From Climate Data to Accelerated Test Conditions

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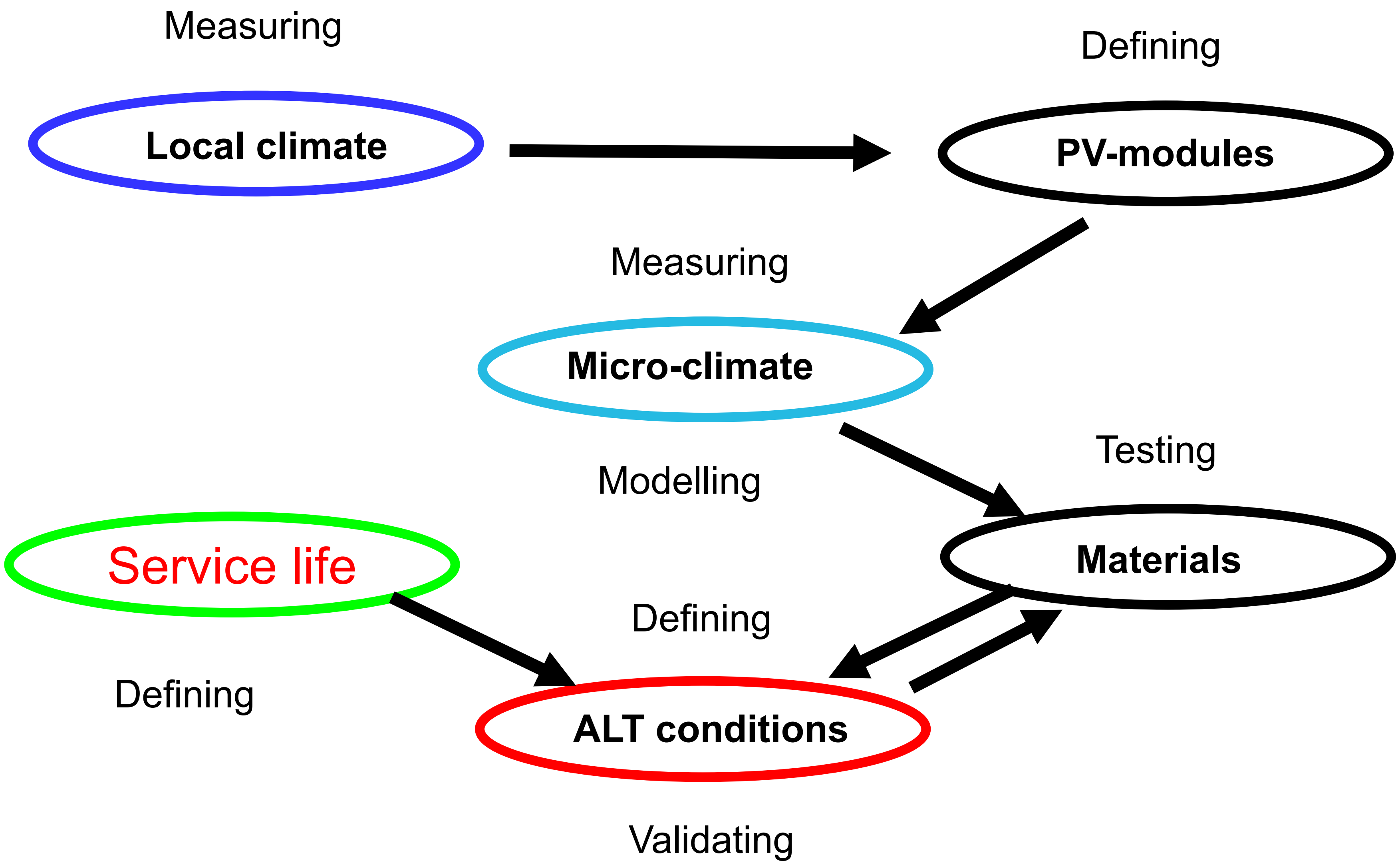
General methodology

Modeling the ALT conditions based on realistic loads



Measuring

Local climate

Defining

PV-modules

Measuring

Micro-climate

Testing

Modelling

Materials

Service life

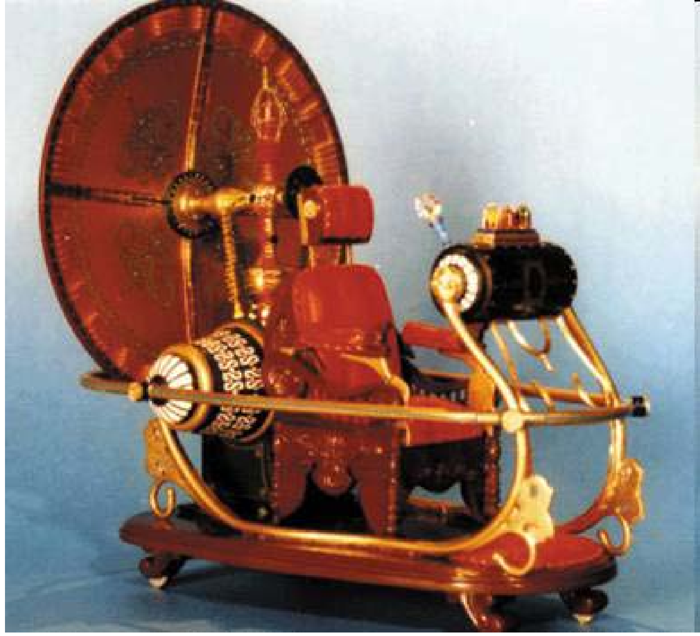
Defining

Defining

ALT conditions

Validating

Simple deterministic model for aging processes: Time-transformation functions



Changes of property P after the testing time Δt_i

$$\Delta P = \Sigma^{m}_{j=1} \{$$

Temperature	$+ A\ \Delta t_i \exp[-E_A / RT_i]$
Moisture	$+ B\ \Delta t_i\ f(rh)_i \exp[-E_B / RT_i]$
UV-Radiation	$+ C\ \Delta t_i\ I^n_i \exp[-E_C / RT_i]$
T cycles	$+ D\ \Delta t_i\ f(\Delta T)_i \exp[-E_D / RT_i]$
Potential I D	$+ E\ \Delta t_i\ f(P)_i\ f_p(rh)_i \exp[-E_E / RT_i]$
Salt	$+ F\ \Delta t_i\ f(S)_i\ f_p(rh)_i \exp[-E_F / RT_i]$
………	$+ \ldots\ldots\ X\ \Delta t_i\ I^n_i\ f(X)_i \exp[-E_X / RT_i] \ldots\ldots \}$

Sample dependent degradation process parameters

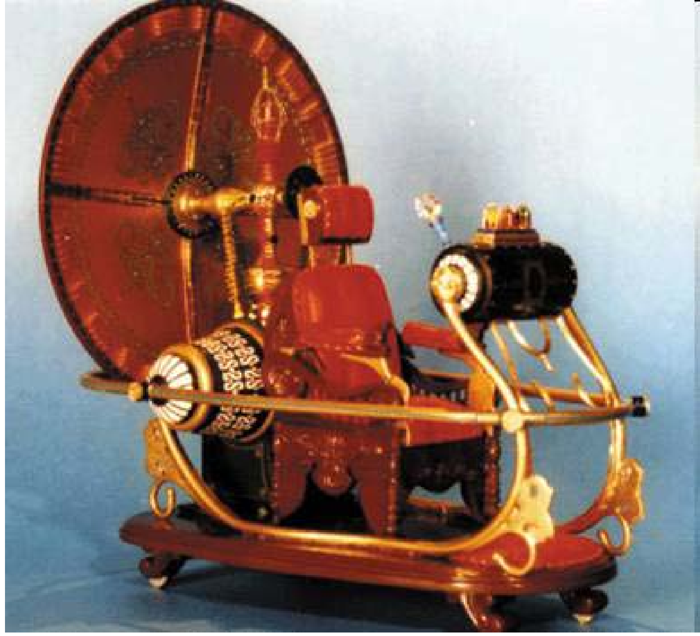
Module temperature T

Micro-climatic stress factor

Time-interval Δt_i

Other degradation factors or synergistic effects

Simple deterministic model for aging processes: Time-transformation functions



Changes of property P after the testing time Δt_i

Degradation factor	$\Delta P = \Sigma^m_{j=1} \{$
Temperature	$+ A\ \Delta t_i \exp[-E_A / RT_i]$
Moisture	$+ B\ \Delta t_i\ \mathbf{f(rh)}_i \exp[-E_B / RT_i]$
UV-Radiation	$+ C\ \Delta t_i\ I^n_i \exp[-E_C / RT_i]$
T cycles	$+ D\ \Delta t_i\ f(\Delta T)_i \exp[-E_D / RT_i]$
Potential I D	$+ E\ \Delta t_i\ f(P)_i\ \mathbf{f_p(rh)}_i \exp[-E_E / RT_i]$
Salt	$+ F\ \Delta t_i\ f(S)_i\ \mathbf{f_p\ (rh)}_i \exp[-E_F / RT_i]$
………	$+\ldots\ldots X\ \Delta t_i\ I^n_i\ f(X)_i \exp[-E_X / RT_i]\ \ldots\ldots\}$

Sample dependent degradation process parameters

Starting point: Outdoor exposure testing

Sites with extreme stresses

City or reference:

Freiburg Germany

Alpes

Zugspitze

Germany

Desert

Sede Boqer

Israel

Tropical

Serpang

Indonesia

Maritimes

Pozo Izquierdo

Gran Canaria

Monitoring degradation factors for modelling degradation

Measurement of module performance over time for validation of ALT

End point: Outdoor exposure anywhere

Sites with climatic conditions known for one year at least

Examples (irradiation, wind, temperature, humidity data from 2007):

	Average temperature	Irradiation	UV dose
Goodwin Creek (warm and humid)	16,6 °C	1631 kWh/m²a	83,20 kWh/m² a
Desert Rock (Hot and dry)	19,0 °C	2095 kWh/m²a	106,87 kWh/m² a

Temperature

Difficulties:

1. Micro – climate (module temperature depends on module and climate)

2. Transient behaviour (changing temperature continuously, but delayed)

3. Accelerator for all degradation processes

Pay attention to thresholds changing degradation processes:

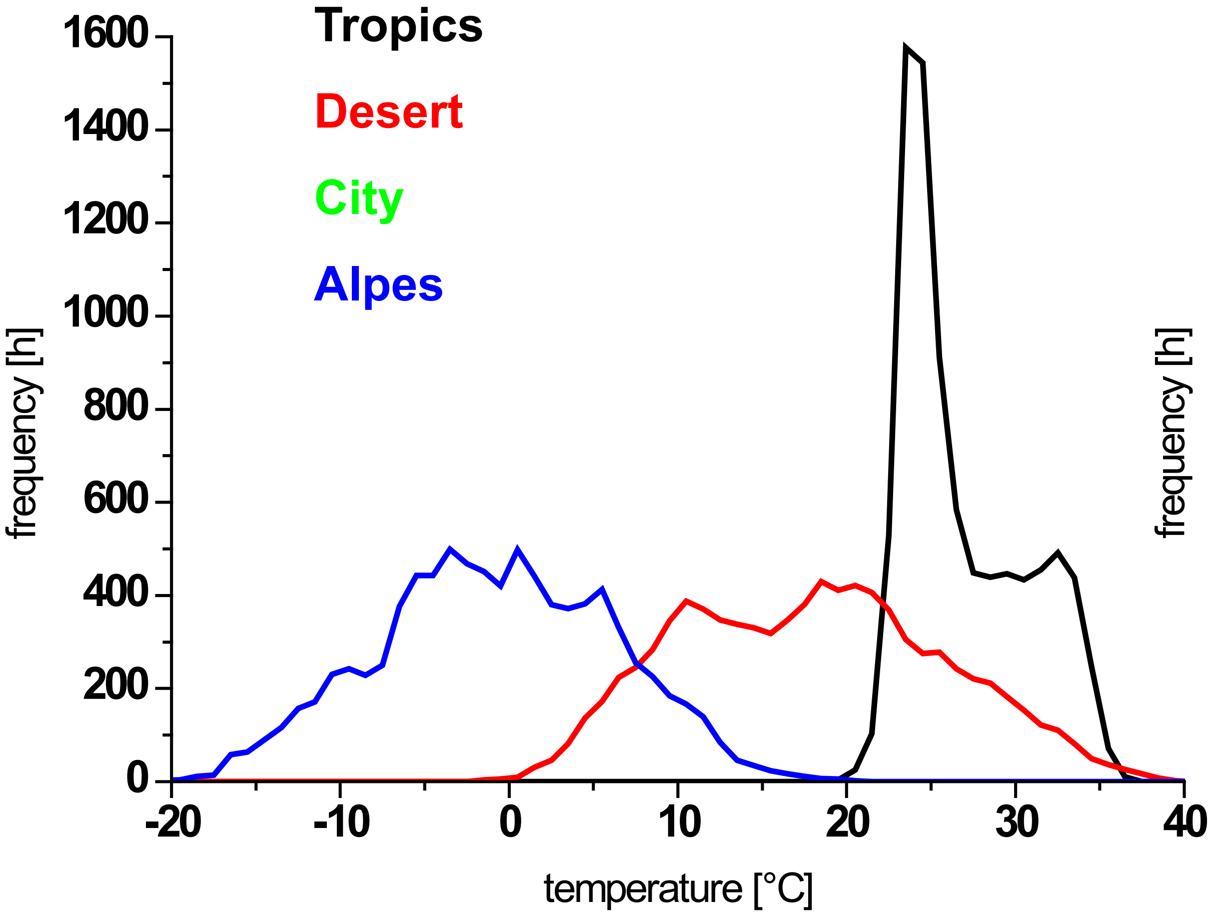
„ You never got a chicken by boiling an egg“

