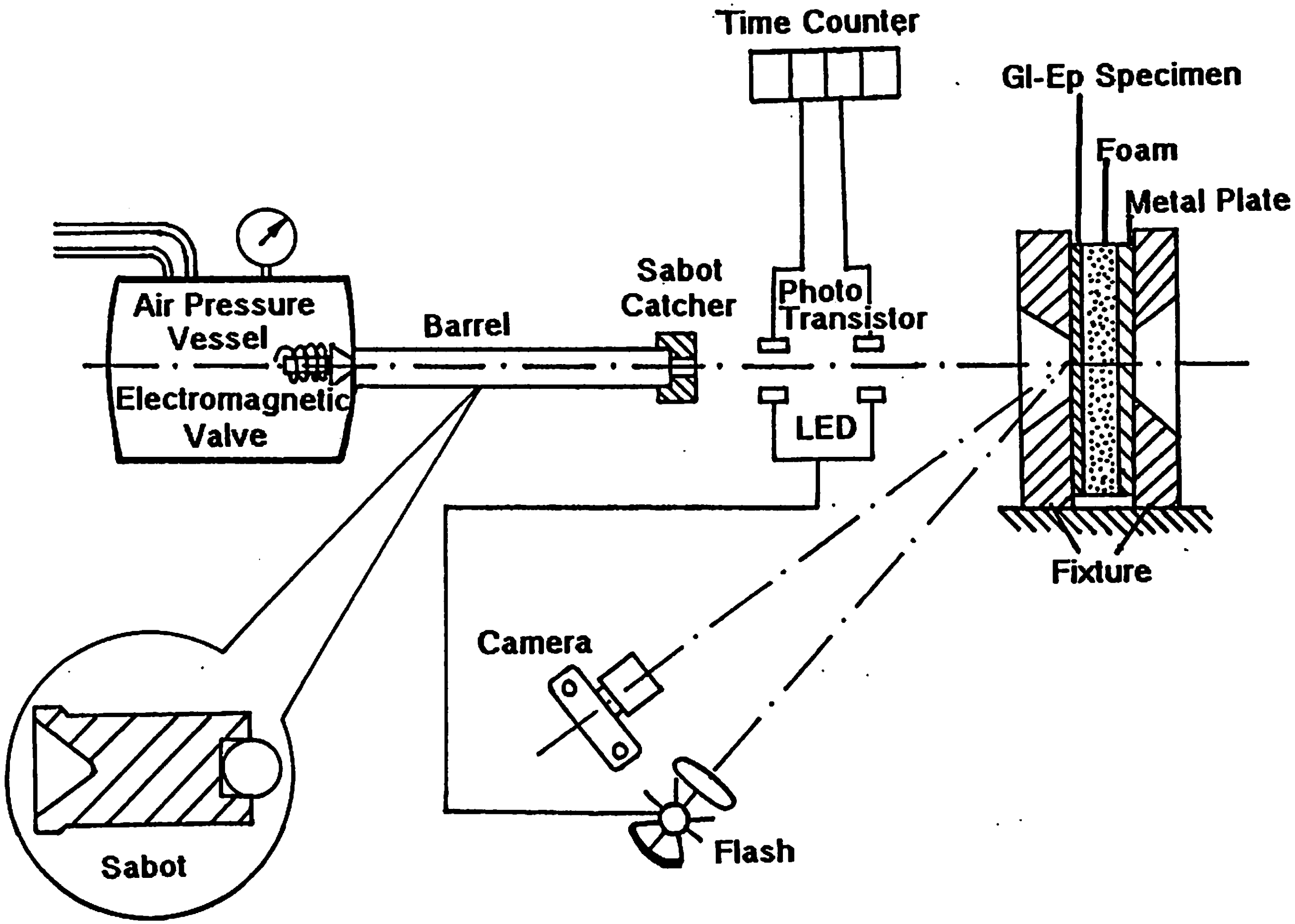

Moisture Absorption at 45°C/90%
and Desorption at RT in Exsiccator
Moisture Content, %
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
2
4
6
8
10
12
Specimen 2AJ-6
(days)^1/2

DEBRA - 25 n = 50 1/min Radius $r_2 = 12.5m$

Stone-Ø [mm]	Mass [g]	V_∞ [m/s]	V_R [m/s]	V_{Wind} [m/s]	V_{total} [m/s]	E_{total} [J]
10	0,3	9	65,4	35	101,5	1,54
15	1,9	12,4	65,4	35	102,5	10
21	5	16,2	65,4	35	104	27,1
25	8	18,7	65,4	35	105,1	44,22
31	15	22,2	65,4	35	106,9	85,74
37	25	25,6	65,4	35	108,8	148

Tab.1: Terminal velocity and energy of hail stones on a wind turbine

DLR


Time Counter
Gl-Ep Specimen
Foam
Metal Plate
Air Pressure Vessel
Barrel
Sabot Catcher
Photo Transistor
Electromagnetic Valve
LED
Fixture
Camera
Flash
Sabot

