ESTIMATION OF THE LIFETIME OF SOLAR CELLS IN REAL CONDITIONS USING ACCELERATED AGING UNDER THE INFLUENCE OF NEUTRON AND GAMMA RADIATION

by

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In the paper, in a long-term test procedure, monocrystalline silicon cells were subjected to examination. Cells were tested in well-controlled laboratory conditions and real conditions. In laboratory conditions, white light of the artificial sun and monochromatic brightness of yellow sodium lamps were used. The testing was aimed at achieving the same aging regime in the laboratory conditions as in real conditions. This would allow for the laboratory aging algorithm of solar cells as in real conditions, to be defined, hence their working life of commercial exploitation in urban areas to be determined. By complex mathematical methods, i.e. using the theory of time duration, it was found that laboratory exposing solar cells to thermal neutrons causes their aging with the same mechanism as in real conditions.

Key words: solar cell, aging, gamma radiation, radiation by fast and thermal neutrons

INTRODUCTION

Solar energy plays an important role in the different types of renewable energy sources. The first silicon solar cell was made in 1954 and it had a modest efficiency of 6%. Present-day solar cells achieve an efficiency of 25% which is close to a theoretical maximum of 31% [1, 2].

In the development of solar cells (photovoltaic) technology, great attention has been dedicated to increasing their efficiency and reducing their production costs. This is a prerequisite for wider commercialization of solar power sources. Namely, the production price (i.e. the energy invested in the technological process of production) and the lifetime of solar cells are such that during their exploitation, not all energy invested can be recovered. For this reason, solar energy is used in conditions where other energy sources are unavailable. In such conditions most often there is no possibility of regular servicing and replacement of parts of solar cells. This causes the solar cells to be stable and long-lasting. However, as with all other semiconductor devices, the structure of solar cells is degraded during their exploitation, which leads to a change of their characteristics and their aging. Those effects are more pronounced when solar cells are applied in real conditions than when tested in laboratory conditions. For this reason, testing the lifetime of solar cells is carried out in laboratory conditions employing accelerated aging, using radioactive radiation [3-6].

The development of small semiconductor technologies, using thin films, has enabled the miniaturization of electronic components. This has led to high sensitivity of electronic components (and assemblies) to deposited energy, increasing their sensitivity to radiation. The energy deposited by radioactive radiation is considerably higher than the energy deposited in real conditions thus allowing for testing the aging rate of semiconductor components by an accelerated process [7-10].

This paper aims to quantify aging test results of solar cells by an accelerated procedure concerning tests carried out on solar cells placed on residential buildings in urban conditions. The quantification procedure will be done by examining the curves of a lifetime on statistical samples of experimentally obtained random variables: solar cell currents and resistance of solar cells.

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CURVES OF THE LIFETIME AND EXPONENT OF THE LIFETIME OF SOLAR CELL CURRENTS

If \( n \) samples are tested on time for which the current from the solar cell decreases to 70 % of its initial value \( (t_{70}) \), i.e. the corresponding value of the current density \( (J_{70}) \), under constant conditions of the experiment, \( n \) result of the variable of time for which the current has decreased to 70 % of the nominal current, has been obtained \( (t_{70}^{(i)}) \).

Empirical time distribution function \( F(t_{70}; J_{70}) \), fig. 1(a), is obtained based on the experiment performed and is conveniently described by Weibull distribution [11-14]

\[
F(t_{70}; J_{70}) = 1 - \exp \left[ - \left( \frac{t_{70}}{t_{63}^{(i)}(J_{70})} \right)^{\delta_i} \right] \tag{1}
\]

where \( t_{70} \) is the time for which the current density decreases to 70 % of its initial (nominal) value, \( \delta_i \) Weibull exponent, 63 % quantile of the Weibull distribution of time \( t_{70} \).

Diagram \( J_{70}^{(i)}/t_{70} \), the so-called characteristic of the lifetime can be constructed using the selected quantiles of this distribution. Experience has shown that such a diagram forms the right line on a double exponential scale, figs. 1(b) and 2. If the confidence intervals are known for the given quantiles, they can be transmitted to the characteristic of the lifetime. For each row of quantiles \( t_{70} \), quantile \( p \) distribution \( F(t_{70}; J_{70}^{(i)}) \), characteristic of the lifetime is described as follows

\[
J_{70,p} = k_{70,p} t_{70}^{-1/r} \tag{2}
\]

where \( k_{70,p} \) is a constant that characterizes the geometry of the structure, and \( r \) is an exponent of the lifetime that depends mainly on the material. Spinning in the characteristic of the lifetime indicates a change in the aging mechanism.