Outdoor testing

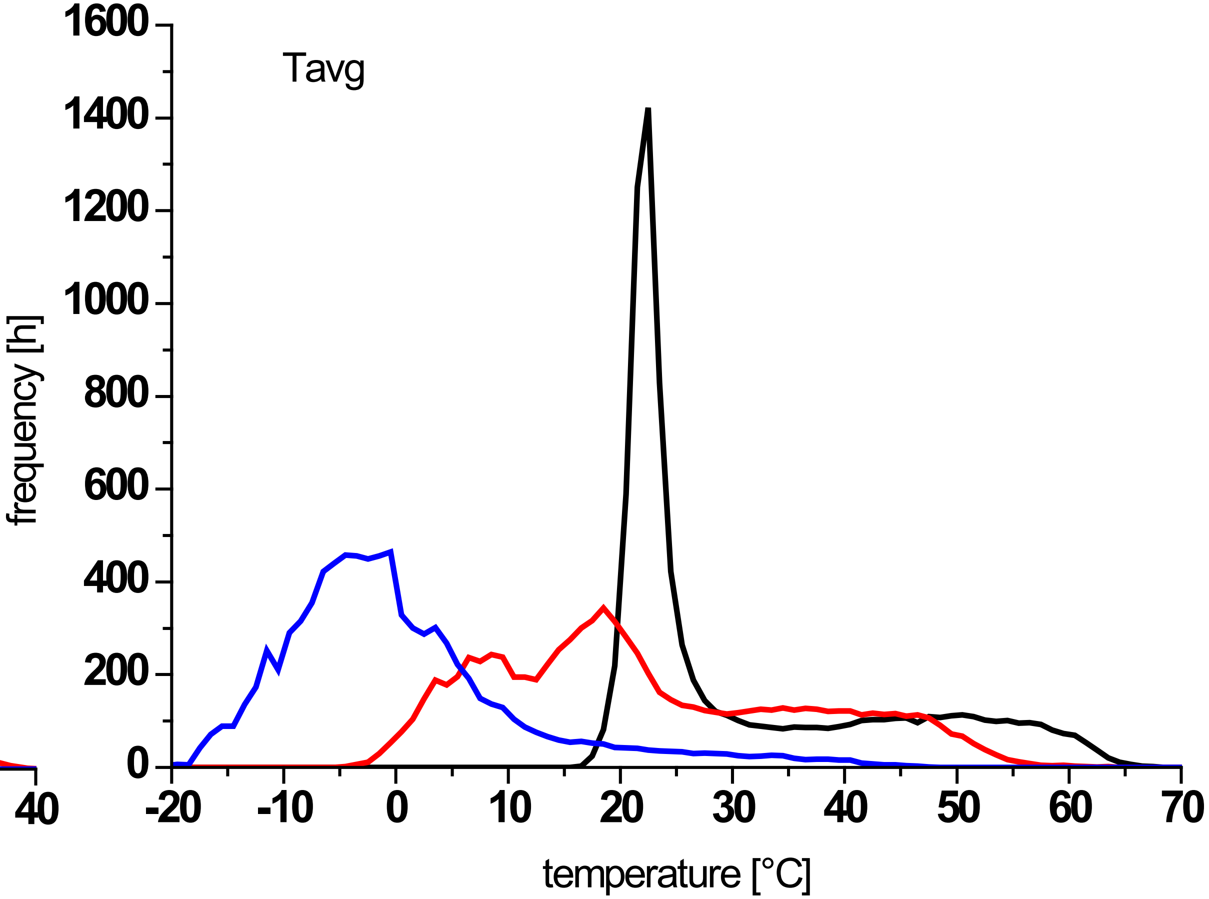
Temperature monitoring

Macro – climate => Micro – climate

Ambient temperature

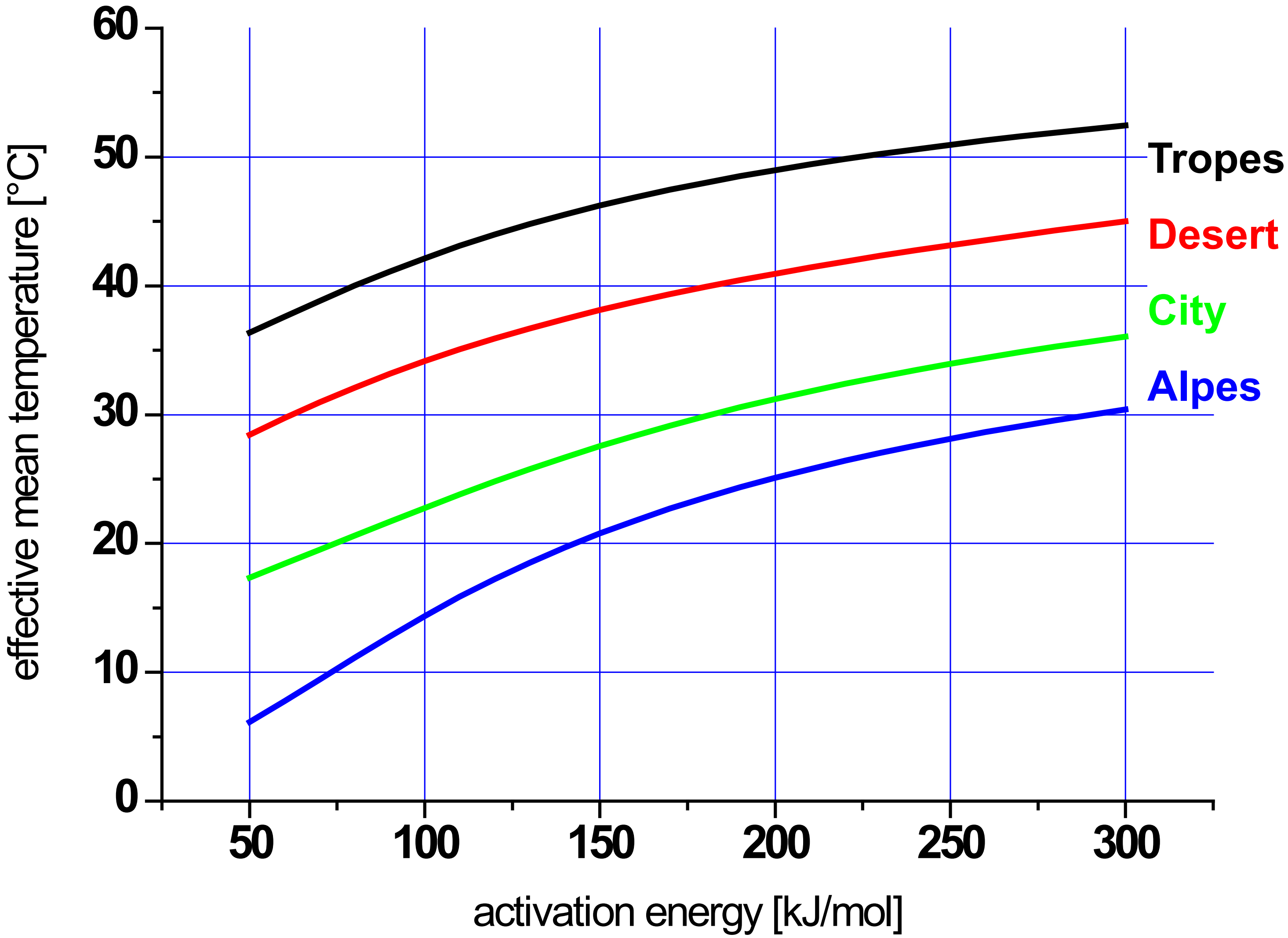


Average module temperature (c-Si)



Temperature evaluation for c-Si

$$\exp[-E_p\,\boxed{/RT_{eff}}] = 1/(t_{max}-t_{min})\,\Sigma^{tmax}_{tmin}\,\exp[-E_p\,/RT(t)]\Delta t$$



Effective Mean Temperature,

Constant test temperature that

Corresponds to the natural load in the same period

Depends on the activation energy of the degradation process

Life testing for degradation factor temperature

If their would be a degradation process without any external reaction partners

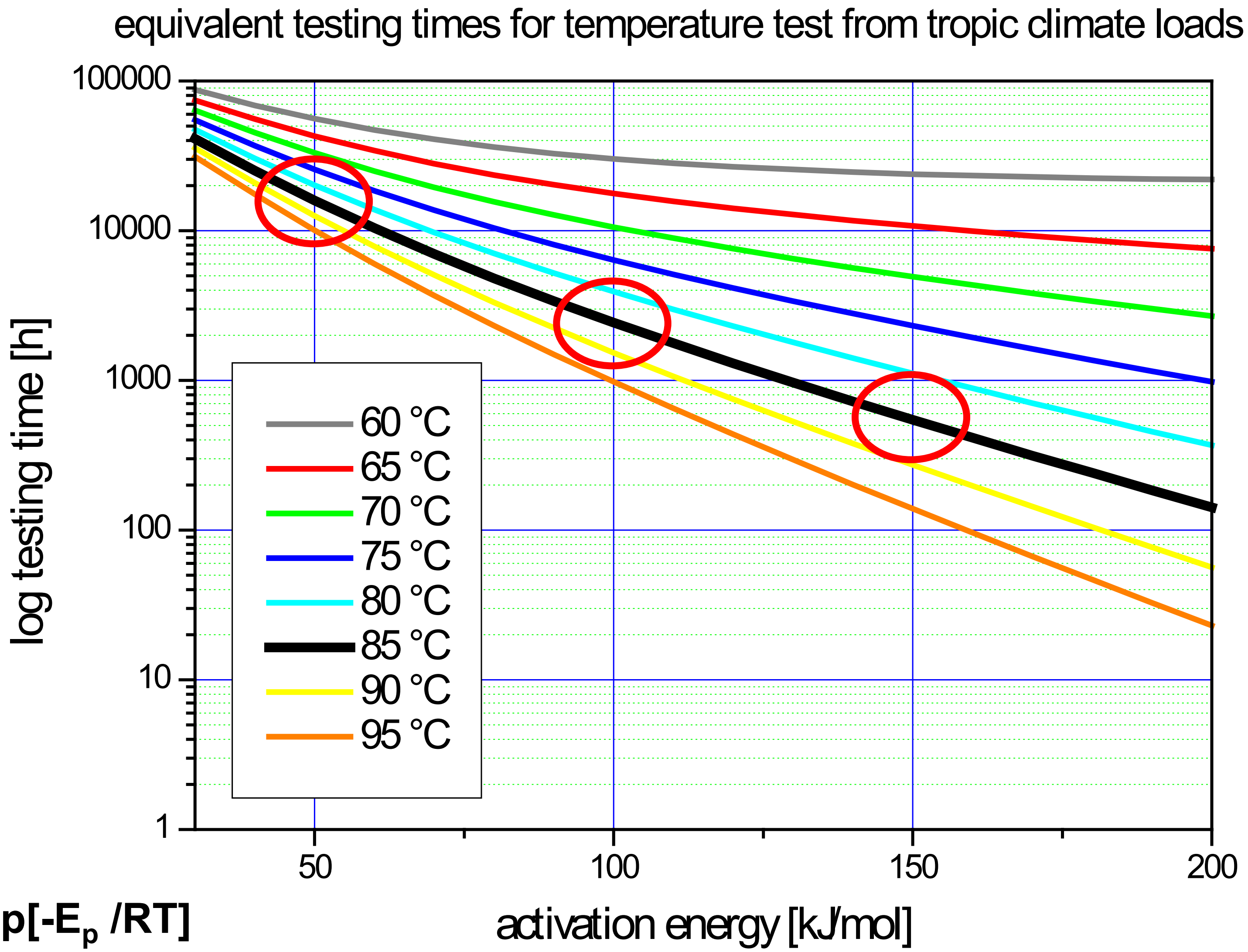
Might be tested simultaneously with the damp-heat test:

Some 100 to 10000 h

Equivalent Temperature Testing Times

for c-Si

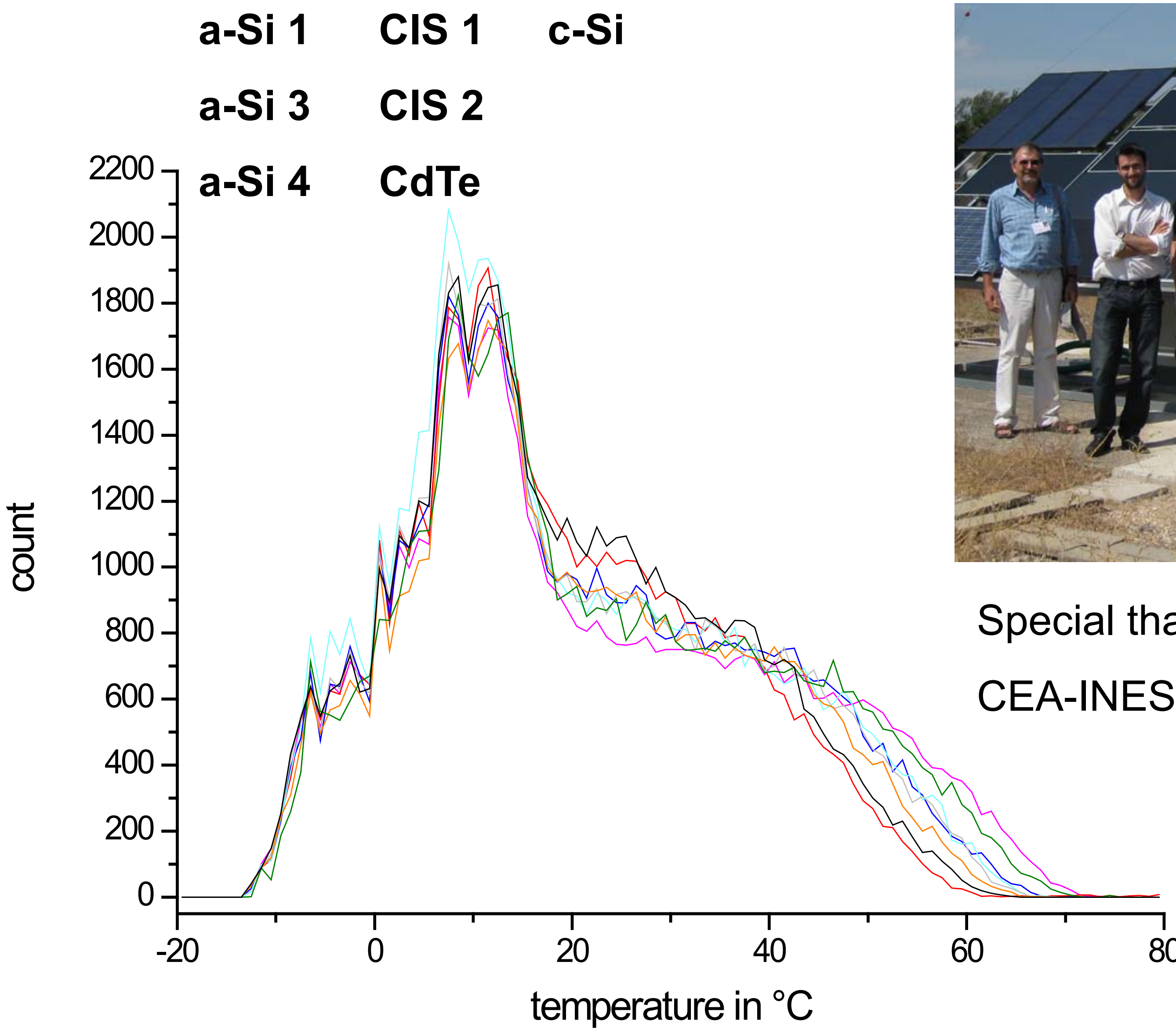
for 25 a in tropical climates



$$t_{test} = 25*8760 \exp[-E_p /RT_{eff}] / \exp[-E_p /RT]$$

Histogram of measured module temperatures in Cadarache, F

What about Thin Film Modules?



Special thanks to Antoine Guerin de Montgareuil,

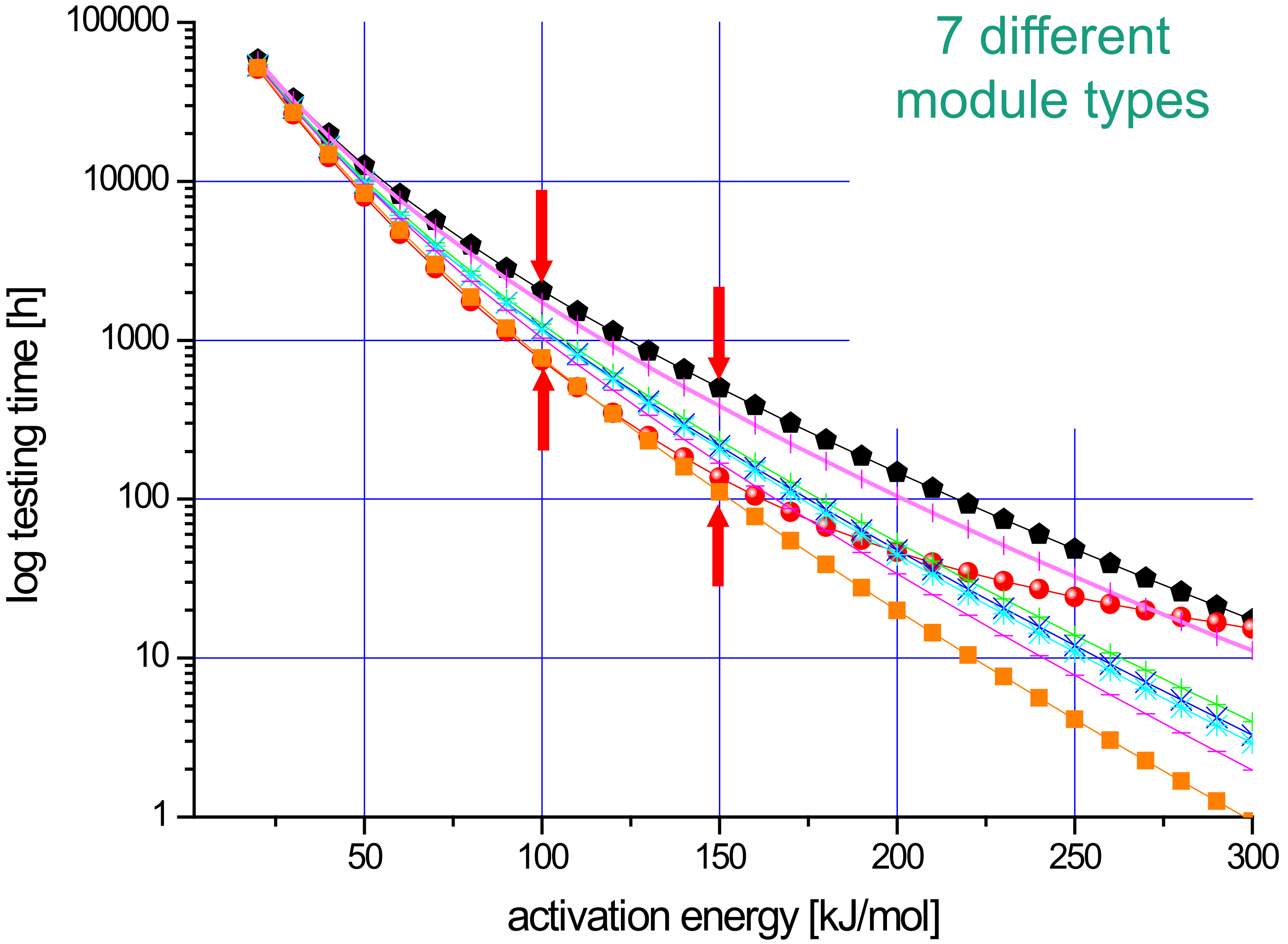
CEA-INES, Cadarache, France

Module temperature for one year

Corresponding temperature testing times at 85°C for 25 a exposure in Cadarache, France

based on monitored module temperatures

testing times @ 85°C for different thin film modules exposed in Cadarache



7 different module types

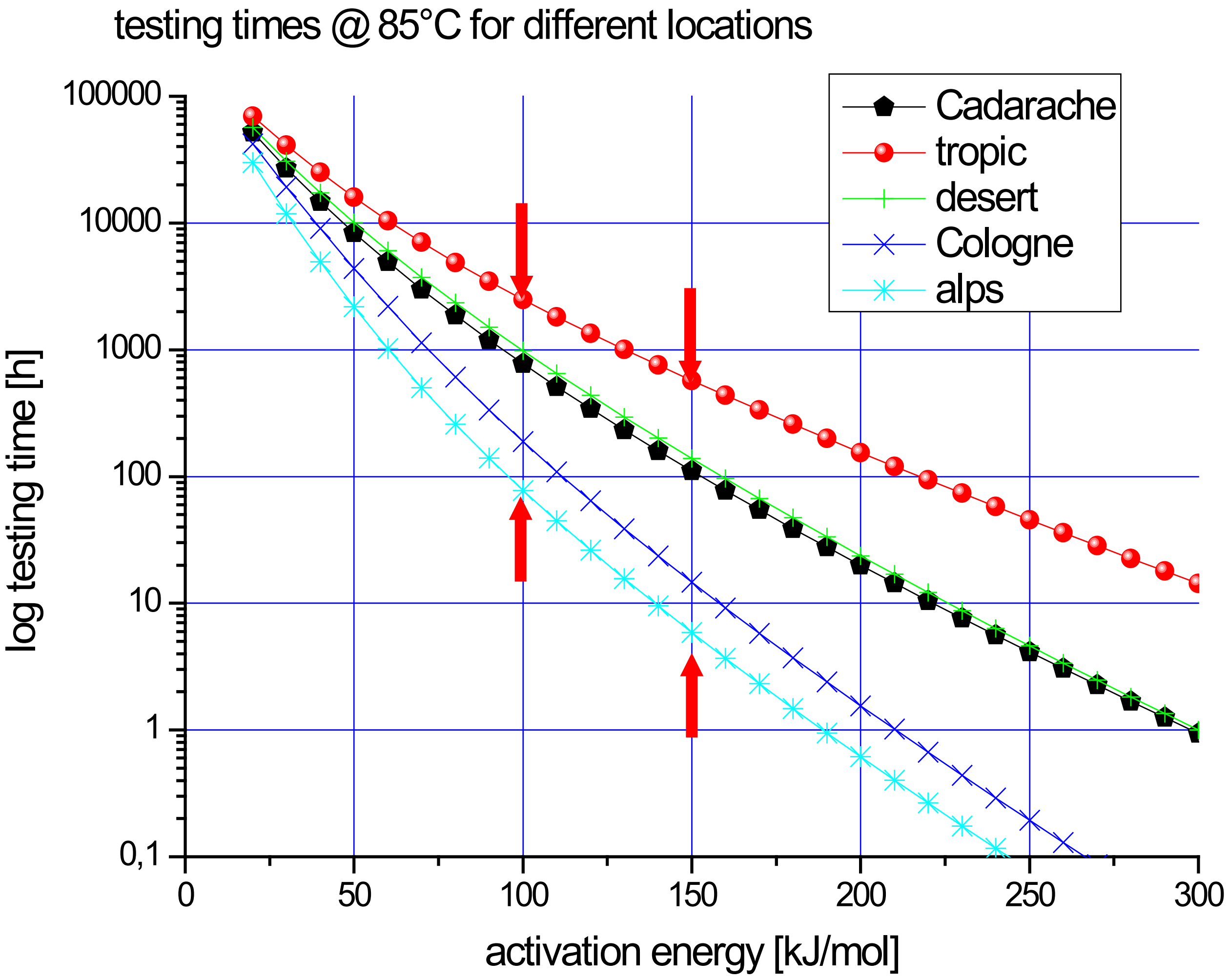
Different cell-types:

Factor 2 – 4 in testing time (depending on the degradation processes)