DLR

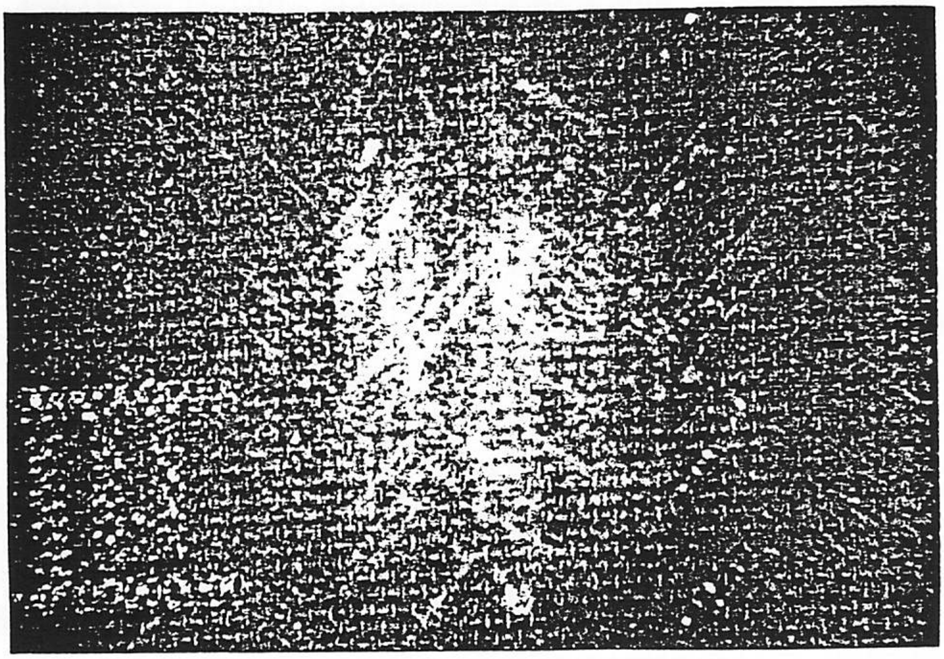


Fig. 2: Crack Pattern on Backside of Impacted Gl- Ep Specimen

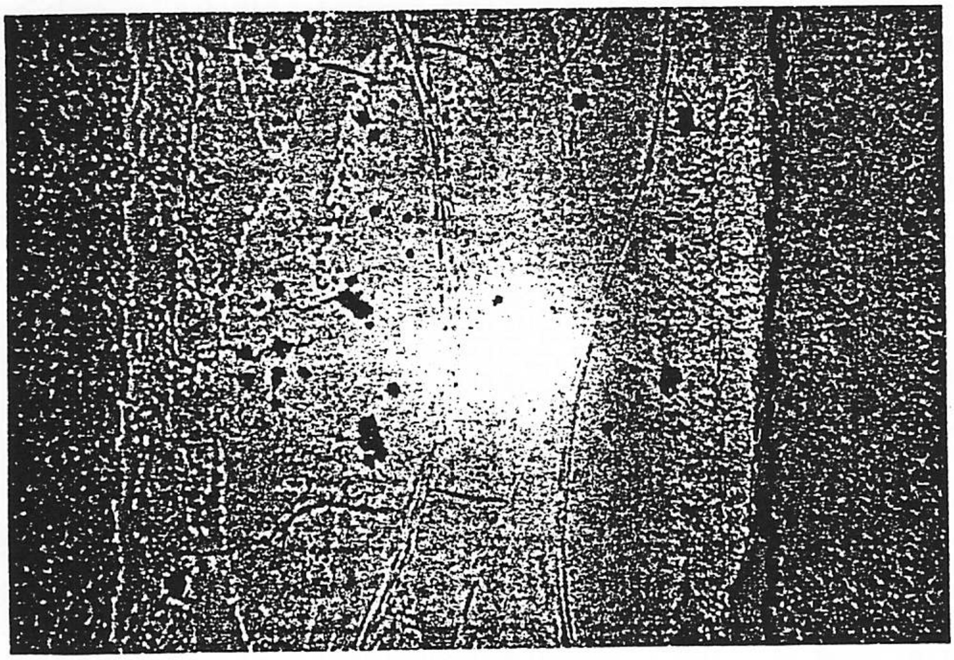


Fig. 3: Crack Pattern in Cross Section of Specimen

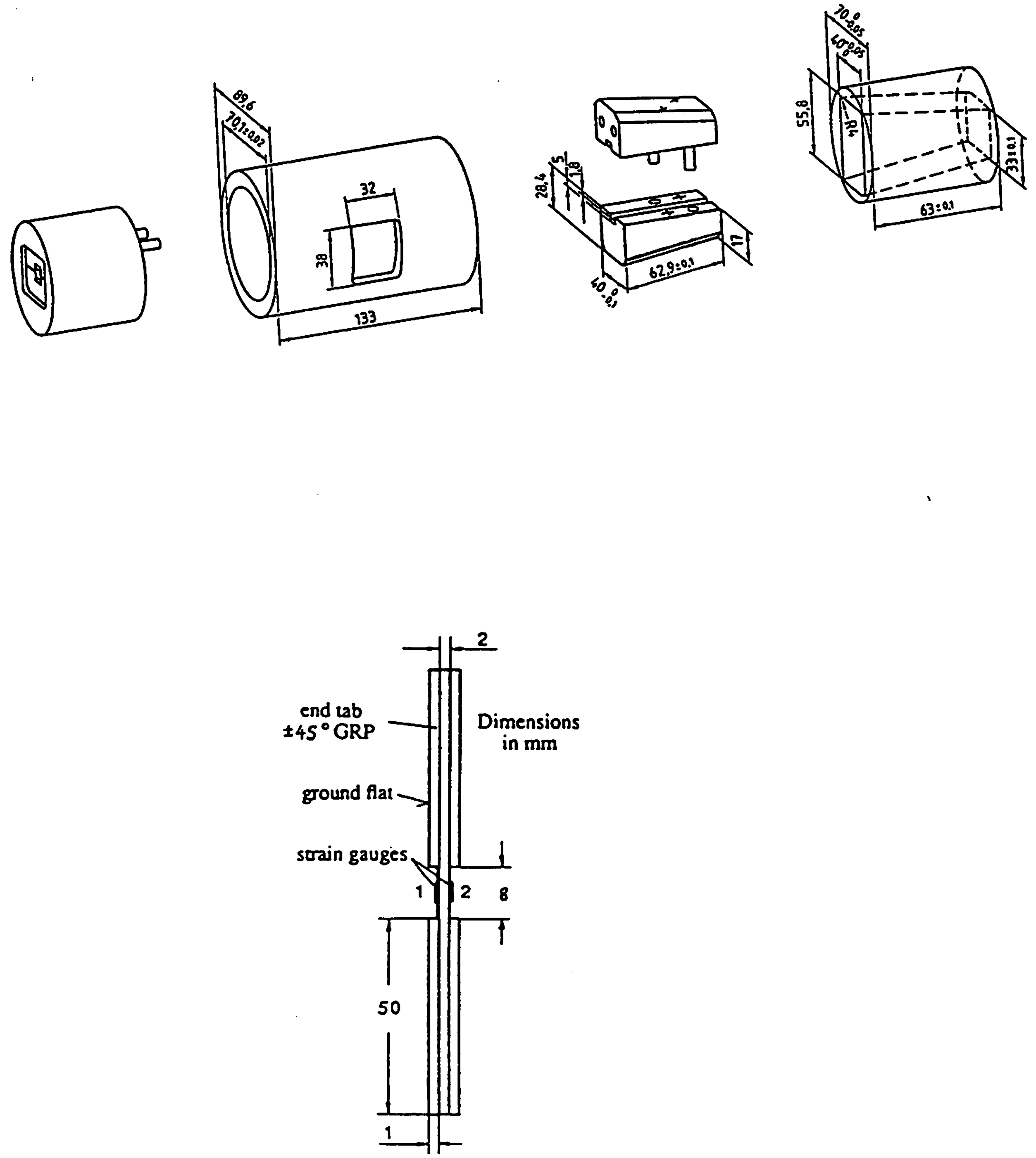


Fig. 1: Compression Test Specimen (Type Celanese) with Clamping Device

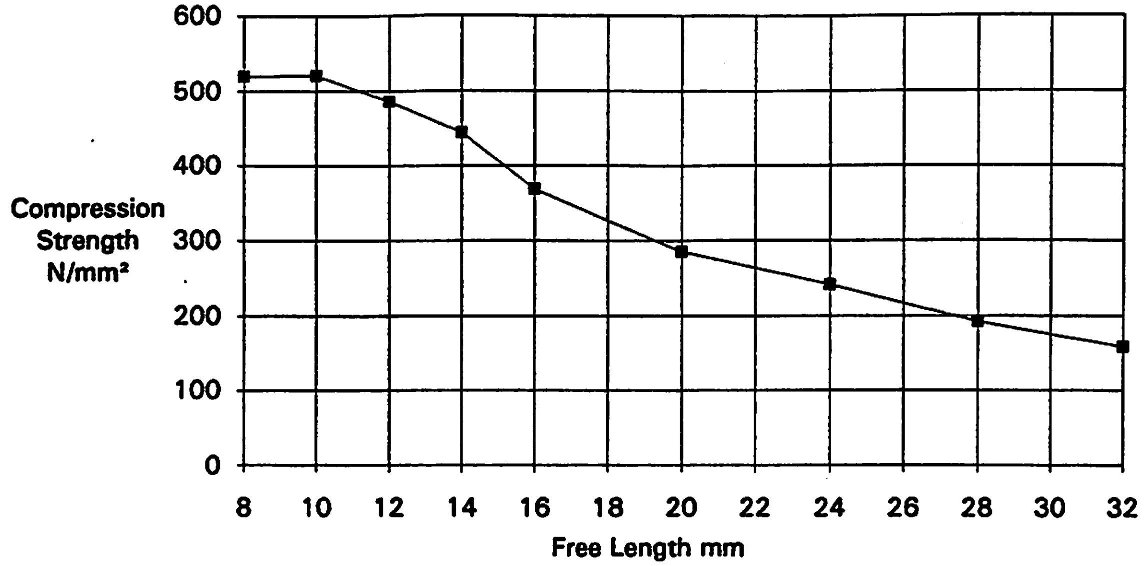


Fig. 4: Static Compression Strength of Gl- Ep (UD/±45°) versus Free Length

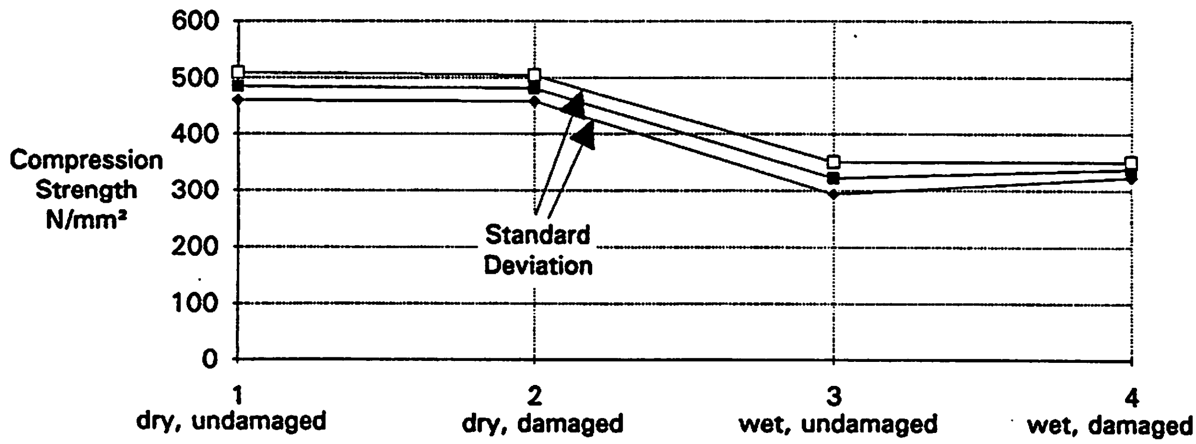


Fig. 5: Static Compression Strength of Gl- Ep (UD/±45°) Depending on Damage and Environmental Effects (Free Length 12 mm)

