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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 miniaturizations 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 (i_{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 ($t_{70}^{(1)}$).

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

$$F(t_{70}; J_{70}^{(1)}) = 1 - \exp\left[-\left(\frac{t_{70}}{t_{63}J_{70}^{(1)}}\right)^{\delta_t}\right] \quad (1)$$

(a)

Logarithm of time $t_{70}^{(1)}$

(b)

Logarithm of time $t_{70}^{(1)}$
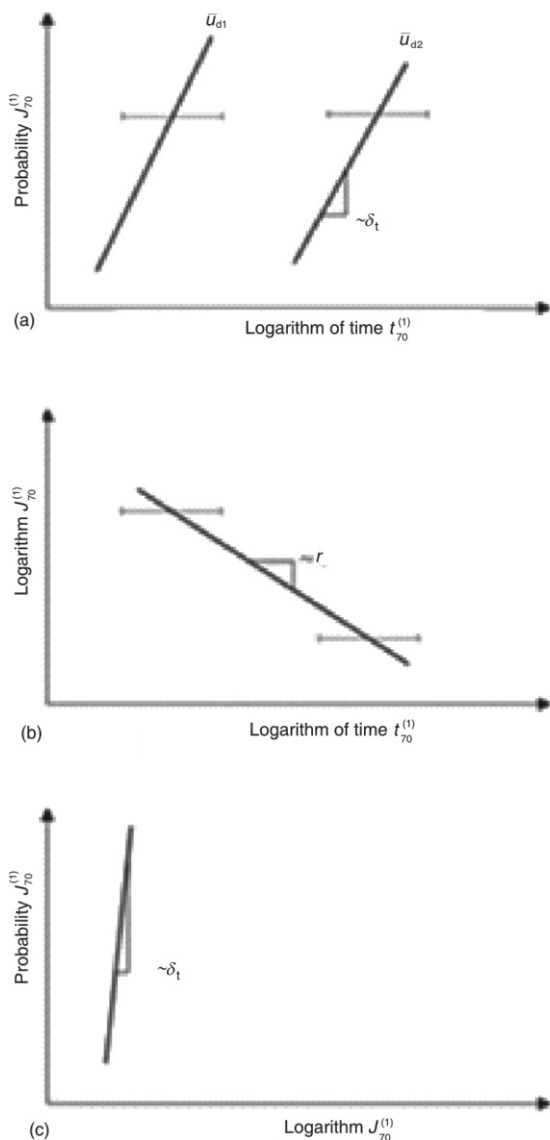
(c)

Logarithm $J_{70}^{(1)}$

Figure 1. Determination of functions and time distribution $t_{70}^{(1)}$ (a), characteristics of the lifetime (b), and functions of the current flow $J_{70}^{(1)}$ (c)

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

Diagram $J_{70}^{(1)} / t_{70}$, 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 $F(t_{70}; J_{70}^{(1)})$, characteristic of the lifetime is described as follows

$$J_{70p} = k_{70p} t^{1/r} \quad (2)$$

where k_{70p} 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

$$F(J_{70}^{(1)}; t_{70}^{(1)}) = 1 - \exp\left[-\left(\frac{J_{70}^{(1)}}{J_{70,63}(t_{70}^{(1)})}\right)^{\delta_t}\right] \quad (3)$$