In the range of damp/heat

Corresponding temperature testing times at 85°C for 25 a exposure of c Si modules in different climates

based on monitored module temperatures



Worst case tropics

Different climate-types:

Factor 20 – 100 in testing time (depending on the degradation processes)

Physical modeling of module temperature for each of the different module types using David Faiman‘s approach (could be King, Fuentes……as well)

Macro – climate => Micro – climate

Irradiation, wind, ambient temperature => T_{mod}

$$T_{\mathrm{mod}} = T_{amb} + \frac{H}{U_0 + U_1 \cdot \mathrm{v}}$$

	U1	U0
a-Si 1	10,7	25,7
a-Si 3	5,8	25,8
a-Si 4	4,3	26,1
CIS 1	3,1	23,0
CIS 2	4,1	25,0
CdTe	5,4	23,4
c-Si	6,2	30,0

T_{mod} module temperature

T_{amb} ambient temperature

v wind velocity

H solar radiation

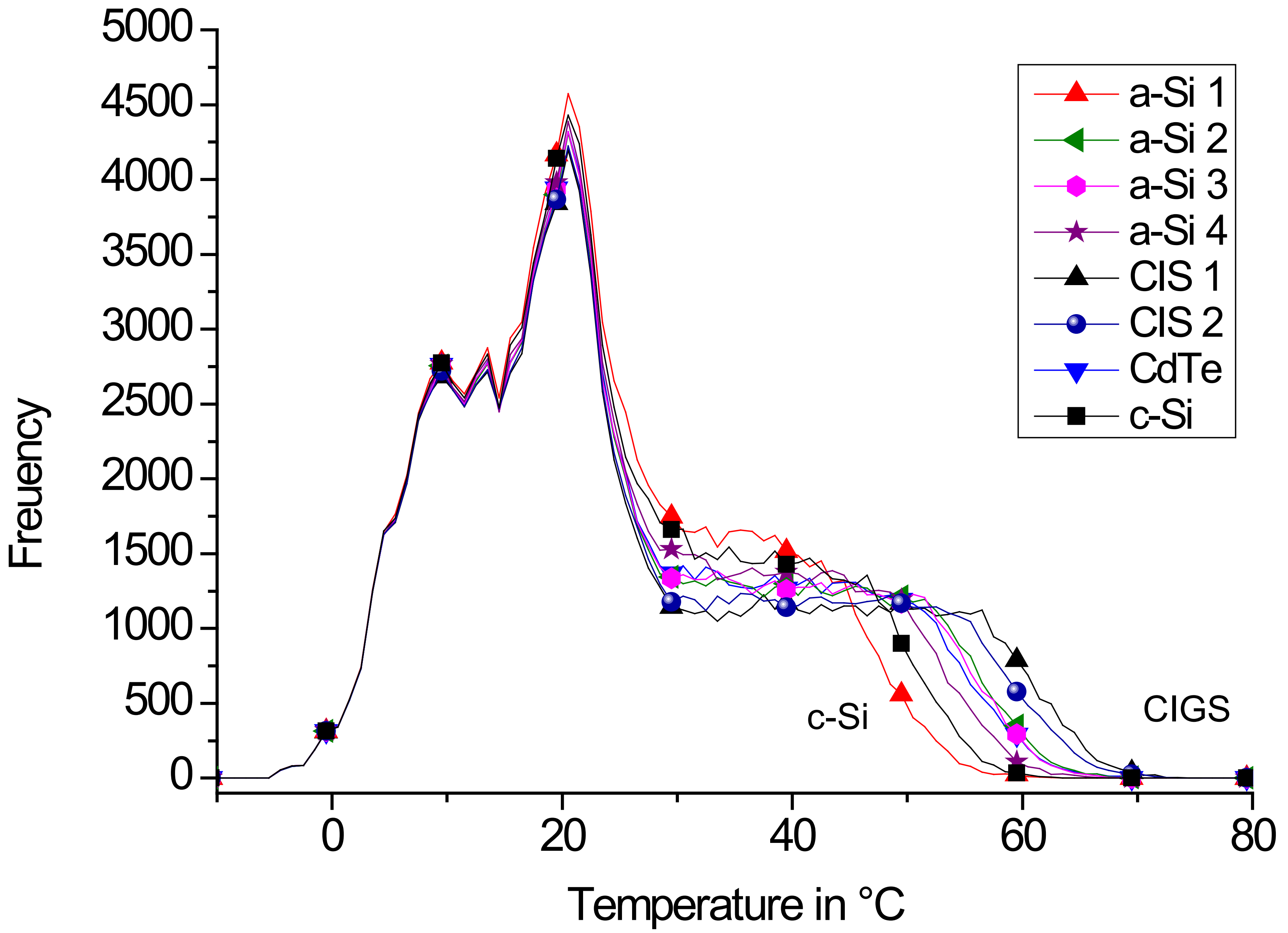
U_0 , U_1 = module dependent parameters

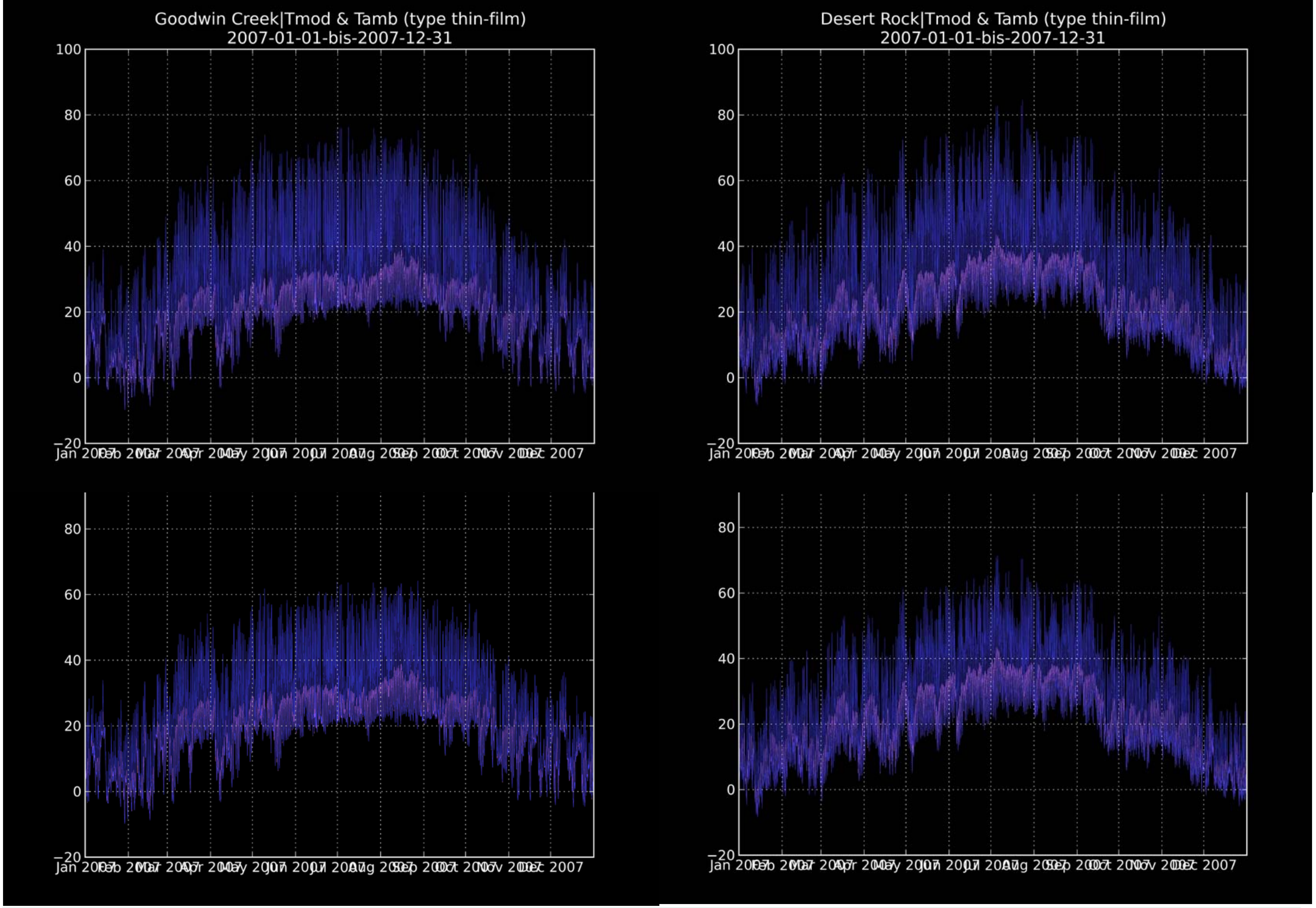
Neglected: IR-radiation exchange and natural convection

The parameters U are module-specific but location independent

M.Koehl et.al.: Modelling of the nominal operating cell temperature based on outdoor weathering, Sol. Energy Mat. Sol. Cells (2011)

Histogram of simulated module temperatures in the Negev




Goodwin Creek|Tmod & Tamb (type thin-film)
2007-01-01-bis-2007-12-31
Desert Rock|Tmod & Tamb (type thin-film)
2007-01-01-bis-2007-12-31
100
80
60
40
20
0
−20
Jan 2007
Feb 2007
Mar 2007
Apr 2007
May 2007
Jun 2007
Jul 2007
Aug 2007
Sep 2007
Oct 2007
Nov 2007
Dec 2007

Temperature load

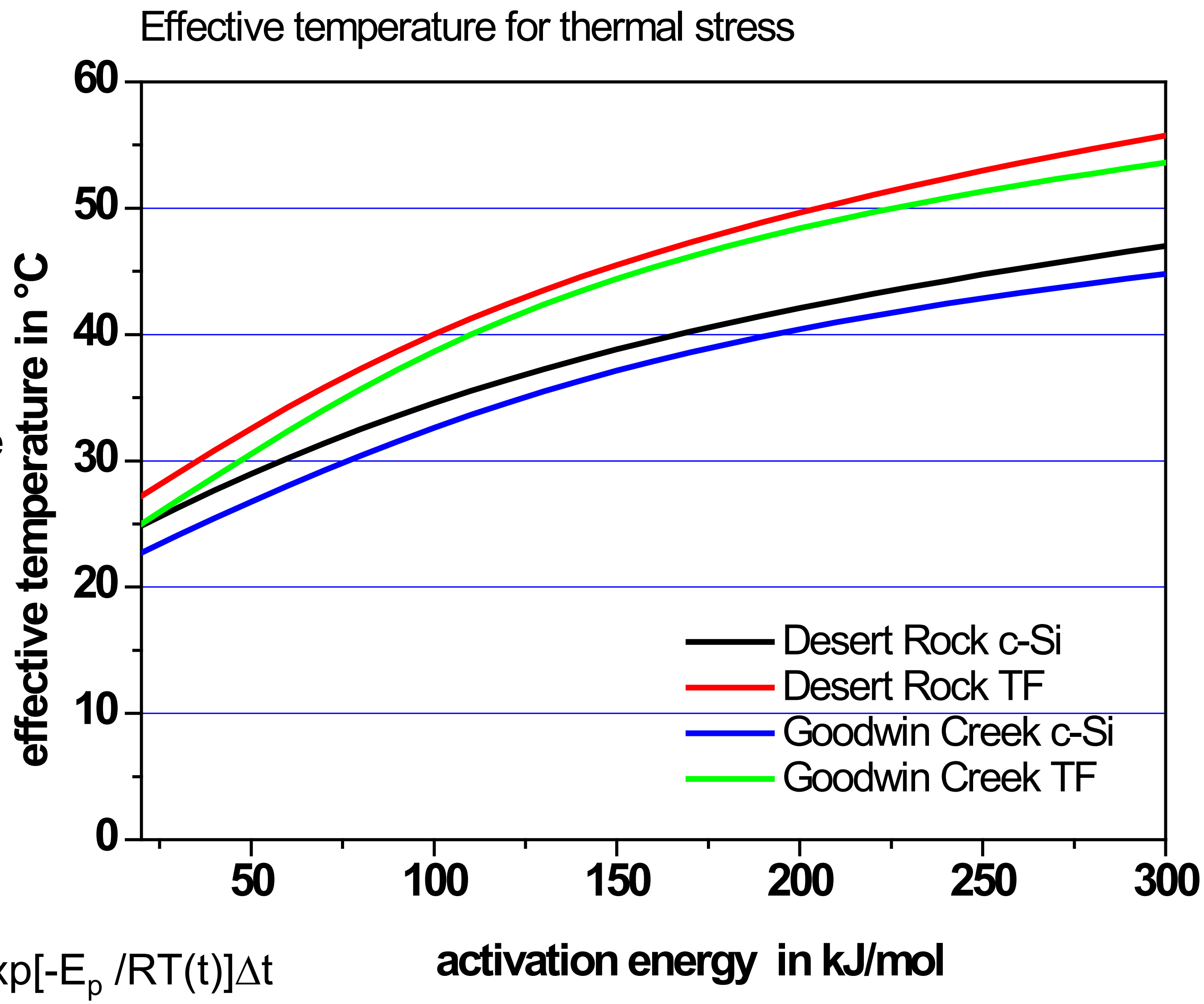
Accelerator for all degradation processes