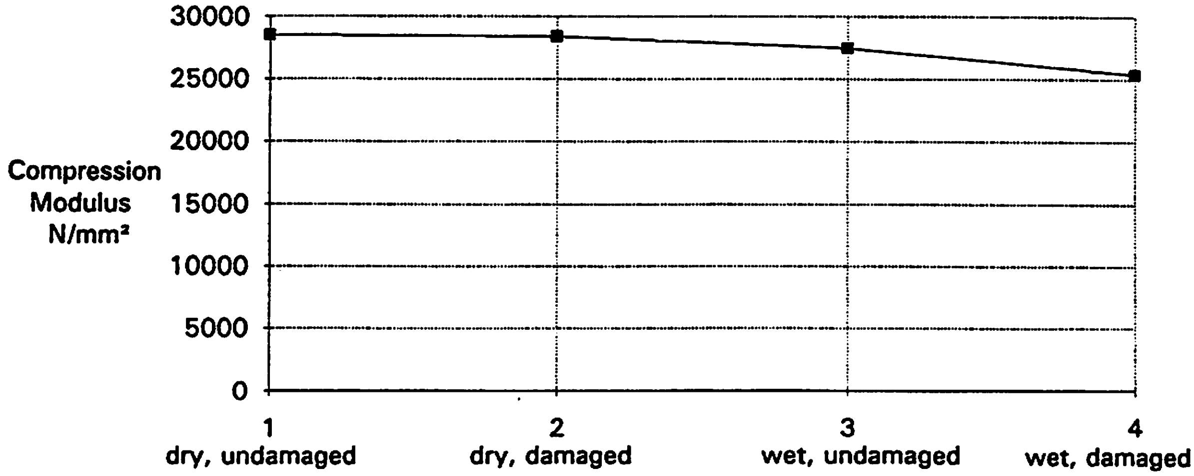
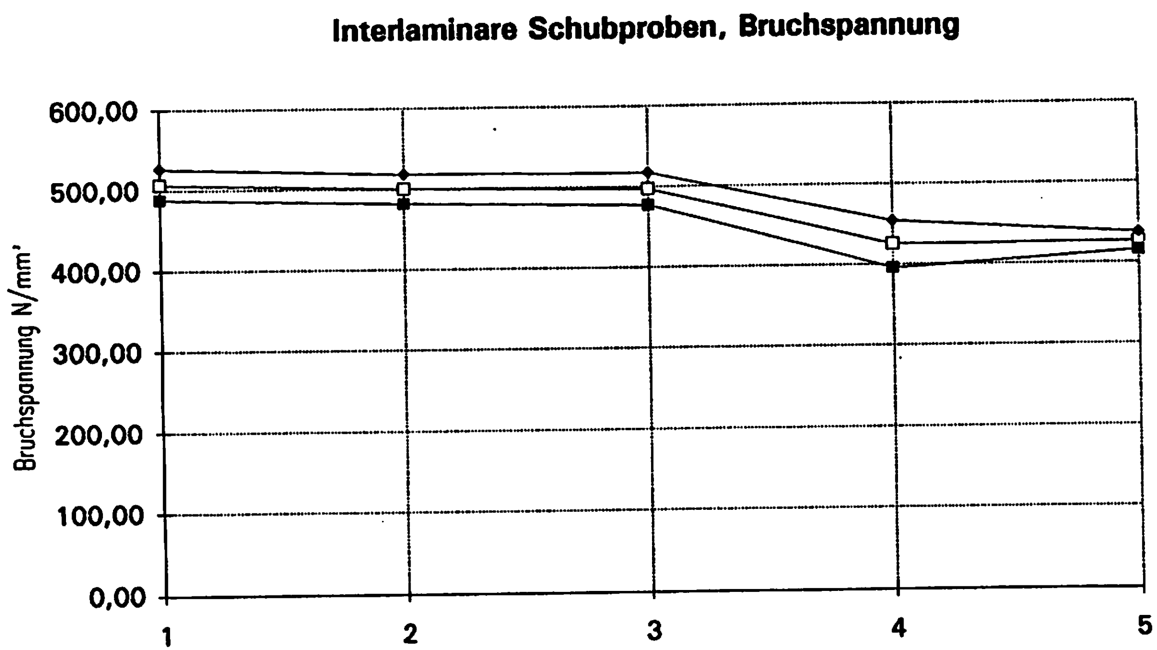
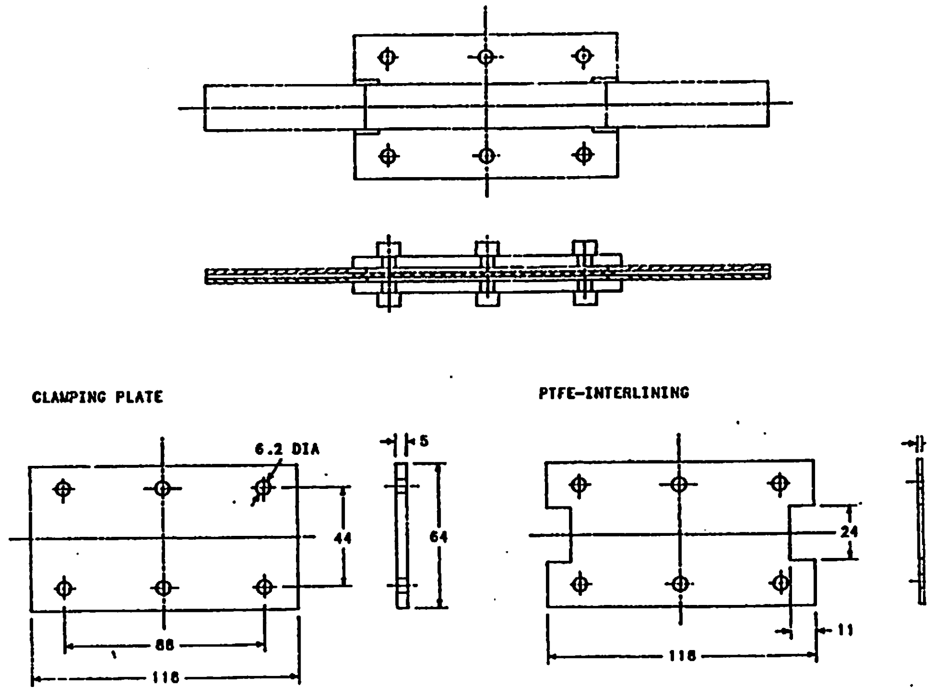


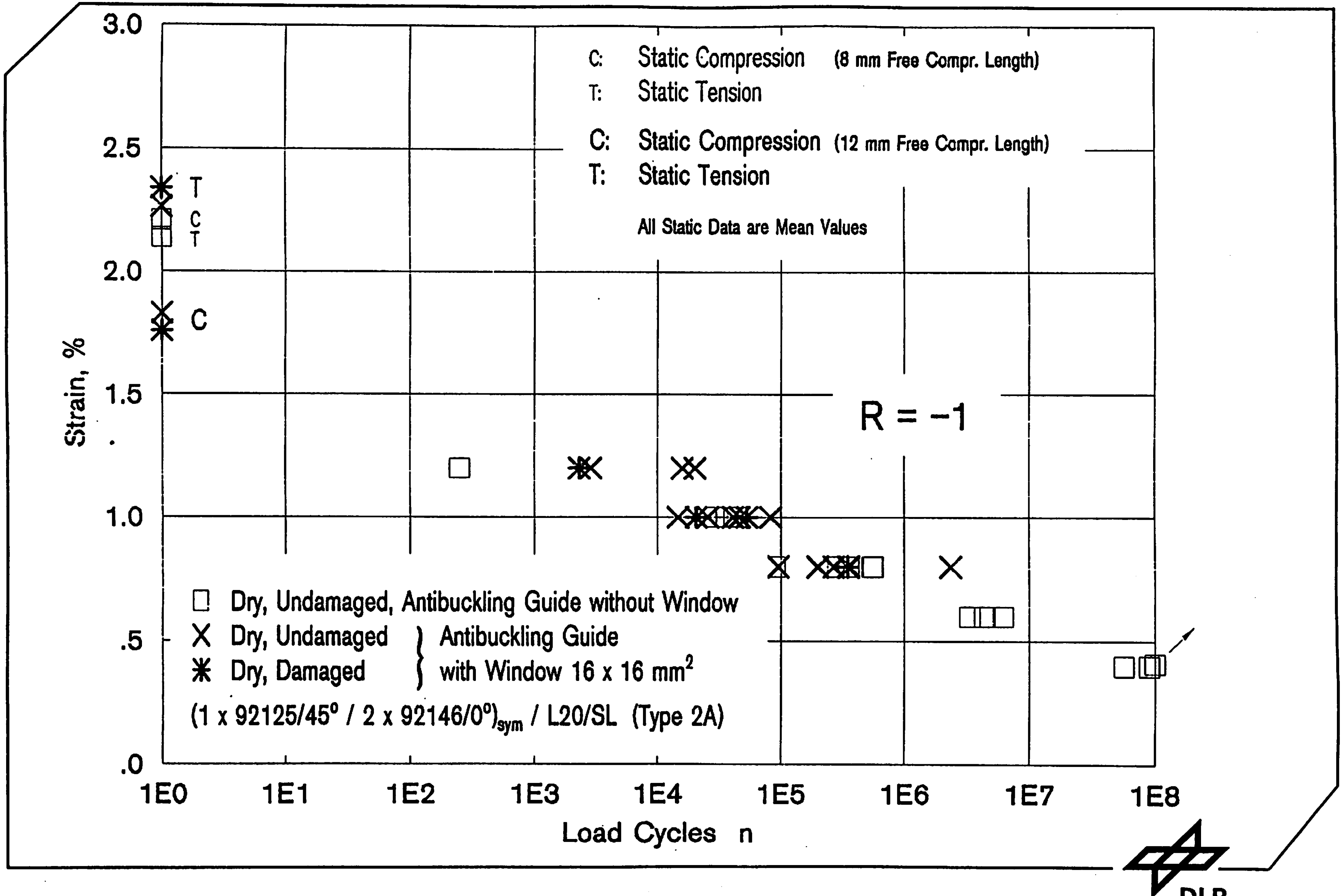
Fig. 6: Compression Modulus of Gl- Ep (UD/±45°) Depending on Damage and Environmental Effects (Free Length 12 mm)


Interlaminare Schubproben, Bruchspannung
Bruchspannung N/mm²
600,00
500,00
400,00
300,00
200,00
100,00
0,00
1
2
3
4
5