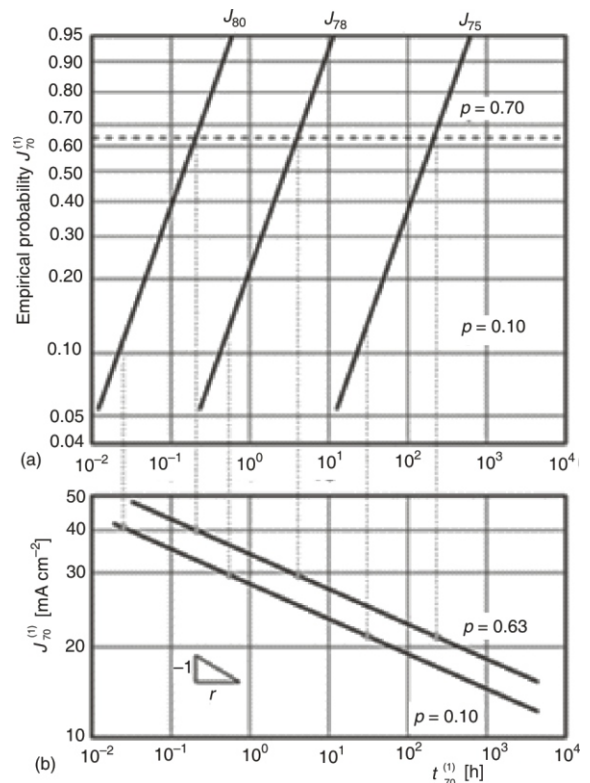and for current J_{70} with fixed time t_{70}, then the same probability is

(a)

(b)

Figure 2. Determination of the lifetime in the test: distribution function $J_{70}^{(1)}$ (Weibull paper) (a), characteristic of the lifetime $J_d = k_d t_{70}^{1/r}$ (b)

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$$F(t_{70}^{(1)}; J_{70}^{(1)}) \quad F(J_{70}^{(1)}; t_{70}^{(1)})$$

i.e.,

$$J_{70,63}(t_{70}^{(1)})(t_{71})^{\delta_t/\delta_J} \quad J_{70}^{(1)}(t_{70,63}(u_{70}^{(1)}))^{\delta_t/\delta_J} \quad (4)$$

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 $(J_{70}^{(1)} \quad J_{70,63}; t_{70}^{(1)})$ is

$$J_{70,63}(t_{70}^{(1)})[t_{70}^{(1)}]^{1/r} \quad k_{70,63} \quad (5)$$

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} ($\delta_J; \delta_t$) and the exponent of the lifetime is obtained, in the form

$$r \quad \frac{\delta_J}{\delta_t} \quad (6)$$

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.
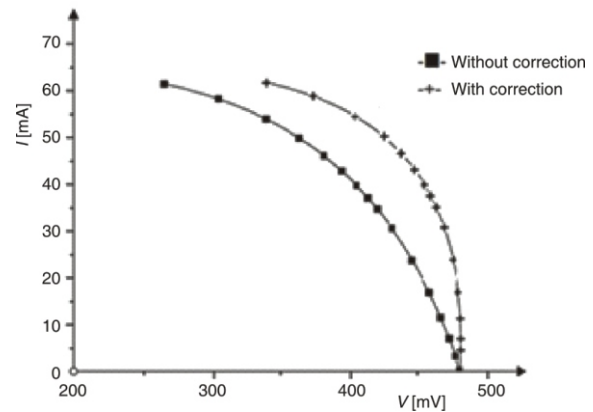
Figure 3. Corrected and uncorrected current-voltage characteristics of the tested solar cell