Effective temperature:

The constant temperature needed for obtaining the same degradation as for outdoor exposure

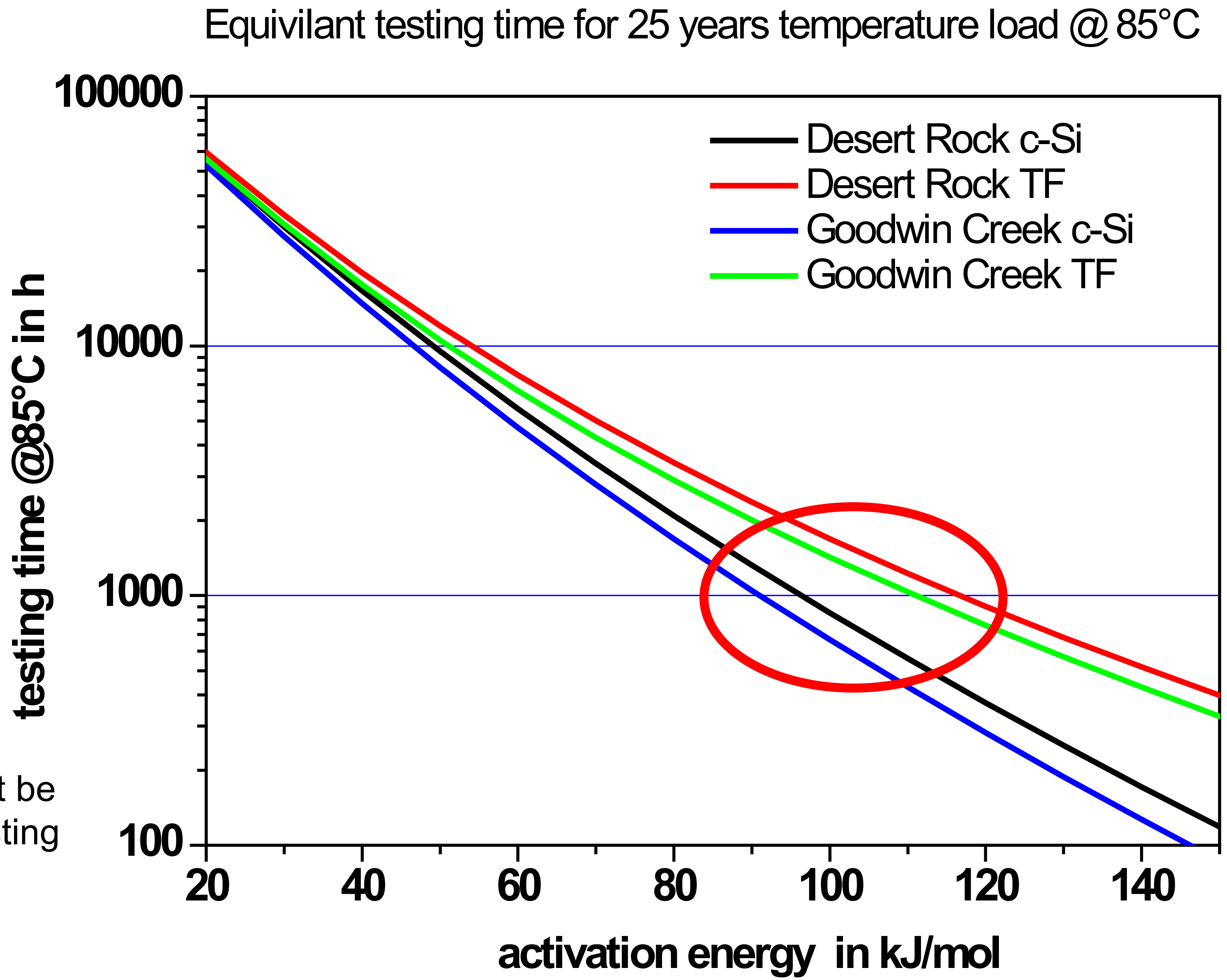
Characteristic for location and module type

Type is more relevant here



$$\exp[-E_p / RT_{eff}] = 1/(t_{max}-t_{min}) \Sigma^{tmax}_{tmin} \exp[-E_p / RT(t)]\Delta t$$

Temperature testing



Temperature testing might be included in damp-heat testing without distinguishing the degradation processes

UV-radiation

Problems:

1. Measurement of UV-radiation
2. Reciprocity (Dose is I*t, or t = Dose/I)
3. Spectral sensitivity of the samples is not known
4. Differences of the UV-sources of the test facilities *
5. Temperature impact

**IEC TC82 WG2 – Round Robin for measurements of UV testing devices*

Outdoor testing

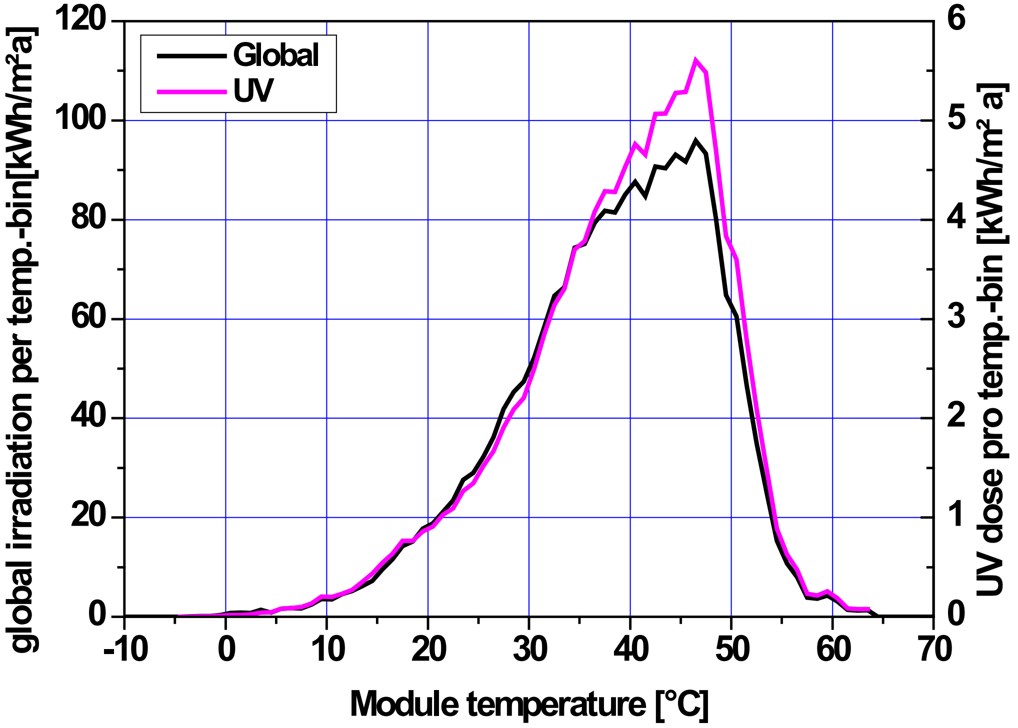
Radiation monitoring

Accumulated dose of UV- and solar radiation for one year in the desert:

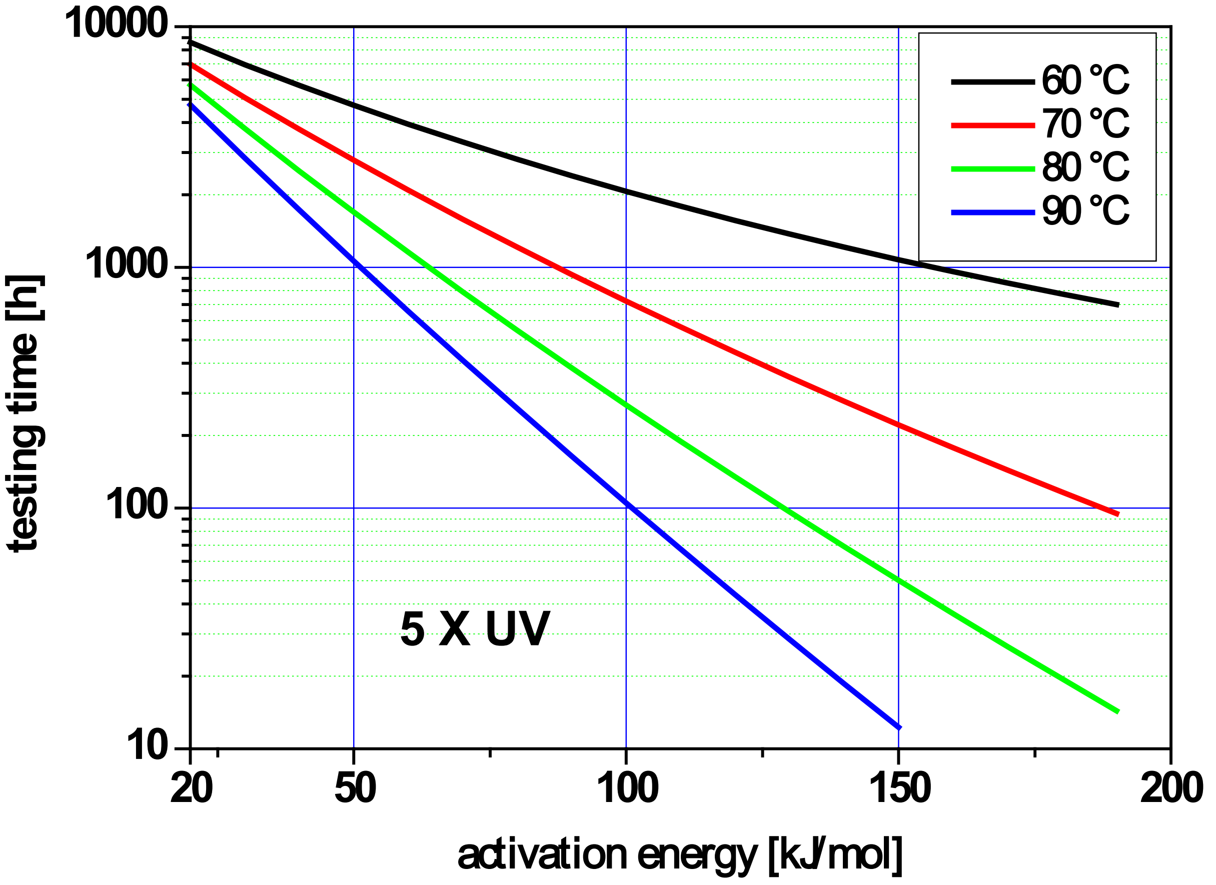
120 kWh/m² (about 8 x IEC)