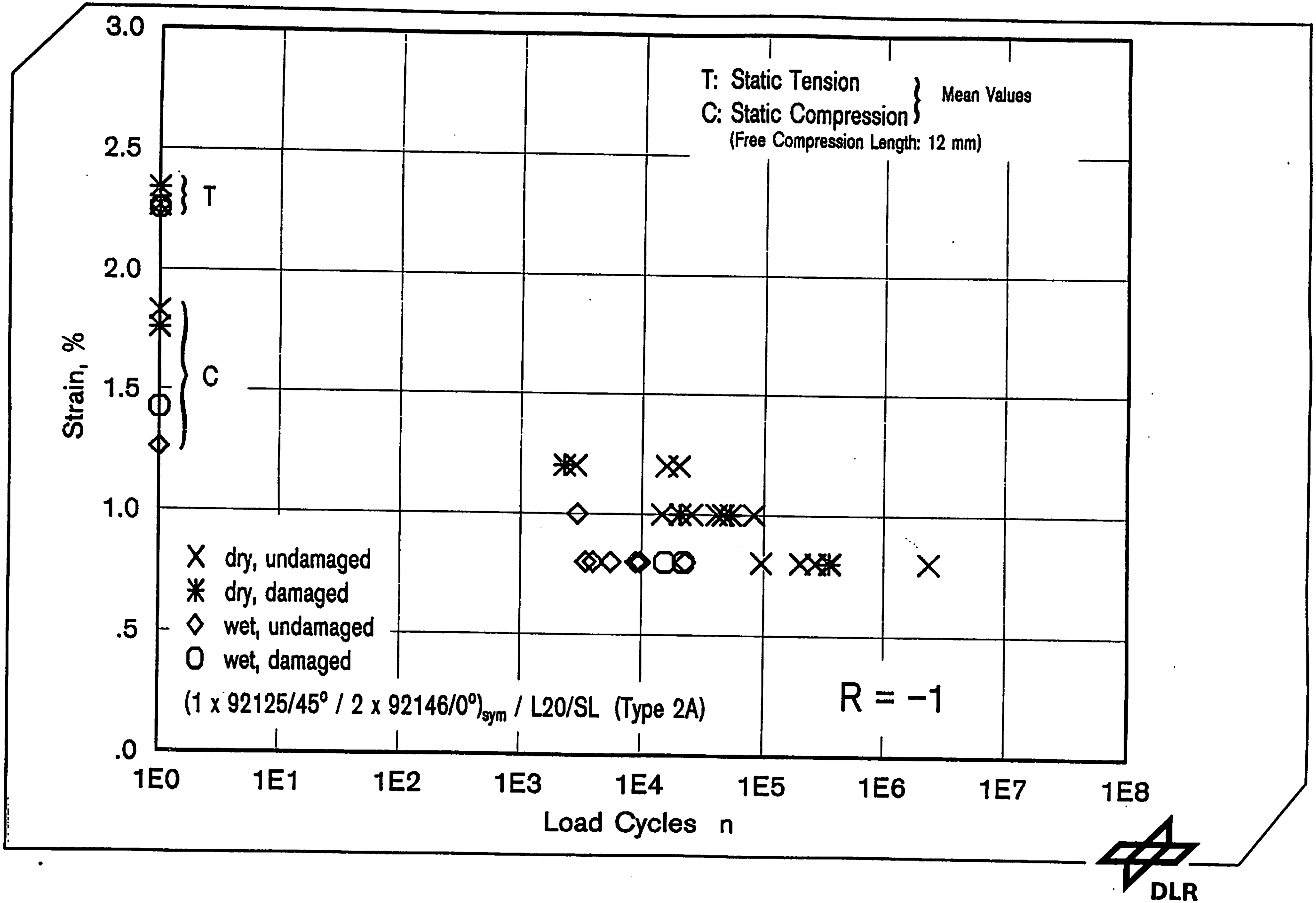
DLR

DLR - Antibuckling Guide

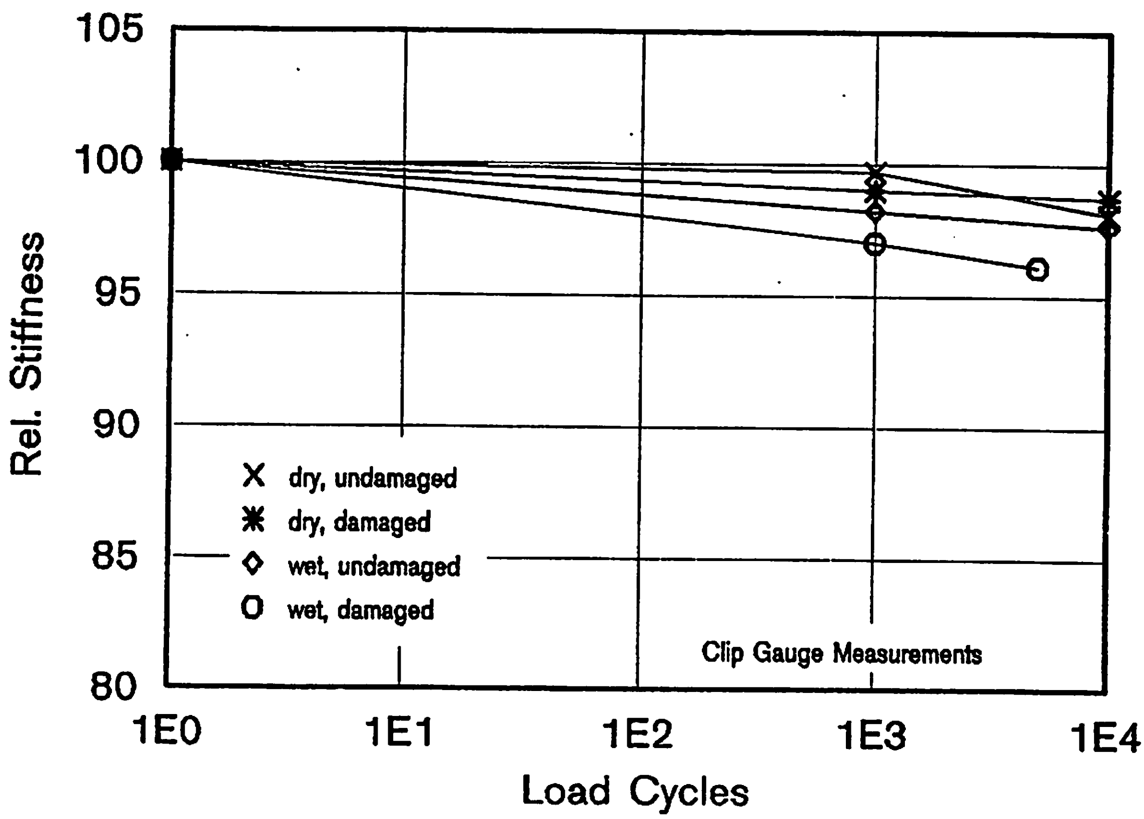




C: Static Compression (8 mm Free Compr. Length)
T: Static Tension
C: Static Compression (12 mm Free Compr. Length)
T: Static Tension
All Static Data are Mean Values
R = −1
Dry, Undamaged, Antibuckling Guide without Window
Dry, Undamaged
Dry, Damaged
Antibuckling Guide with Window 16 x 16 mm²
(1 x 92125/45° / 2 x 92146/0°)sym / L20/SL (Type 2A)
Strain, %
Load Cycles n
3.0
2.5
2.0
1.5
1.0
.5
.0
1E0
1E1
1E2
1E3
1E4
1E5
1E6
1E7
1E8
T
C
T
C
DLR



T: Static Tension
C: Static Compression
Mean Values
(Free Compression Length: 12 mm)
Strain, %
3.0
2.5
2.0
1.5
1.0
.5
.0
T
C
dry, undamaged
dry, damaged
wet, undamaged
wet, damaged
(1 x 92125/45° / 2 x 92146/0°)sym / L20/SL (Type 2A)
R = −1
1E0
1E1
1E2
1E3
1E4
1E5
1E6
1E7
1E8
Load Cycles n
DLR



Rel. Stiffness
105
100
95
90
85
80
1E0
1E1
1E2
1E3
1E4
Load Cycles
dry, undamaged
dry, damaged
wet, undamaged
wet, damaged
Clip Gauge Measurements

DLR

Conclusions

- o Moisture Absorption in Gl-Ep by Analysis (Gel Coat not Considered) and by Experiment: 0.5 %
- o Significant Influence of Moisture on Static and Fatigue Properties
- o No Significant Influence of Hailstone Impact on Static and Fatigue Properties

Recommandations

- o Periodical Inspection of Rotor Blades (particularly in Humid and Cold Areas) on
  - Gel Coat Cracks
  - Gel Coat Chalkying
- o Refurbishing Gel Coat if Cracks or Chalkying

Icing of Wind Turbine Rotor Blades During Operation

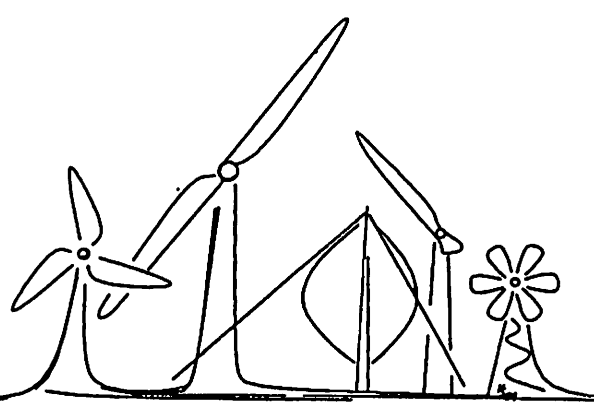
Henry Seifert
Deutsches Windenergie-Institut

June 16, 1992

Paper presented at

22th IEA-Expert Meeting Effects of Environment on Wind Turbine Safety and Performance

June 16, 1992 in Wilhelmshaven, Germany



also presented at BOREAS

10-14th February, 1992
ENONTEKIÖ, FINLAND

Deutsches Windenergie-Institut, Ebertstr. 96, 2940 Wilhelmshaven, Germany, Tel.: ++4421-4808-0 Fax.: ++4421-4808-43

Icing of Wind Turbine Rotor Blades During Operation

Henry Seifert
Deutsches Windenergie-Institut
Germany

DEWI

Abstract

Certifying wind turbines for cold and mountainous regions needs reliable procedures for the prediction of ice amount. It is pointed out that the certification rules of different countries show a wide scatter of possible ice built-up to be taken into consideration for the appropriate load cases. The basis for these regulations are mostly derived from standards for buildings. However, investigations concerning icing of wind turbines during operation at the DLR test site *Ulrich Hütter Test Station* in Southern Germany showed, that real ice loads are of other quality.
Thus, based on these experiences and on wind tunnel tests a proposal for simplified load assumptions for certification regulations has been worked out.