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}C0 and neutron radiation (of accuracy α-Be source). Figure 4 shows the spectrum of neutron radiation of the applied
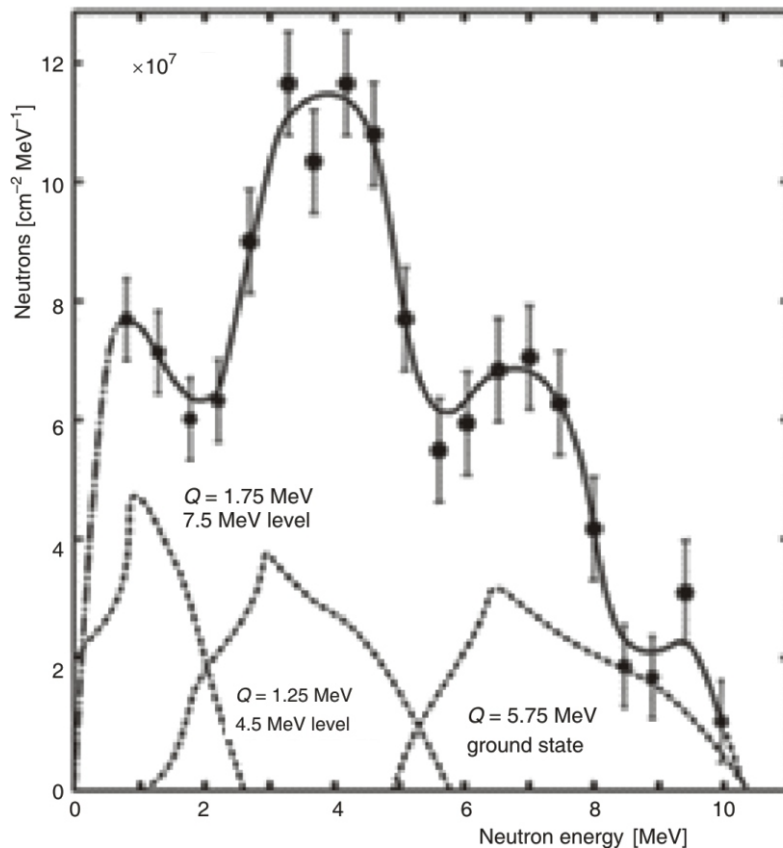
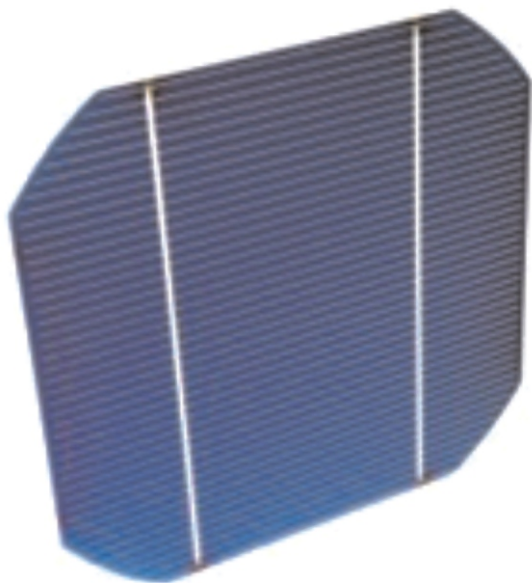**Figure 4. Energy distribution of neutrons from a neutron source**

Figure 5. Used sample of solar cell

source. 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 measure-

ment 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, χ^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 χ^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.
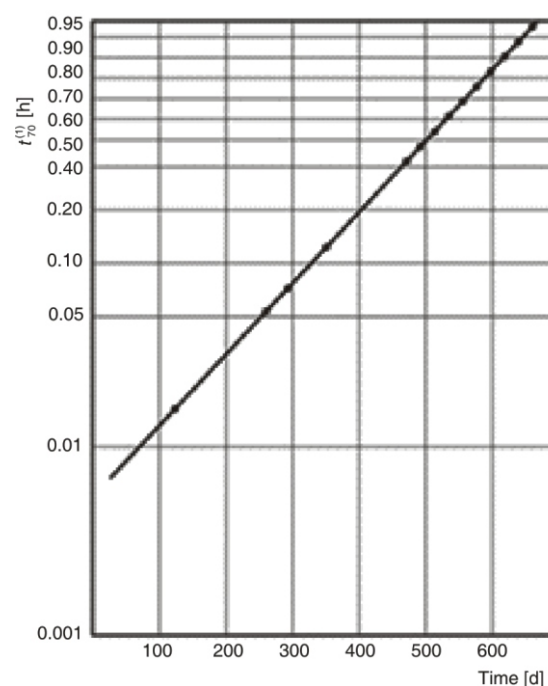