Reciprocity: p = 1

$$t_{test} = (I_i / I_{test})^p \, \Delta t_i \cdot \exp[-(E_a / R) \cdot (1/T_{test} - 1/T_i)]$$



equivalent testing times for five suns UV test for desert climate loads



UV = 5.X % of solar radiation

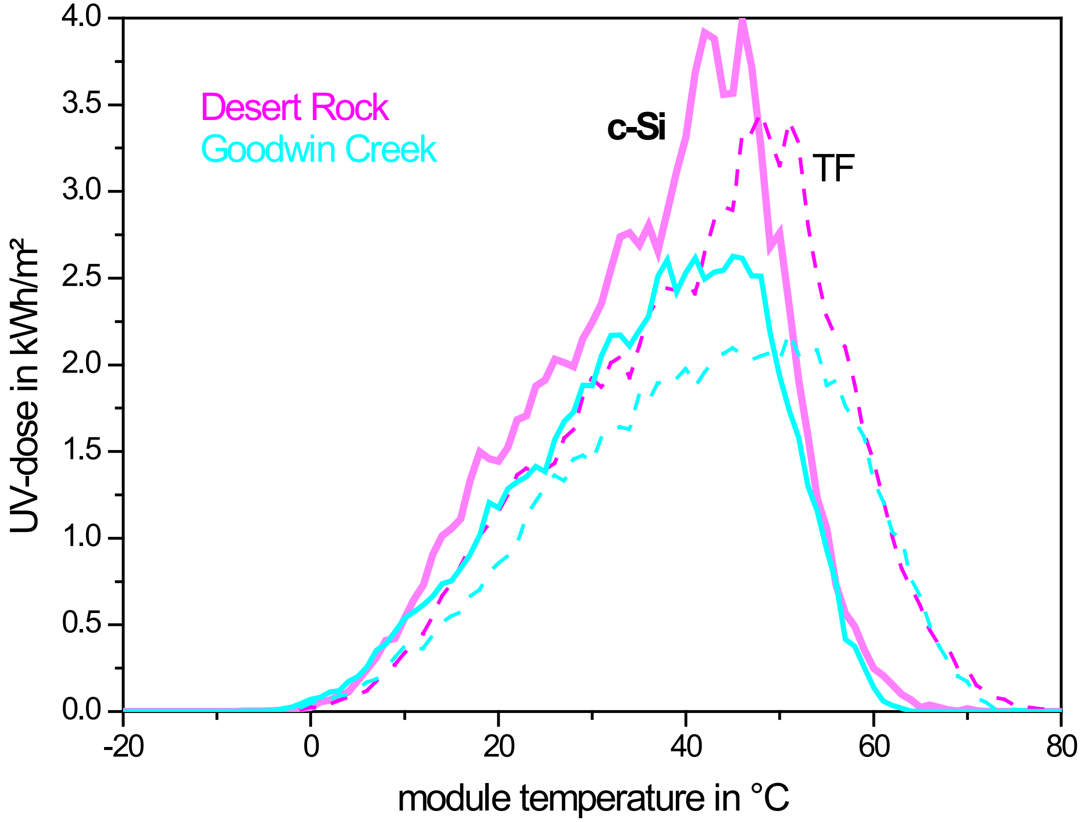
UV - radiation modelling

Desert Rock: 106 kWh/a m²

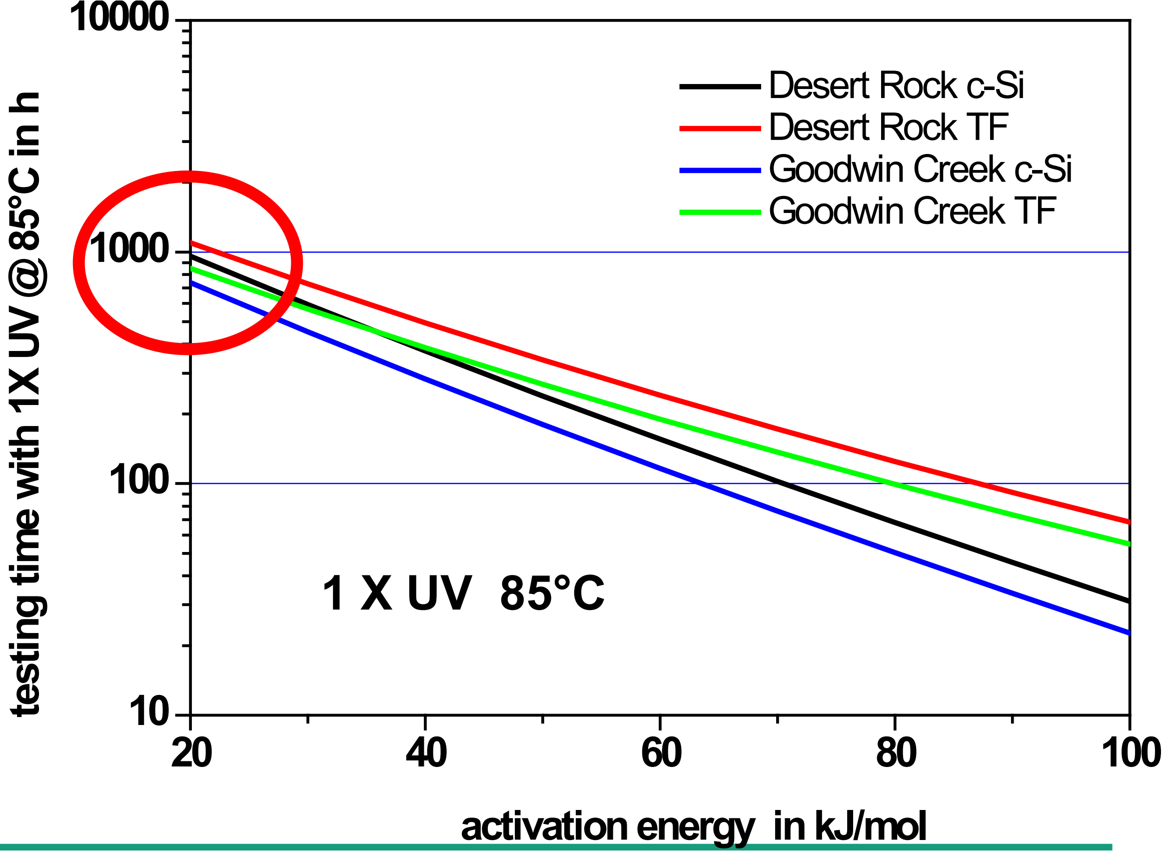
Goodwin Creek: 83 kWh/a m²

4-5 suns

Elevated temperature



Equivalent constant load for 1 sun UV @ 85°C for 1 year



Humidity

Problems:

1. Assessing micro – climate

2. Transient behaviour (changing partial pressure gradients)

3. Slow diffusion in encapsulants or edge sealants (hard to accelerate)

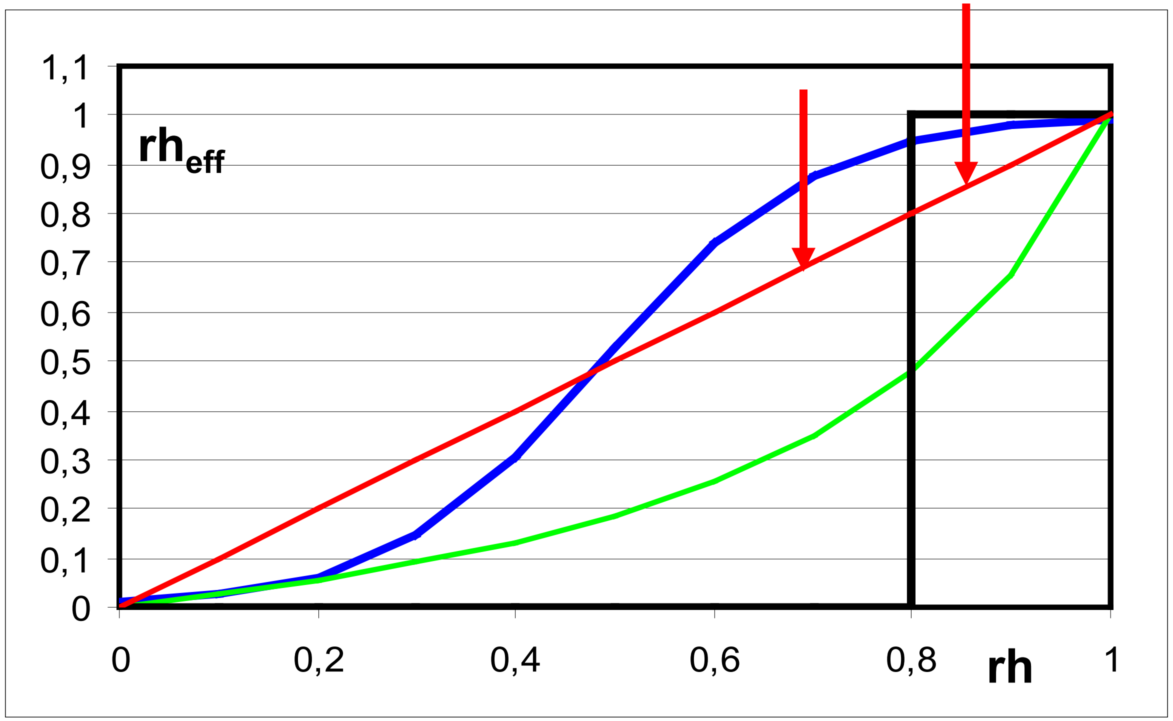
=> non-uniform polymer degradation above cells after 4000h damp-heat*

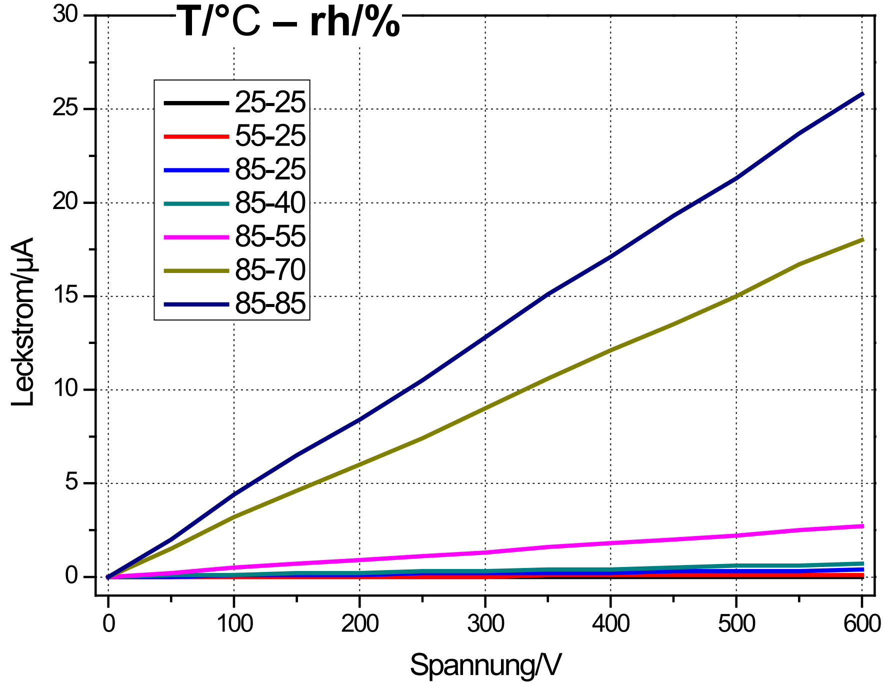
**C. Peike et.al.: Non-destructive degradation analysis of encapsulants in PV modules by Raman Spectroscopy, Sol. En. Mat. Sol. Cells (2011)*