If, in analogy with eq. (1), Weibull distribution is adopted

\[
F(J_{70}^{(i)}; t_{70}^{(i)}) = 1 - \exp \left[ - \left( \frac{J_{70}^{(i)}}{J_{70,63}(t_{70}^{(i)})} \right)^{\delta_i} \right] \tag{3}
\]

and for current \( J_{70} \) with fixed time \( t_{70} \), then the same probability is

\[
J_{70,p} = k_{70,p} t_{70}^{-1/r} \tag{b}
\]
According to expression (2), assuming that the exponent \( r \) applies to all quantiles, the next expression for the same dependency and a couple of values \((J_{70}^{(0)}, t_{70}^{(0)})\) is

\[
F(t_{70}^{(0)}; J_{70}^{(0)}) = F(t_{70}^{(0)}; J_{70}^{(0)})
\]

\[
J_{70,63}(t_{70}^{(0)})(t_{71}^{(0)})^{\delta_j/\delta_i} = J_{70}^{(0)}(t_{70,63}^{(0)}(t_{70}^{(0)}))^{\delta_j/\delta_i}
\]

(4)

By comparing the coefficients on the left sides of the eqs. (4) and (5), a connection between the Weibull exponents for \( J_{70} \) and \( t_{70} \) \((\delta_j; \delta_i)\) and the exponent of the lifetime is obtained, in the form

\[
r = \frac{\delta_j}{\delta_i}
\]

(6)

This equation is true only if both variables \( J_{70}, t_{70} \) have Weibull distribution fig. 1(c). It should be emphasized that the eq. (6) and this model can be used only if \( r \) is equally valid for all quantiles, [15-17].

EXPERIMENT AND PROCESSING OF EXPERIMENTAL RESULTS

During the experiment, long-term recording of current-voltage characteristics of a large number of monocrystalline silicon solar cells of the same type (identical), were performed, fig. 3.

![Figure 3. Corrected and uncorrected current-voltage characteristics of the tested solar cell](image)

Measurements of solar cells exploitation were made both in the laboratory and in real conditions. Laboratory measurements were carried out in well-controlled conditions with the variable parameter such as type of illumination, the intensity of light, type of radioactive radiation. Two types of lighting were used: white light (artificial sun) and monochrome light (sodium sox lamp under pressure). The intensity of light was changed by the distance of the light source from the solar cell and measured by a calibrated standard cell and a lux meter. Types of radioactive radiation were: gamma radiation (cobalt lamp \(^{60}\)Co and neutron radiation (of accuracy \(\alpha\)-Be source). Figure 4 shows the spectrum of neutron radiation of the applied
Gamma radiation doses were in the range of 10 Gy and 4353 Gy. A neutron source was used in the air (fast neutrons), wherein the neutron radiation dose was expressed by the exposure time of the solar cell to the radiation. In real conditions, solar cells were placed on the facades of four residential buildings in the wider area of Belgrade.

Measurements were performed on groups of fifty statistically identical solar cells, fig. 5.

Their statistical identity was defined by determining the maximum power and current density at the point of maximum power and checking the belonging of these random variables to the unique statistical samples, using the U statistical uncertainty test less than 5 %. During measurements, in the laboratory and real conditions of exploitation, at even time intervals (12 hours), the current-voltage characteristic was recorded and the value of current density at the point of maximum power was determined. Besides, other relevant parameters of solar cells were determined every thirty days (open circuit voltage, short circuit current, internal regular resistance, maximum power, the voltage at the point of maximum power and efficiency). Based on the measurement results, ordered pairs of values were formed (the time since the beginning of the measurement, the current density at the maximum power point). In laboratory conditions, solar cells were exposed to the lightness of the lamps while in real conditions to the influence of climate. In laboratory conditions, solar cells, between two consecutive measurements, received certain doses of radioactive samples. Besides, measurements in the laboratory also included a control group of solar cells to which no radiation dose was applied [18]. The combined measurement uncertainty of the experimental procedure was less than 5 % [19, 20]. Processing of the measurement results was performed according to the following steps:

- application of Chauvenet's criterion for rejecting suspected measurement results,
- application of the U test to statistical samples to determine the identity of the statistical distribution to which they belong,
- testing statistical samples of random variables obtained by experiment for belonging to the distribution of extreme values (Weibull exponential and double exponential) using a graphic test, $\chi^2$-test and Kolmogorov's test,
- drawing curves for the lifetime, and
- determining the exponent of the lifetime according to the expression (6) [21, 22].

RESULTS AND DISCUSSION

Figures 6(a) and 6(b) show the results of the graphic test of belonging random variables $t_{70}^{(1)}$ and $J_{70}^{(1)}$ of one series of measurements in the laboratory, to Weibull distribution.

Figures 6(a) and 6(b) show that the random variables $t_{70}^{(1)}$ and $J_{70}^{(1)}$ of one series of measurements belong to the Weibull distribution. Results obtained by the graphic test were confirmed by $\chi^2$ test and Kolmogorov test of 5 % statistical uncertainty. The same results were obtained for random variables $t_{70}^{(1)}$ and $J_{70}^{(1)}$ measured in real conditions, i.e., on solar cells on the facades of residential buildings in the wider city center of Belgrade.
As it has been established that random variables $J_{70}^{(1)}$ and $J_{70}^{(2)}$ belong to the Weibull distribution, it was possible to determine the curves of the lifetime and the exponent of the lifetime according to the previously described procedure.