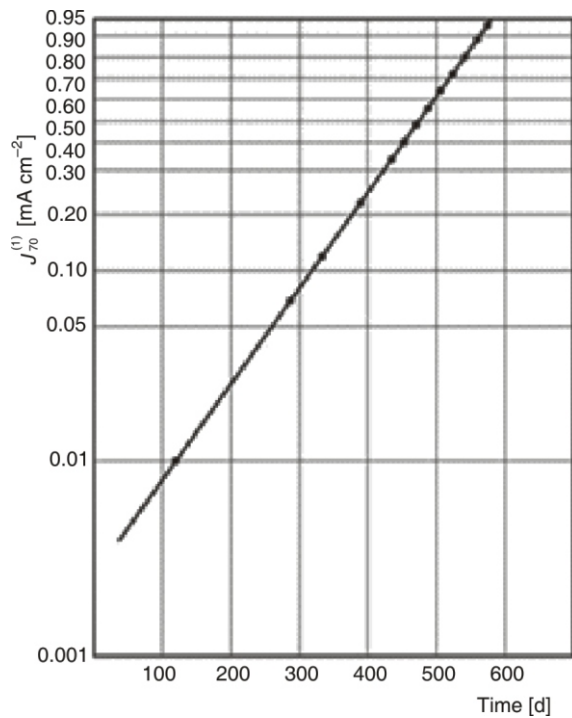**Figure 6(a). Random variable $t_{70}^{(1)}$ on the Weibull probability paper**

Figure 6(b). Random variable $J_{70}^{(1)}$ on the Weibull probability paper

As it has been established that random variables $t_{70}^{(1)}$ and $J_{70}^{(1)}$ 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
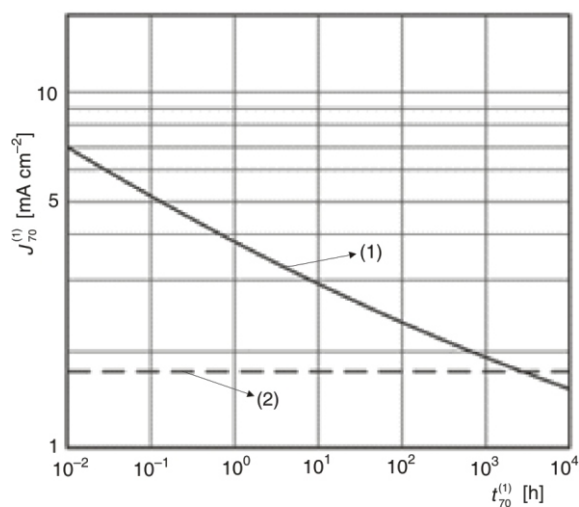
under the influence of white light than under the influence of monochromatic light. Analogous results have been obtained with different values of the light flux which shows that the solar cell aging process does not depend on the light flux. Figure 8 shows the curves of the lifetime of solar cells exposed 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 9 shows the curves of the lifetime of the solar cell exposed to the artificial sun (light flux of 32 Wm^{-2}) that previously received a dose of neutron radiation for 0,1 to 10 days.

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.

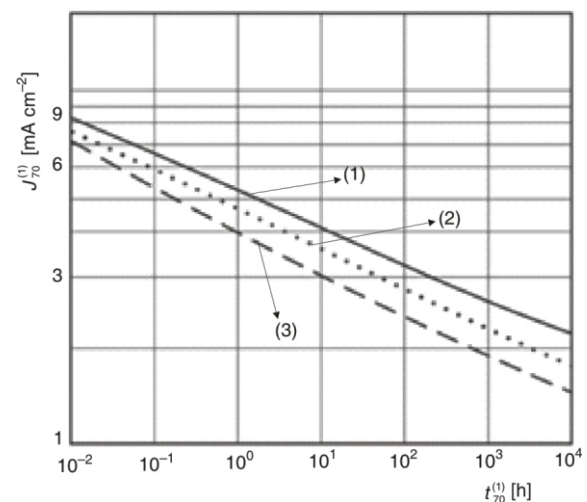Table 1 shows the exponent values of the lifetime with the relevant experimental parameters.