List of Symbols

λ	-	Tip speed ratio
$\lambda_{Bl} = t_a/t_i$	-	Taper ratio of rotor blade
$\Lambda = R^2/A_{Bl}$	-	Aspect ratio of rotor blade
ρ_E	kg/m^3	Density of ice amount
$\zeta = r/R$	-	Normalized blade radius
A_{Bl}	m^2	Area of rotor blade
A_E	m^2	Area of ice section at ζ
A^*	m^2	Area related to $d(\zeta)\, t_E(\zeta)$
$c_E = \frac{A_E}{A^*}$	–	Ice coefficient
d	m	Thickness of profile
g	m/s^2	Gravity constant
m_E	kg	Mass of ice
r	m	Radius
R	m	Radius of rotor blade
t_a	m	Chord length at $\zeta = 1$
t_E	m	Depth of ice at the leading edge
t_{Ea}	m	Depth of ice at leading edge at $\zeta = 1$
t_w	m	Chord length at $\zeta = 0$

1 Introduction

Up to now the certification regulations or recommendations differ in philosophy concerning icing of wind turbine rotor blades. The ice loads in the existing recommendations [3, 2, 7] are derived mostly from helicopter design codes or from building standards, because of missing investigations on wind turbines. Due to the fact that more and more wind turbines are operating at sites where icing is likely to occur the prediction of ice amount in the recommendation becomes more important. Based on experiences including measurements at the wind energy test site *Ulrich Hütter* during several years [4, 1, 6] a recommendation is proposed to predict ice loads during wind turbine operation. However, this can only be a first attempt and the objective is to stimulate a further discussion.

2 Definitions of Ice Loads

2.1 Existing Recommendations

Figure 1 shows the assumption of ice amount at the leading edge according to the German Germanischer Lloyd (GL) recommendation [3]. For load cases including ice loads the first third of the rotor blade , beginning from the leading edge, is assumed to be covered with a 30 mm thick ice layer with a density of $\rho_E = 700kg/m^3$. The ice distribution over the radius is shown in that Figure as well.
The Netherlands Energy Research Foundation (ECN) regulation [2] is rather similar. For calculating the load case icing during operation it is recommended to cover the whole blade with an ice layer of 1 mm thickness with a density of $\rho_E = 900kg/m^3$.
The ice load cases of the Swedish recommendation, used in the design of AEOLUS II rotor blades [7] are based on an approximation formula assuming that the ice mass distribution is depending on the tip speed ratio λ as follows:

$$m_E(r) = 0.3\frac{\lambda^2}{R^2}r^2 \tag{1}$$

The total ice amount on one blade in kg can be calculated with:

$$m_E = 0.1\lambda^2 R \tag{2}$$

2.2 Proposal for Recommendation

Based on observations and measurements an approximation formula has been developed at DEWI. To simplify the approach, some basic assumptions, based on rotor blade statistics, have to be defined:
In the proposed recommendation the chord length distribution of the rotor blade is assumed to be linear along the radius r. The chord length of the blade root at $R = 0$ is extrapolated to simplify the calculation. The following equation results from the chord distribution of a trapezium rotor blade:

$$t(\zeta) = (t_a - t_w)\,\zeta + t_w \tag{3}$$

To assume the thickness of the blade with relation to the radius, statistical data of different sized rotor blades were evaluated. This results in a linear distribution of profile thickness beginning at $r = 0$ with a relative value of $d(0) = 0.3\,t_w$; the relative thickness at the blade tip is assumed to be $d(R) = 0.15\,t_a$. The normalized thickness distribution along the radius can then be easily derived:

$$d(\zeta) = (-0.15\,\zeta + 0.3\,)\,t(\zeta) \tag{4}$$

Most of the observations at iced rotor blades during operation showed that the ice built-up is linear from blade root to the tip with a maximum depth of ice at the outer part (1 in Figure 1). The ice at the outer part of the blade breaks off and grows again, but the maximum distribution will be the linear one, not the saw-tooth-distribution. Ice depth distribution is assumed to be

(5) $$t_E(\zeta) = t_{Ea}\,\zeta$$

The maximum depth of ice amount at the tip is thereby t_{Ea} depending on the size of the turbine. Some values for two different sized wind turbines are known and are used as a basis for the following approximations. For larger scaled turbines as well as for verification purposes more measurements have to be carried out at different turbines under different meteorological conditions. As an approximation the maximum ice depth at the blade tip is related to the radius R:

(6) $$t_{Ea}(R) = t_a\,(0.45\,e^{-0.05R_0} + 0.14) \qquad \text{with } R_0 = \frac{R}{C} \text{ with } C = 1m \text{ and } R \text{ in [m]}$$

This approximation is based on observations of two different rotor sizes (Figure 2).

2.2.1 Definition of the Ice Coefficient

Those observations made at the *Ulrich Hütter* test site showed [5] that the shape of the leading edge ice is depending on different parameters as:

1. Scale of the wind turbine;
2. Radius location of the ice;
3. Type of icing, clear ice [6] or rough ice [1, 4];
4. Other effects, not investigated up to now.

First estimations for clear ice showed, in spite of higher density, very low additional loads compared to all recommendations. This is due to the fact that the amount of leading edge ice is very small (Typ 1 in Figure 3). The following investigations are therefore limited to rough ice. Relating the area of the ice cross section at the radius r to the area derived by the multiplication of ice depth with the local thickness of the profile it can be shown that this coefficient is nearly constant at each radius. The coefficient varies for different scaled turbines. Some cross sections are shown in Figure 3. Related to the area

(7) $$A^*(\zeta) = d(\zeta)\,t_E(\zeta)$$

the ice coefficient c_E Figure 4 is defined as follows:

(8) $$c_E = \frac{A_E(\zeta)}{A^*(\zeta)} \qquad \text{with } A^* \text{ from (7)}$$

The dependence of the ice coefficient on the size of the turbine has been found empirically and has to be verified and improved by other measurements:

(9) $$c_E(R) = 9\,e^{-0.33R_0} + 0.5 \qquad \text{with } R_0 = \frac{R}{C} \text{ with } C = 1m \text{ and } R \text{ in [m]}$$

2.2.2 Ice Loading on the Rotor Blade

Transforming the equations (1) to (7) the line load of the ice amount at the leading edge can be determined:

$$q(\zeta) = \rho_E\, g\, A_E(\zeta) = \rho_E\, g\, c_E\, d(\zeta)\, t_E(\zeta) \qquad [N/m]$$

$$(10) \quad q(\zeta) = 0.15\, \rho_E\, g\, c_E\, t_{Ea}\, ((t_w - t_a)\, \zeta^3 - (3\, t_w - t_a)\, \zeta^2 + 2\, t_w\, \zeta) \qquad [N/m]$$

Related to [5] the density of the ice is assumed to be $\rho_E = 660\, kg/m^3$. A typical ice mass distribution for a medium sized rotor blade is shown in Figure 5. The total amount of ice per blade for different diameters and several recommendations and two measurements are pointed out in Figure 6. The total mass of ice of each blade can be calculated:

$$(11) \qquad m_E = 0.15\, \rho_E\, g\, c_E\, t_{Ea}\, R \int_0^1 d(\zeta)\, t_E(\zeta)\, d\zeta \qquad [kg]$$

$$(12) \qquad m_E = \frac{3}{80}\, \rho_E\, c_E\, t_{Ea}\, R\, (t_w + \frac{5}{3} t_a) \qquad [kg]$$

Putting in the values from the empirical equations (4) and (7) with $0.15 \rho_E g \approx 1000$ the ice line load can be expressed in kN/m:

$$(13) \qquad q(\zeta) = c_E(R)\, t_{Ea}(R)\, ((t_w - t_a)\, \zeta^3 - (3\, t_w - t_a)\, \zeta^2 + 2\, t_w\, \zeta) \qquad [kN/m]$$

As an approximation of ice amount during operation and as a basis for load case calculation only the equations (6), (9) and (10) are necessary where the values of equations (6) and (9) can be taken from the Figures 2 and 4.

2.3 Additional Aerodynamic Loads

Additional to the changed mass forces due to ice amount as centrifugal forces and edge wise bending moment (Figure 8) the aerodynamic properties of the blade will be changed as well. The profil coefficients c_l, c_d and c_m will depend on the type and magnitude of ice amount. A first wind tunnel investigation is described in [1] showing that the lift coefficient will not be changed significantly. However, the drag will increase dramatically as well as the aerodynamic torsional moment due to the displacement of the aerodynamic centre. Figure 7 shows lift versus drag coefficients of this wind tunnel test where the maximum ice amount at leading edge had a depth of 40 per cent of chord length. Other measurements in the field of aircraft technology are pointed out as well [8]. Further measurements are necessary for different amount and types of ice to improve the knowledge and have a data base for aerodynamic coefficient prediction.