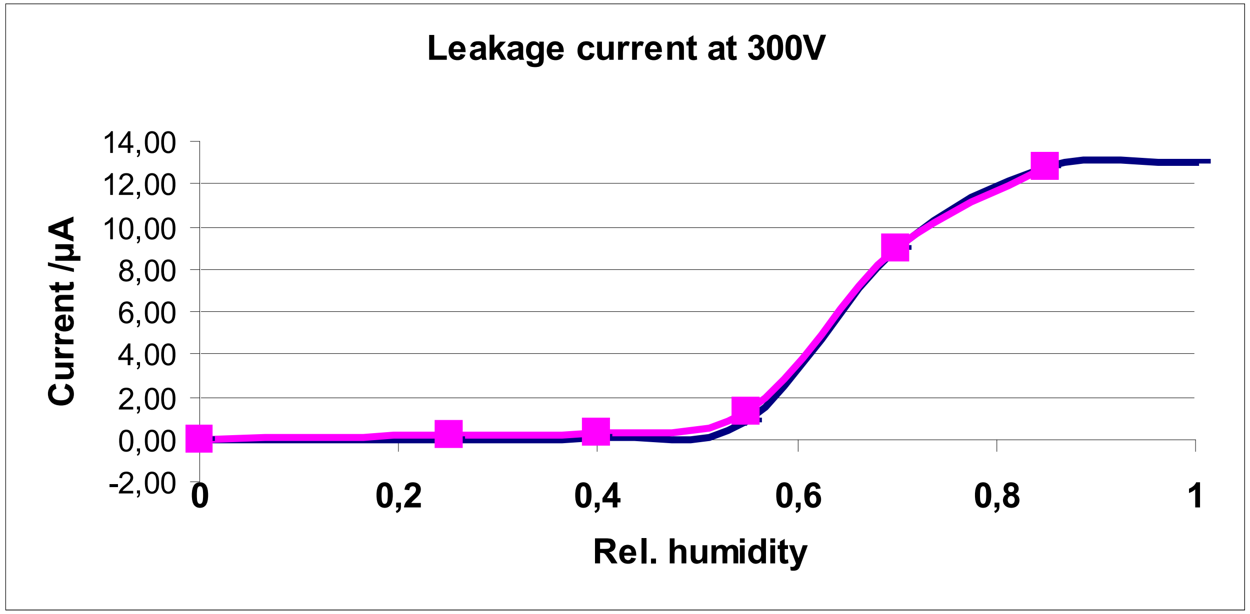
Effective humidity

Modelling humidity impact onto modules
based on surface humidity

- Climatic cabinet
- Leakage current







Sigmoidal Model: $I_{leak} = G/(G + \exp(-rh*k) *(G/f(0)-1))$

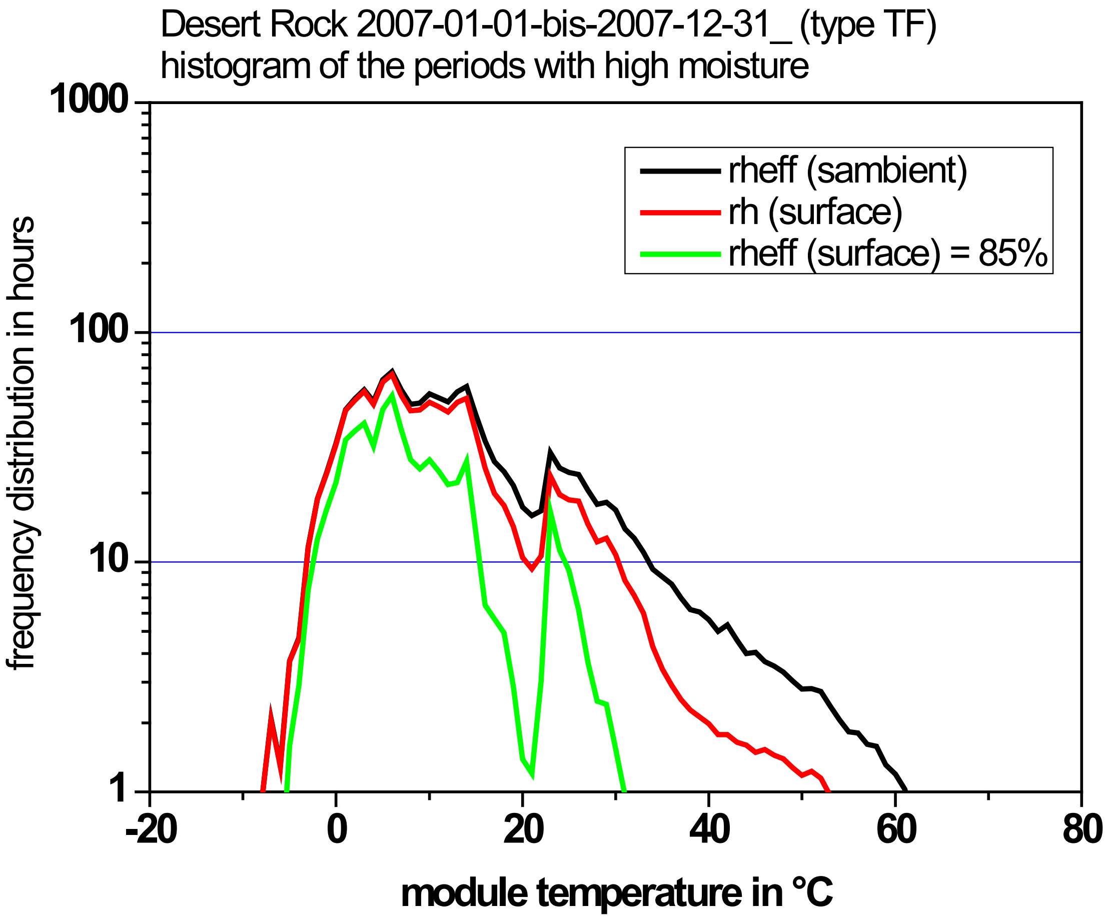
Simulated histograms of the relative humidity

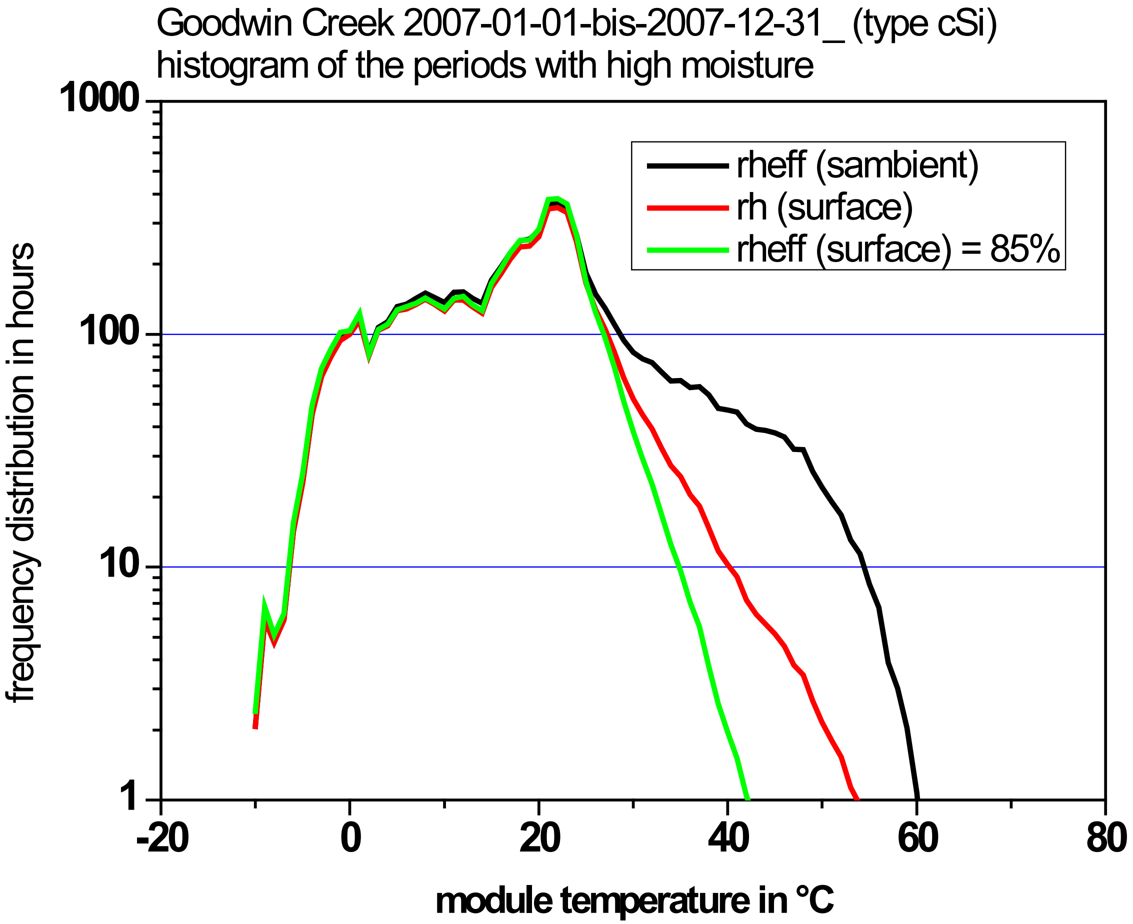
Ambient humidity = partial pressure / saturation pressure (T_{amb})

Surface humidity = partial pressure / saturation pressure (T_{modul})

Eff. Humidity: $rh_{eff} = 1/(1+ \exp(-rh*k) *(1/f(0)-1))$

Humidity dose: $\Delta t_{eff} = \Delta t * rh_{eff} / 0.85$



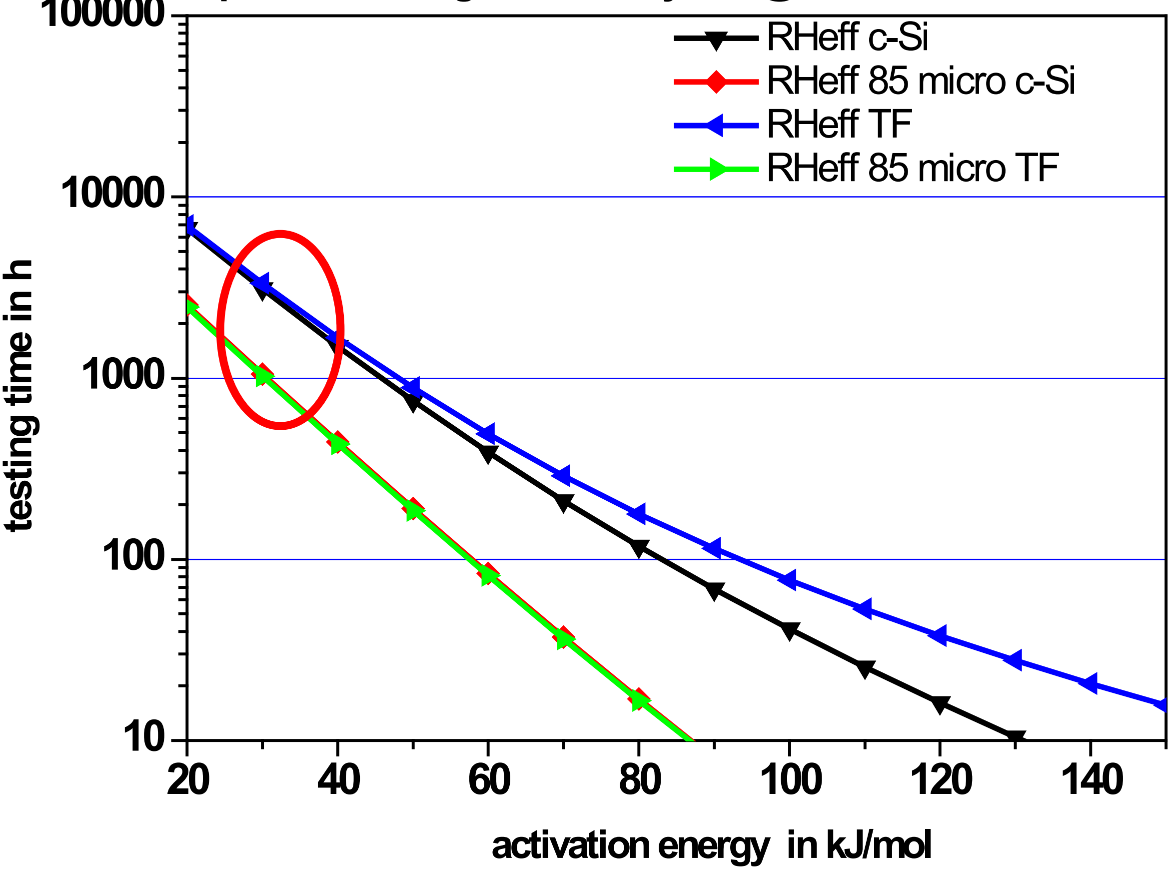


Damp-heat test conditions at 85°C and 85% rh

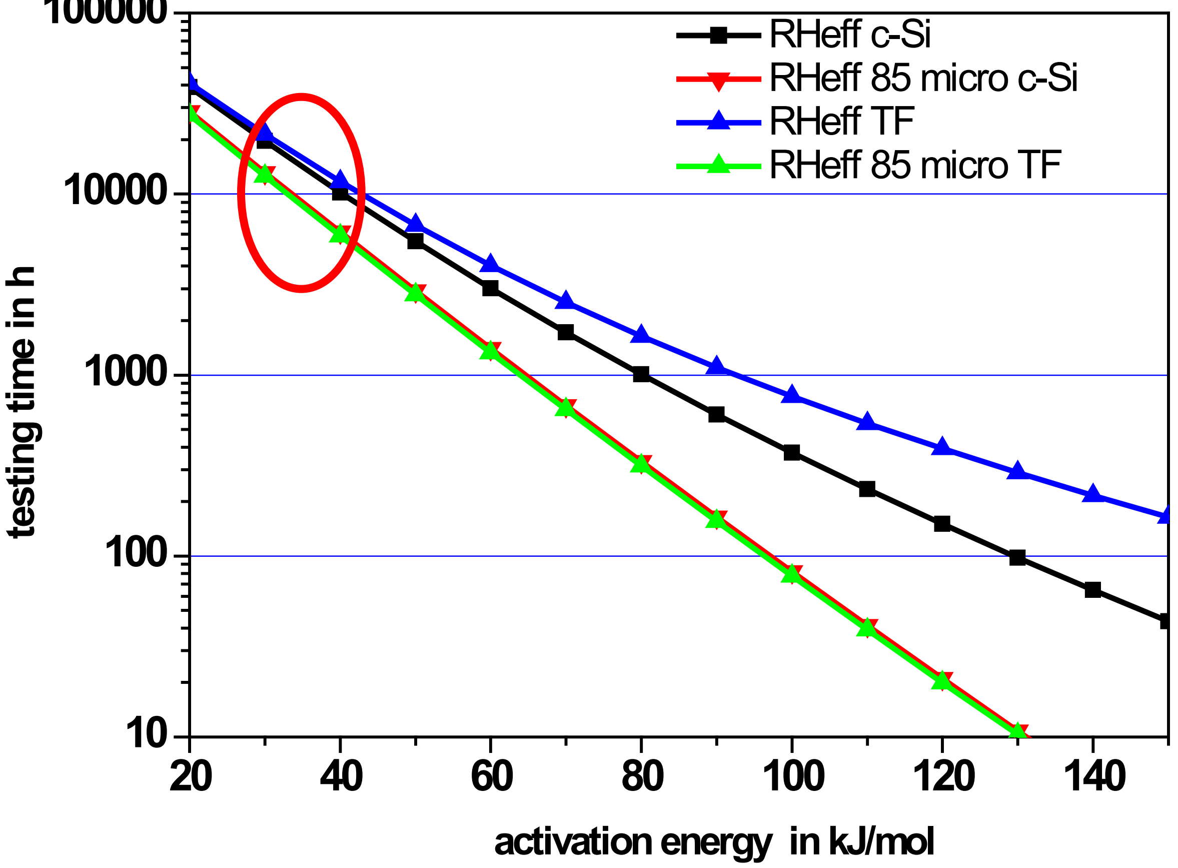
Considering the surface humidity instead of the ambient humidity reduces the testing time by a factor of 2 for humid and 3 for desert climates