Figure 7 shows the curves of the lifetime of the solar cells exposed to the artificial sun (light flux of 32 Wm$^{-2}$) and monochromatic brightness of sox lamp (light flux of 8.58 Wm$^{-2}$) without exposure to radioactive radiation.

Based on the results shown in fig. 7, it can be concluded that solar cells in laboratory conditions age by a unique mechanism and that they age much faster under the influence of white light than under the influence of monochromatic light. Analogous results have been obtained with different values of the light flux which shows that the solar cell aging process does not depend on the light flux. Figure 8 shows the curves of the lifetime of solar cells exposed to the artificial sun (light flux of 58 Wm$^{-2}$) that previously received a dose of gamma radiation of 0.617 kGy and 1522 kGy.

Figure 8 shows the results indicating that solar cells in laboratory conditions age faster if they received a dose of gamma radiation. It can also be concluded that the rate of aging of the solar cell increases with the amount of the previously received dose of gamma radiation.

Figure 8 shows the results indicating that solar cells in laboratory conditions age faster if they received a dose of gamma radiation. It can also be concluded that the activity of neutrons over a long period leads to a change in aging mechanisms.

The results shown in fig. 9 lead to the conclusion that solar cells age faster if exposed to neutron than to gamma radiation. It can also be concluded that the activity of neutrons over a long period leads to a change in aging mechanisms.

From fig. 10, it can be concluded that solar cells in real conditions age faster than the same cells examined in laboratory conditions. It can also be concluded that with the passage of time, the aging mechanism for solar cells changes in real conditions. By comparing the results obtained for solar cells placed at different locations in the wider area of the city of Belgrade and taking into account the rose of the wind, it can be concluded that solar cells exposed to the Košava wind during exploitation, age the fastest and with the most pronounced change in the aging mechanism.

Table 1 shows the exponent values of the lifetime with the relevant experimental parameters.

**Figure 7. Curves of the solar cell lifetime:**
(1) solar cell exposed to artificial sun,
(2) solar cell exposed to monochromatic light of sox lamp

**Figure 8. Curves of the solar cell lifetime:**
(1) solar cell exposed to the artificial sun, (2) solar cell that received a dose of gamma radiation of 617 kGy,
(3) solar cell that received a dose of gamma radiation of 1522 kGy
Based on the results shown in tab. 1, it is easily noticed that gamma and neutron radiation cause a decrease in the efficiency and acceleration of the aging process. It can be quantitatively concluded that the solar cell irradiated with thermal neutrons for 30 days, for these two parameters, is closest to the solar cell exploited in real conditions (installed on the facade of the building). Figures 11–13 show the time dependence of other relevant parameters of solar cells exposed to the white light flux of 32 \( \text{Wm}^{-2} \) which previously received a dose of thermal neutrons for a period of 30 days, and solar cells from real conditions exposed to maximum wind power.

### Table 1. Exponent values of the lifetime with the relevant experimental parameters: (a) dose of gamma radiation, (b) time of exposure to fast neutrons, (c) time of exposure to thermal neutrons, (d) real conditions

<table>
<thead>
<tr>
<th>Light flux of white light ([\text{Wm}^{-2}])</th>
<th>A dose of (\gamma) radiation ([\text{kGy}])</th>
<th>Efficiency ([%])</th>
<th>Exponent of lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0</td>
<td>617</td>
<td>1522</td>
</tr>
<tr>
<td>58</td>
<td>0</td>
<td>617</td>
<td>1522</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>Light flux of white light ([\text{Wm}^{-2}])</th>
<th>Time of exposure to fast neutrons ([\text{d}])</th>
<th>Efficiency ([%])</th>
<th>Exponent of lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>58</td>
<td>0</td>
<td>30</td>
<td>300</td>
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(b)

<table>
<thead>
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<th>Light flux of white light ([\text{Wm}^{-2}])</th>
<th>Time of exposure to thermal neutrons ([\text{d}])</th>
<th>Efficiency ([%])</th>
<th>Exponent of lifetime</th>
</tr>
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<tbody>
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<td>32</td>
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<td>300</td>
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<td>58</td>
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(c)

<table>
<thead>
<tr>
<th>Real conditions (experimental)</th>
<th>Efficiency ([%])</th>
<th>Exponent of lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real conditions (experimental)</td>
<td>3.2</td>
<td>6.9</td>
</tr>
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</table>

(d)

**CONCLUSIONS**

In the paper, a long-term experiment was carried out in the laboratory and real conditions in the urban environment, related to exploitations of monocrystalline silicon cells of the same type and the same characteristics (in statistical terms).
ACKNOWLEDGMENT

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REFERENCES


AUTHOR’S CONTRIBUTION

V. Z. Trifunović-Dragišić designed the research, carried out measurements and processed the results. M. D. Stanković reviewed measurements and accuracy of results. D. V. Brajović processed results from the aspect of the error. N. M. Kartalović worked on the production of samples and equipment.


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