3 Fatigue Load Prediction

Operation time of wind turbines up to 15 days under icing conditions have been observed at the *Ulrich Hütter* test site [5]. During that period the wind speed exceeded the cut in wind speed of the turbines. Due to the deteriorated aerodynamic properties these wind speeds led to only 50 per cent of normal power production. Those observations are of course strongly site dependent and need to be verified or improved by further investigations. When calculating the fatigue load cases it is proposed to assess the additional ice loads of 7 days continuous operation in icing conditions. During that time one rotor blade is assumed to be iced with an ice distribution according to equation (10) whereas the other blades are loaded with half of this distribution. The wind speed should be 10 m/s. This assumption takes the mass and aerodynamic unbalance into account and can be regarded as a worst case because most of the observations showed that the blades were iced in a similar way.

4 Further Questions

The proposed method to predict ice loads is only valid for rotor blades during operation. However, other questions concerning icing of wind turbines remain unanswered and need to be investigated:

- What meteorological conditions lead to what type of ice ?
- How do thrown away ice pieces affect the surrounding of a wind turbine ?
- Are the building standards applicable on parked wind turbines ?
- What is the maximum wind speed where icing can occur during operation or standstill of the wind turbine (extreme load case) ?
- How long operates a wind turbine with what type of icing (Fatigue load calculation) ?
- How differently will the rotor blades gather ice (unbalanced rotor) ?
- What aerodynamic coefficients can be used to calculate aerodynamic unbalance ? (Figure 7 shows values of differently iced profiles [1, 8])
- How does ice built-up affect the dynamic properties of the structure e.g. change of the natural frequencies ?

5 Conclusions

Most of the questions remain unanswered and up to date's measurements cover only a small number of wind turbines. To generalize the approximation for all sizes of wind turbines and for most of the appropriate sites there is a need for a sufficient data base concerning iced rotor blades. If different ice sections, ice densities and ice distributions are known the ice coefficient and the maximum ice depth approximation can be reviewed. Also the frequency of days where the turbines operate under icing conditions has to be known more exactly for a better fatigue load prediction. Finally, human safety requires to know the sizes and thrown distances of ice pieces or how ice built-ups during operation can be detected in time to stop the operation for safety reasons.

References

[1] H. Seifert, *Additional Loads Caused by Ice on Rotor Blades During Operation*, In Conference Publication - ECWEC 1990, Madrid, Spain, 1990

[2] W.J.Stam(ED.) *Regulations for the Type-Certification of Wind Turbines: Technical Criteria*, Technical Report ECN-91-001, ECN, Petten, Netherland, 1991

[3] Germanischer Lloyd *Vorläufige Richtinie für die Zertifizierung von Windkraftanlagen*, Technical Report, Hamburg, Germany, 1989

[4] M. Mayer, *Zum Vereisungsproblem von Einblatt-Windturbinen am Beispiel der FLAIR 8 auf dem Windtestfeld* Ulrich Hütter *in Schnittlingen*, Institut für Aerodynamik und Gasdynamik der Universität Stuttgart, Institutsbericht 87-8, Stuttgart, März 1987

[5] Cornelia Schloz, *Betrieb von Windkraftanlagen unter Vereisungsbedingungen* DLR, Institut für Bauweisen- und Konstruktionsforschung, Institutsbericht IB 435-90/60(1990), Stuttgart, Juni 1990

[6] H. Seifert, *Messungen an der Windkraftanlage AEROMAN 12/20 auf dem Testfeld Schnittlingen* DLR, Institut für Bauweisen- und Konstruktionsforschung, Institutsbericht IB 435-85/19(1985), Stuttgart, 1990

[7] N.N. *Unpublished Recommendations used for AEOLUS II ice loads*

[8] Fritz Dubs. *Aerodynamik der reinen Unterschallströmung* Birkhäuser Verlag, Basel, 1990

6 Figures

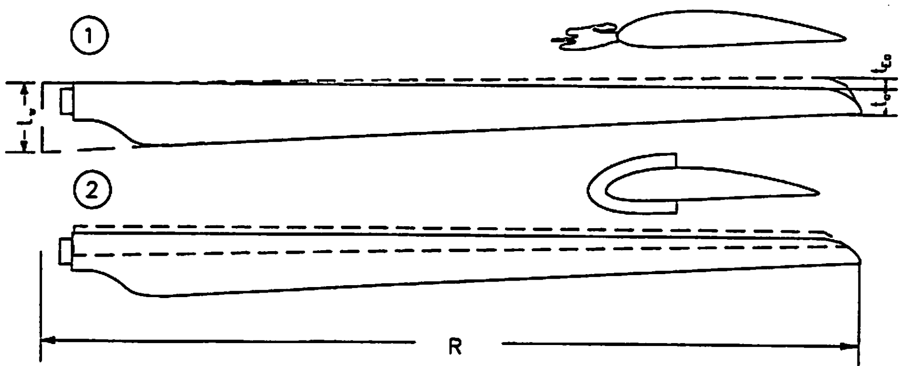


Figure 1: Ice distribution and typical ice section observed ① and recommended by Germanischer Lloyd ②

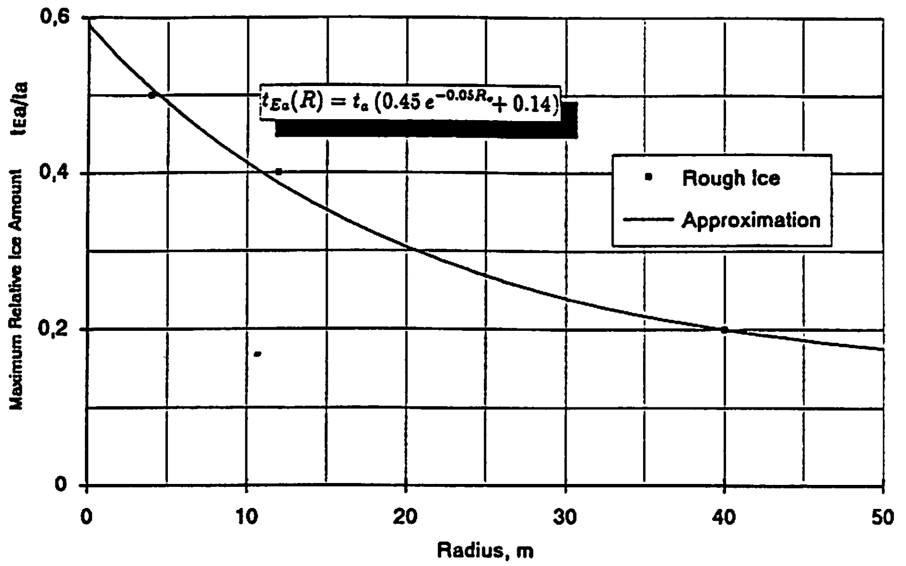


Figure 2: Approximated maximum ice amount

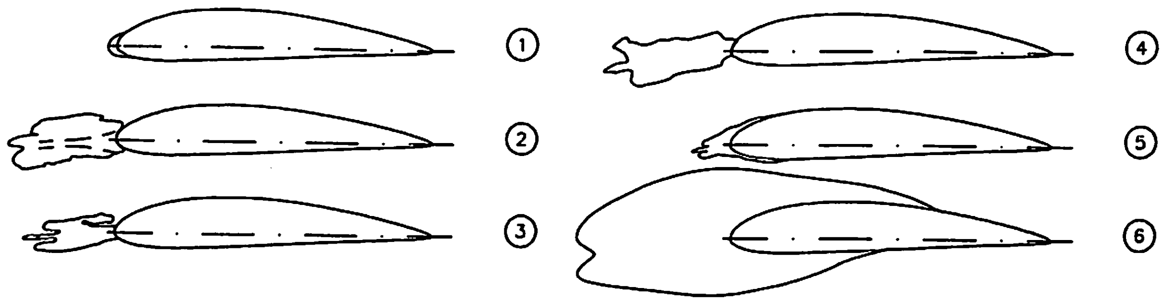


Figure 3: Measured sections of leading edge ice ① clear ice $R = 6m$, ② to ⑤ rough ice $R = 12.5m$, ⑥ rough ice $R = 4m$