Ten times longer testing time needed for the more humid site

The 1000h test suits for desert rock (could be 500 h)



Desert Rock 2007-01-01-bis-2007-12-31
equivalent testing time for 25 years @85%r.h. and 85°C



Goodwin Creek
equivalent testing time for 25 years @85%r.h. and 85°C

Testing times needed for service life testing (25 years)

Unfortunately strongly depending on the degradation processes in the materials

Test designs are needed which allow assessment of the material-dependent parameters in the time transformation functions

Service life testing times /h								
	E = 50 kJ/mol				**E = 100 kJ/mol**			
	Goodwin Creek		**Desert Rock**		**Goodwin Creek**		**Desert Rock**	
	c-Si	**TF**	**c-Si**	**TF**	**c-Si**	**TF**	**c-Si**	**TF**
Temperature (85°C)	8200	10500	9500	12000	666	1425	853	1680
Humidity (85/85)	2916	2780	191	185	82	77	4	4
UV (1sun @ 85°C)	4500	6700	6000	8500	575	1375	775	1700
UV (1sun no T-activation)	38000		48000					

Modelling the micro-climatic stress conditions

Time-series of climatic data

ambient temperature and humidity, solar irradiation, wind speed

Modeling the module temperatures

ambient temperature, solar irradiation, wind speed, module-specific coefficients (mounting situation might be considered)

Modeling the UV-radiation

5.5% of the solar radiation, module temperature

Modeling the effective surface humidity

ambient temperature and humidity, module temperature

Modelling the ALT conditions

Use a simple time-transformation function (Arrhenius based, eg)

Time, module temperature and other degradation factors, but separately first

Modeling the module temperature stress

as function of the material-specific activation energy,

(could be eventually included in damp-heat testing)

Modeling the UV-radiation impact

as function of the material-specific activation energy (which is low, UV-dose more important)

Modeling the moisture test

Higher test temperatures needed, as function of the material-specific activation energy,

What else is needed?

Validation of the time-transformation function

Or introduction of alternatices

Materials

Try to determine material dependencies like

activation energies for finding dose-response functions

Micro-climate

Consider the other degradation factors,

Temperature cycling, frost-thaw, high pot, salt, ammonia……..

Local climate

Define or adopt climate-classes and the respective stresses

Mapping, standardised ALT for each class or individual qualification

ALT conditions

Or assess dose response-function and model for given location

Define service-lifetime requirements

Service life

Design life-time, performance limit

Thanks for your attention

NREL for the invitation

To my colleagues

Daniel Philipp

Franz Brucker

Philipp Huelsmann

Markus Heck

Stefan Brachmann

Karl-Anders Weiss

Stefan Wiesmeier

To our partners

TÜV Rheinland

Schott Solar

Solarfabrik

Solarwatt

Solarworld

Solon

solar | glass Scheuten SCHOTT solar solar fabrik SOLARWATT SOLARWORLD SOLON AG für Solartechnik Fraunhofer ISE

Workshop on Reliability of PV-Modules

Testing

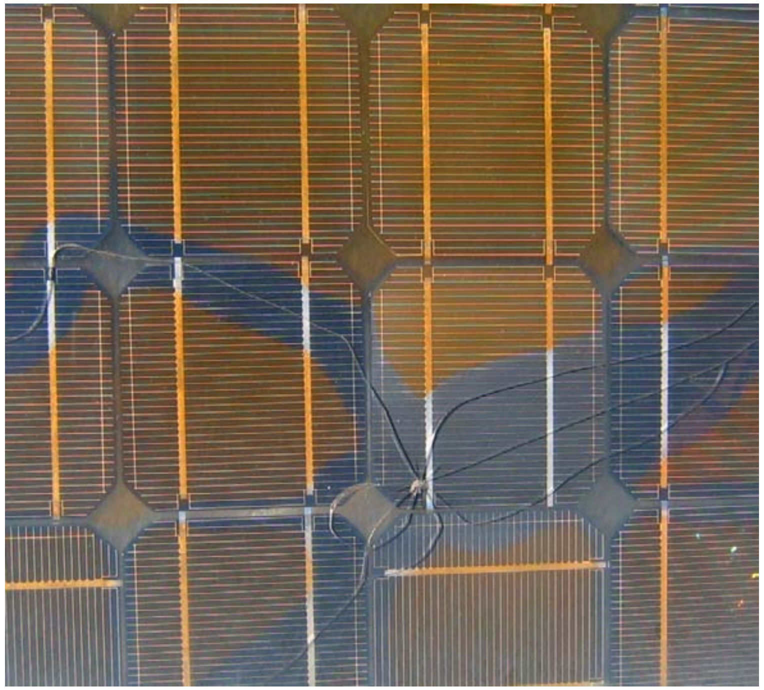
Analysing

Simulating   module - reliabilty

Organised by Fraunhofer ISE and Humboldt-Univ. Berlin

Supported by JRC, PCCL, TÜV Rheinland, VDE - Institute

http://www-pbp.physik.hu-berlin.de/pvr/



Berlin - Adlershof

Germany

April 5 – 6 2011

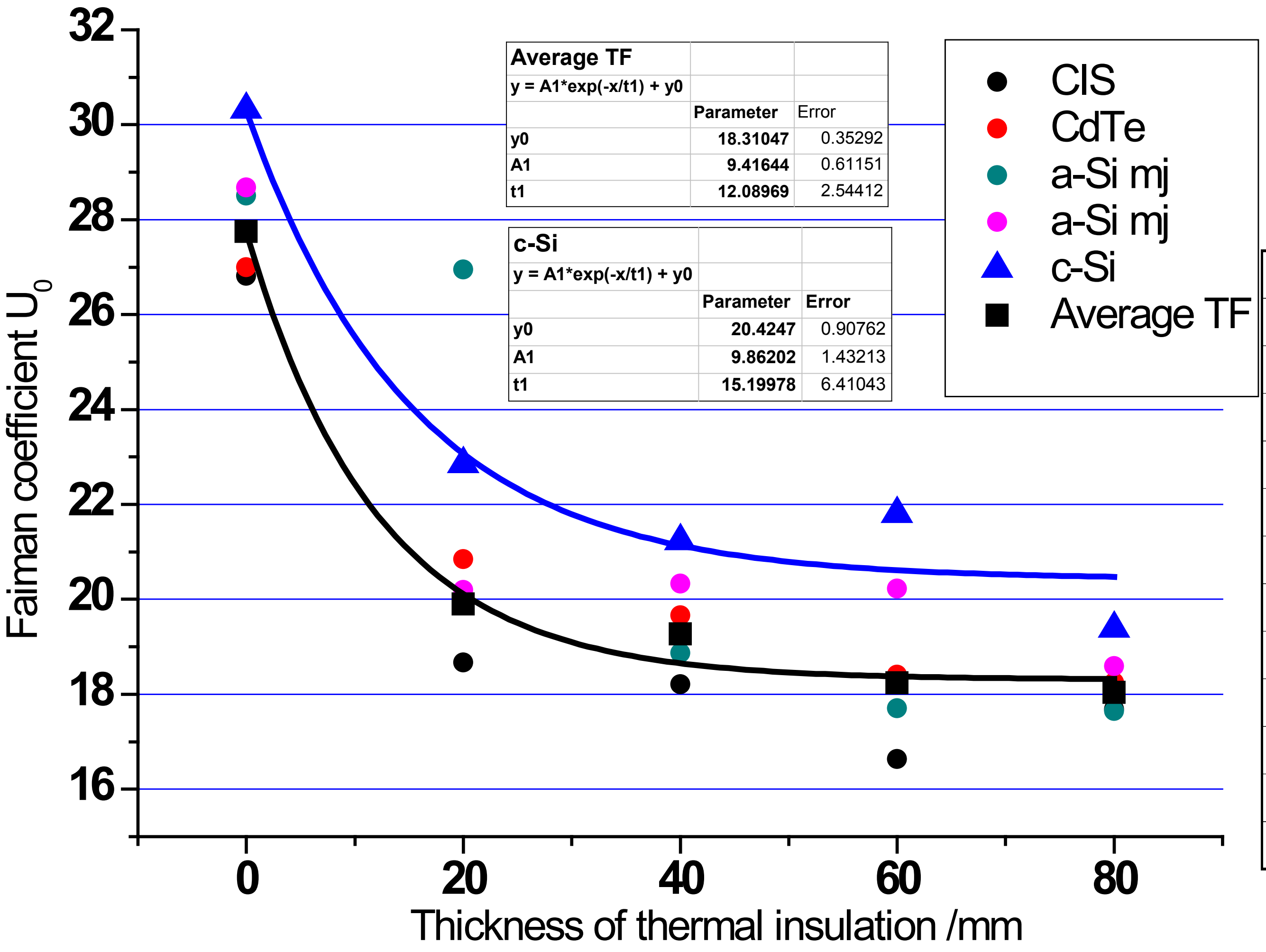
Meeting of the IEC TC82 WG2

Sub-group on Back-Sheets

After the Workshop

Temperature simulation towards BIPV

- Increasing thermal insulation on the back-side
  - Short monitoring periods
  - Inclination 45°



Average TF

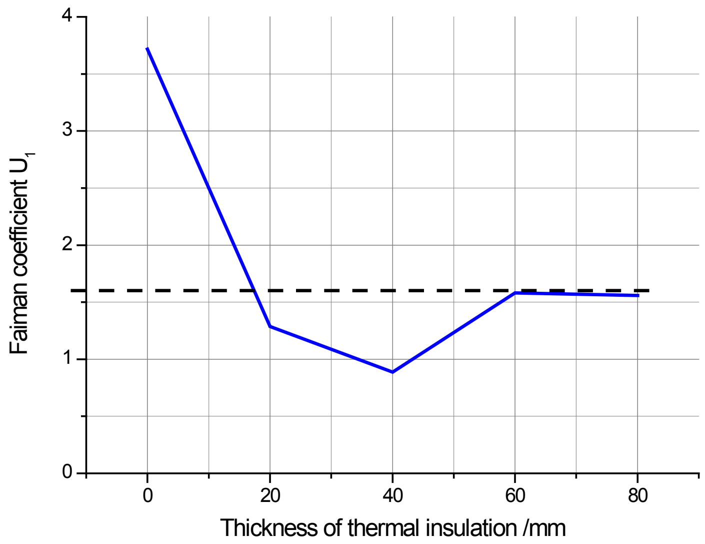
y = A1*exp(-x/t1) + y0

	Parameter	Error
y0	18.31047	0.35292
A1	9.41644	0.61151
t1	12.08969	2.54412

c-Si

y = A1*exp(-x/t1) + y0

	Parameter	Error
y0	20.4247	0.90762
A1	9.86202	1.43213
t1	15.19978	6.41043



Wind impact reduction by 50%

	Free		**BIPV**		**45°**	Incl.
	U0	**U1**	**U0**	**U1**		
c-Si	30	6	20	3		
TF	27,7	4	18,3	2		
c-Si	42,2		54,8		**NOCT**	800W
TF	43,7		59,4		Wind: 1 m/s	20°C
c-Si	40,2		51,3		**STC**	1000W
TF	44,3		58,0		Wind: 6 m/s	25°C
c-Si	68,3		85,0		**Maximum**	1000W
TF	71,1		89,6		Wind: 0 m/s	35°C

Module temperature up to 18 K higher