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

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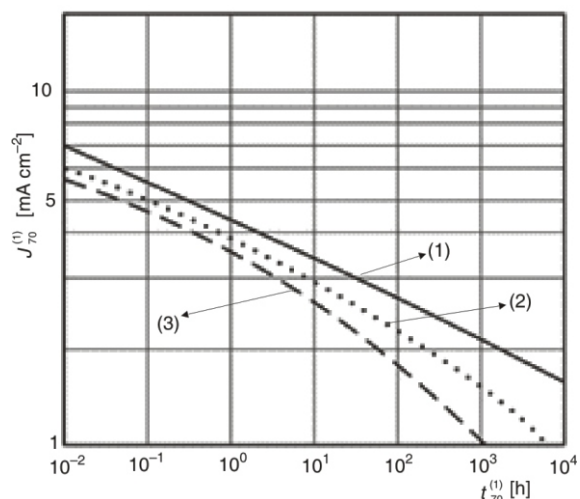
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Figure 9. Curves of the solar cell lifetime: (1) solar cell exposed to the artificial sun, (2) solar cell exposed to the artificial sun that received a dose of fast neutrons for 1 day, (3) solar cell exposed to the artificial sun that received a dose of fast neutrons for 7 days
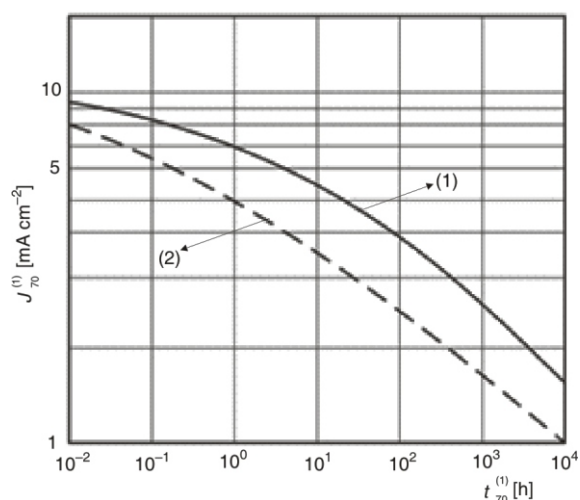

Figure 10. Curves of the solar cell lifetime in real conditions: (1) solar cell at position A, (2) solar cell at position B

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

Light flux of white light [Wm^{-2}]	A dose of γ radiation [kGy]			Efficiency [%]			Exponent of lifetime		
32	0	617	1522	8.37	4.90	4.10	8.10	7.80	6.15
58	0	617	1522	9.35	5.11	4.28	7.80	7.30	6.00

(a)

Light flux of white light [Wm^{-2}]	Time of exposure to fast neutrons [d]			Efficiency [%]			Exponent of lifetime		
32	0	30	300	8.37	3.70	2.10	8.10	7.10	5.00
58	0	30	300	9.35	4.00	2.70	7.80	6.80	4.80

(b)

Light flux of white light [Wm^{-2}]	Time of exposure to thermal neutrons [d]			Efficiency [%]			Exponent of lifetime		
32	0	30	300	8.37	3.10	1.60	8.10	6.90	4.30
58	0	30	300	9.35	2.80	1.00	7.80	5.10	3.60

(c)

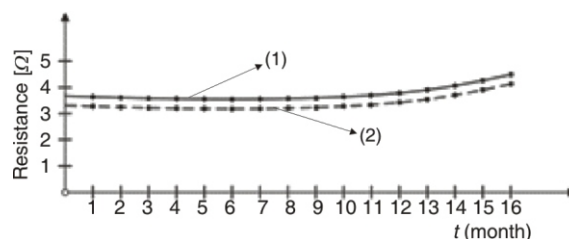| Real conditions (experimental)	Efficiency [%]	Exponent of lifetime
	3.2	6.9

(d)

Figure 11. Dependence of internal regular resistance: (1) solar cell exposed to real conditions, (2) a solar cell that received a 30- day dose of thermal neutrons
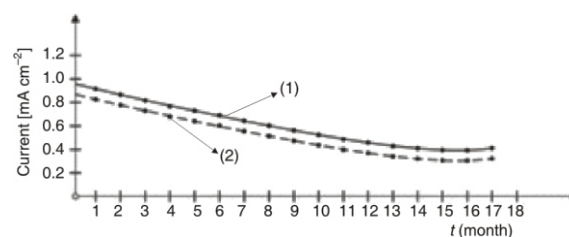

Figure 12. Dependence of short circuit current on time: (1) solar cell exposed to real conditions, (2) a solar cell that received a 30- day

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 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.