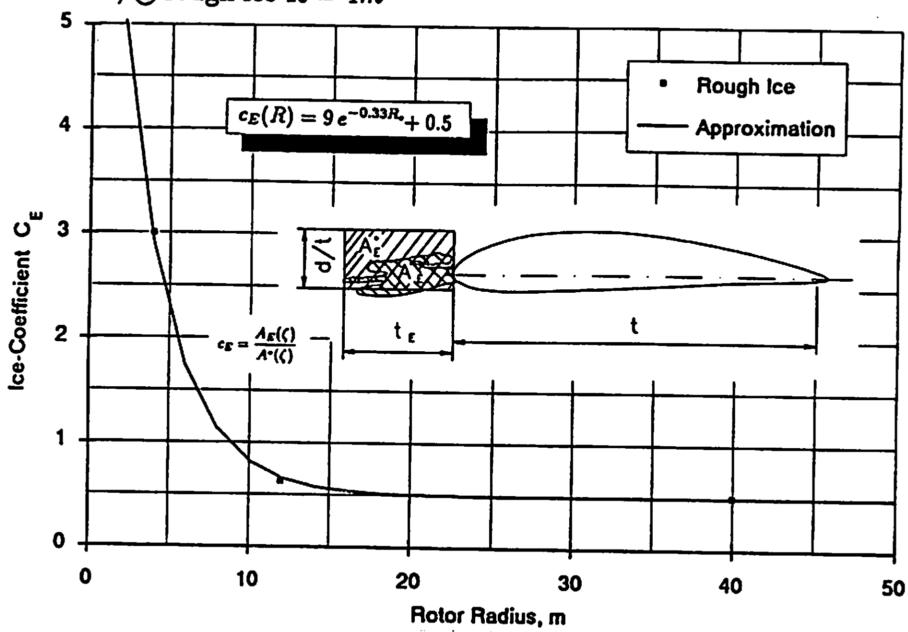


Figure 4: Definition of ice coefficient and approximation related to the radius

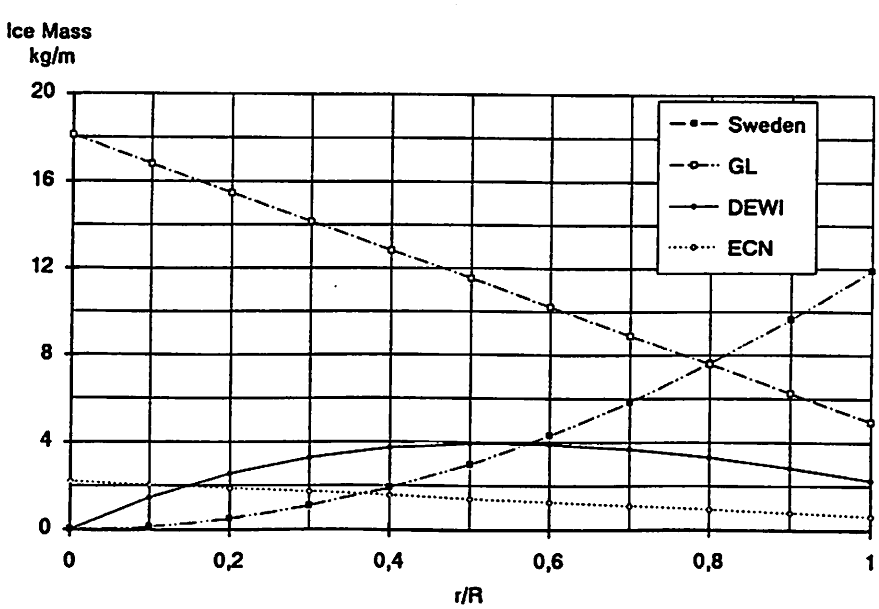


Figure 5: Example for ice mass distribution for different recommendations

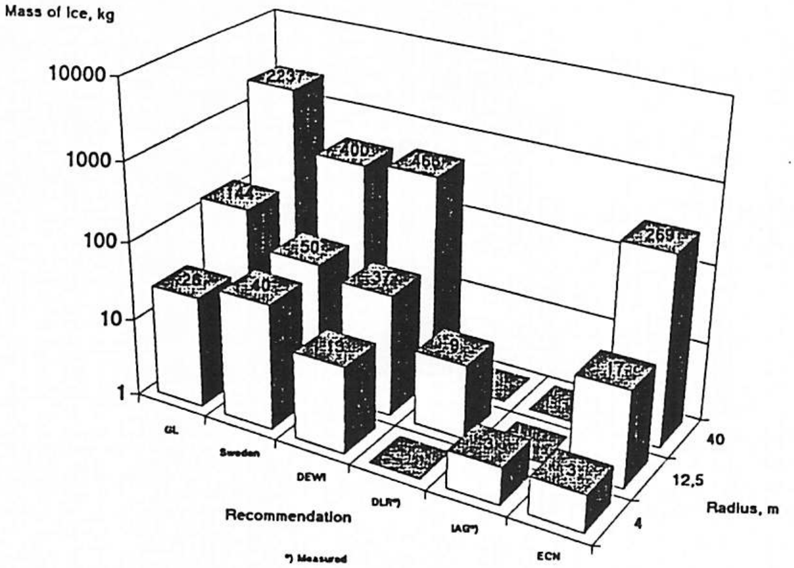


Figure 6: Ices masses of one rotor blade calculated by different recommendations or measured

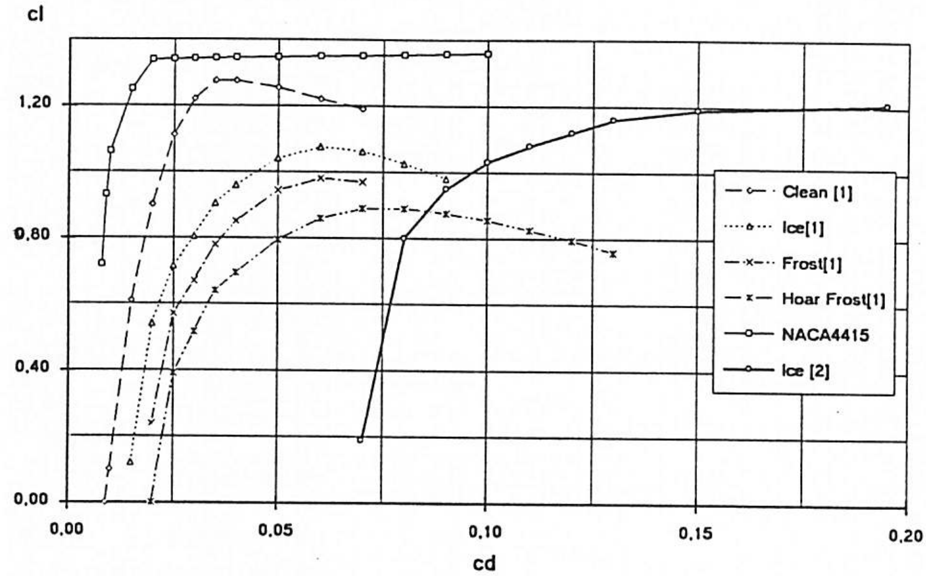


Figure 7: Aerodynamic coefficients of different iced profiles

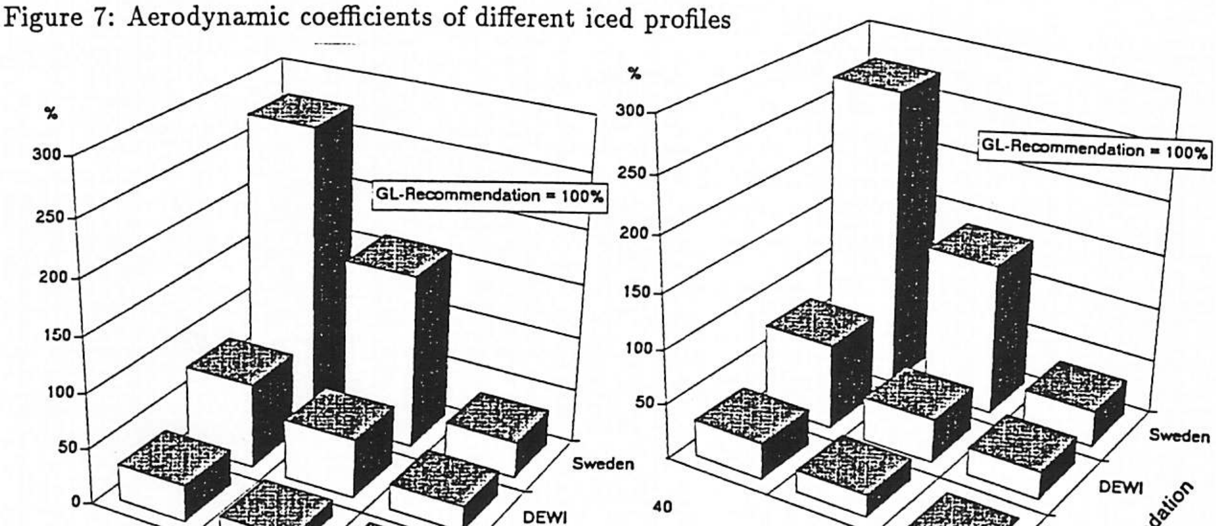


Figure 8: Additional centrifugal loads (left) and edge wise bending moments (right) due to icing; comparison to Germanischer Lloyd Recommendation

Check List for Icing of Wind Turbines

Location (site)................................

Date: ... ... 19.. Time: ...:...

Name..

- Operation mode of the wind turbine type: ....
  - ☐ Idling, standstill
  - ☐ Operating, average power output..............*kW*
- Were meteorological and operational data recorded ?
  - ☐ no
  - ☐ yes
    - ☐ description of measurements: ....
- Take photographs from:
  - all blades of the wind turbine,
  - anemometer und wind vane,
  - typical pieces of ice from the blades (cross section and top view) together with a scale,
  - total view of the site.
- Collect the ice pieces
  - Weigh the ice pieces
  - Determine the ice's density (put ice piece in a glass gauge filled with water and measure change of volume)
  - Register the mass of ice pieces and the location where found
- Available ice and meteorological data

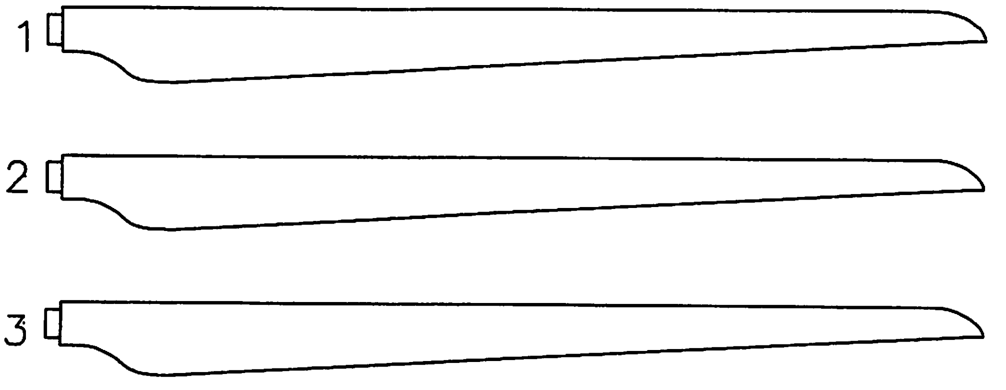
Temperature	....	^0C
Air pressure	....	hPa
Relative humidity of air	....	%
Average wind speed	....	m/s
Wind direction	....	^{0}
Density of ice	....	kg/m^3
Mass of ice pieces	from.....to......	g
Please sketch the locations where ice pieces were found overleaf	from.....to......	m

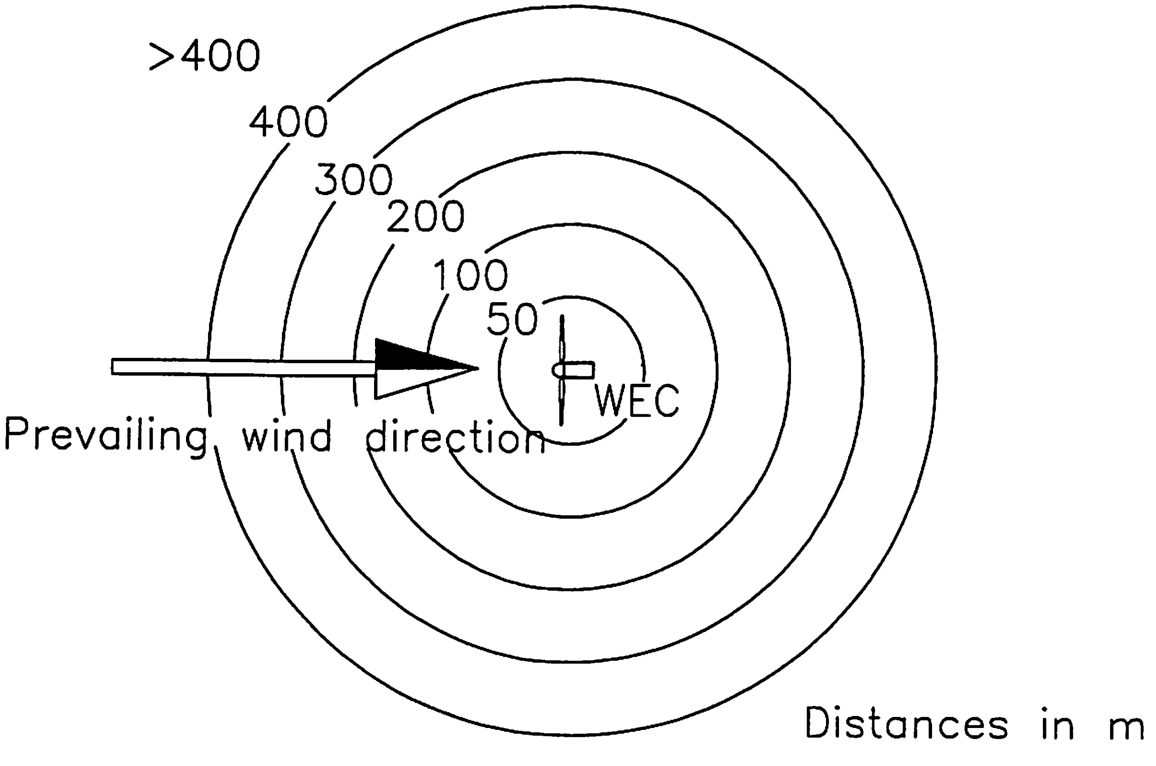
Please send completed form to the following address:

Mr. Henry Seifert
c/o Deutsches Windenergie-Institut
Ebertstr. 96
2940 Wilhelmshaven, Germany
Fax.: ++4421-4808-43 Tel.: ++4421-4808-0

Please turn over⟹

Sketch of blade's icing





Location of ice pieces

Minutes of 22nd IEA-Expert Meeting

Effects of Environment on Wind Turbine Safety and Performance

16 June 1992

Deutsches Windenergie-Institut, Germany

Seven Items of environmental effects on wind turbine safety and performance were discussed. Reported results of investigations and recommendations are listed as follows:

- **Earthquakes**: Two events were reported by Seifert/DEWI and Paulsen/Risø:
  - Earthquake of 13 April 1992 North of Aachen (Strength of 6 in the open Richter-Scale), data not yet evaluated.
  - Earthquake in California/USA, where some wind turbine towers were damaged, however, the machines themselves were not totally destroyed.

  Recommendation:

  - Evaluation of data of affected German wind turbines
  - More information about effects of earthquakes on wind turbines would be useful.

- **Icing** (Seifert/DEWI): Icing occurs during standstill and operation in several countries. Method to predict ice amount was presented. However, more experimental data from other sites with other wind turbines are necessary. A questionaire to gather statistical data was presented.
  Recommendation: All information about icing should be gathered and evaluated to improve the load assumptions due to icing conditions.

- **Hail** (Kensche/DLR): First results of hailstone impact on GL-EP[1] in laboratory do not show significant decrease of material properties. However, micro cracks in gel-coat can occur.
  Recommendation: Statistical data about hail occurences should be ordered from assurance companies to estimate the probability of hail.

- **Humidity** (Kensche/DLR): Decrease of static and fatigue properties by influence of moisture, penetrated in the material due to extreme surrounding conditions in GL-EP was observed.
  Recommendations:

  - Measurement of humidity and temperature inside the rotor blades under operational conditions in comparison to outdoor's data.
  - Influence of moisture on the material properties (e.g. generally GFRP, CFRP[2], wood-epoxy, coatings/paintings) must be investigated on the basis of those more realistic data.

[1] glass-epoxy
[2] GFRP - Glass Fibre Reinforced Plasic, CFRP - Carbon Fibre Reinforced Plastic

- **Lightning:** No presentation, but general discussion. Several damages on components were reported. Though lightning is an important item, too less information is available.
  Recommendation: Information by operators and manufacturers to the concerned research institutes is necessary to efficiently improve the lightning protection system of wind turbines.

- **Salt** (Paulsen/Risø): Tropical coastal climate is very aggressive on materials particulary on load attachment, coatings/paintings.
  Recommendation: Development of investigation method; investigate material and coatings.

- **Extreme wind** (Schmidt/DWD, Paulsen/Risø): Terrain effects on extreme wind speed and wind direction changes on wind turbine sites were reported. No specific recommendations.

Ramakers/ECN reported in general about meteorological effects on wind turbines in the Netherlands. In addition to the above mentioned topics, rain, snow, fog, air pollution, sand and UV-radiation were discussed. No specific recommendations.

In spite of the small number of participants, there was a fruitful discussion of all the items. It was shown that most of the topics are not well covered by the guidelines or recommendations for wind turbine design. Thus, research programmes should be established for improving the knowledge and therefore helping the manufacturers to build safer and more reliable wind turbines.

Wilhelmshaven, 18 June 1992

Ch. Kensche
DLR

H. Seifert
DEWI

LIST OF PARTICIPANTS

NAME	ADDRESS	PHONE AND FAX
Christoph Kensche	DLR Stuttgart Pfaffenwaldring 38-40 D-7000 Stuttgart	0711/68621 phone
Uwe Schmidt Paulsen	Test Station for Windturbine Postboks 49 DK-4000 Roskilde	+0045/42371212 phone 2965 fax
B. Maribo Pedersen	Technical University of Denmark Dep. of Fluid Mechanics DK-2800 Lyngby	+45/45932711 phone +45/42882421 fax
Servaas Ramakers	Energieonderzoek Centrum Nederland (ECN) Postbus 1 NL-1755 ZG Petten	+312246/4949 phone 4480 fax
Heiner Schmidt	Deutscher Wetterdienst Postfach 30 11 90 D-2000 Hamburg 36	040/31908822 phone 8803 fax
Henry Seifert	Deutsches Windenergie- institut GmbH Ebertstraße 96 D-2940 Wilhelmshaven	04421/480812 phone 43 fax

IEA-Implement Agreement R+D WECS - Annex XI
Topical Expert Meetings

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data Acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, Sept. 26-27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21-22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25-26, 1980
6. Reliabiltiy and Maintenance Problems of LS WECS, Aalborg, April 29-30, 1981
7. Costings for Wind Turbines, Copenhagen November 18-19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing, Stockholm, May 26-27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7-8, 1983
10. Utility and Operational Experiences and Issues from Mayor Wind Installations, Palo Alto, October 12-14, 1983
11. General Environmental Aspects, Munich, May 7-9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29-30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30-31, 1985
14. Modelling of Atomospheric Turbulence for Use in WECS Rotor Loading Calculation, Stockholm, December 4-5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17-18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Herndon (Virginia), April 11-12, 1989
18. Noise Generationg Mechanisms for Wind Turbines, Petten, November 27-28, 1989
19. Wind Turbine Control Systems, Strategy and Problems, London, May 3-4, 1990
20. Wind characteristics of Relevance for Wind Turbine Design, Stockholm, March 7-8, 1991
21. Elektrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7-8, 1991

22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshaven, June 16, 1992
23. Fatigue of Wind Turbines, Golden (Colorado), October 15 - 16, 1992
24. Wind Conditions for Wind Turbine Design, Risϕ, April 19 - 30, 1993
25. Increased Loads in Wind Power Stations, "Wind Farms", Göteborg, May 3 - 4, 1993

Note: Nr. 23-25 to be published