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).
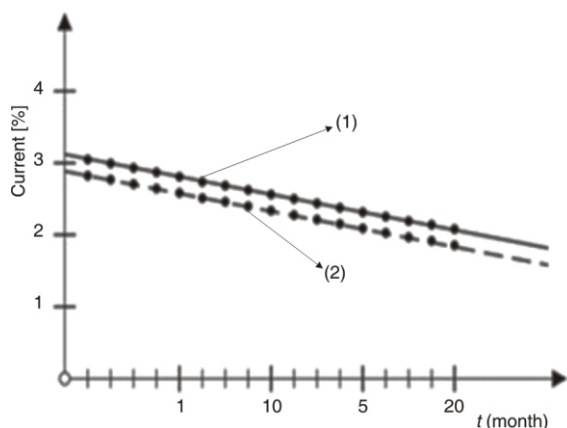
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**Figure 13. Dependence of short circuit current on time:
(1) solar cell exposed to real conditions,
- - - - - - a solar cell that received a 30-day dose
of thermal neutrons**

The purpose of the study was to find out the conditions under which laboratory tests would make possible, in a shorter time, obtaining reliable characteristics of the lifetime of solar cells working in real conditions. The degradation of the solar cell structure due to phonon-photon interaction and thermal stress was assumed as the main cause of aging. It has been shown that gamma radiation and neutron radiation have the effect of destroying the semiconductor structure of the solar cell, very similar to meteorological effects in real urban conditions.

Using experiments with gamma radiation, radiation by fast neutrons and radiation by thermal neutrons, it has been found that the most effective reaction is between *p-n* compound and thermal neutrons, which can be explained by Bragg's effect. In the case of tested monocrystalline silicon cells, it has been found that the 30-day dose of thermal neutrons (obtained by thermalization of the fast neutrons of the described source) gives the same effects of aging as the meteorological conditions on the territory of the city of Belgrade. Based on the obtained results in laboratory tests and testing under real conditions, it can be said with certainty that the use of solar cells in urban environments is not economically justified. Of course, solar cell (photovoltaic conversion of energy) remains irreplaceable in areas where access to other (conventional) sources of energy is not possible. However, in such cases, results presented in this paper can serve to assess the lifetime of applied solar cells (this is especially true in the case of photovoltaic power supply of spacecraft due to the intense effect of primary cosmic radiation).

ACKNOWLEDGMENT

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.

REFERENCES

[1] ***, The History of Solar U. S. Dept. of Energy, EERE, 2004

[2] Green, M. A., Photovoltaic Principles, Special Research Centre for Third Generation Photovoltaics, University of New South Wales, Sydney 2052, Australia, ELSEVIER, *Physica E 14* (2002), 1, pp. 11-17

[3] Obrenović, M. D., *et al.*, The Effects Induced by the Gamma-Ray Responsible for the Threshold Voltage Shift of Commercial *p*-Channel Power VDMOSFET, *Nucl Technol Radiat, 33* (2018), 1, pp. 81-86

[4] Perazić, L. S., *et al.*, Application of an Electronegative Gas as a Third Component of the Working Gas in the Geiger-Muller Counter, *Nucl Technol Radiat, 33* (2018), 3, pp. 268-274

[5] Dekić, S., *et al.*, Conditions for the Applicability of the Geometrical Similarity Law to Impulse Breakdown in Gases, *IEEE Transactions on Dielectrics and Electrical Insulation, 17* (2010), 4, pp. 1185-1195

[6] Nikolić, D., *et al.*, Comparative Study of Gamma Radiation Effects on Solar Cells, Photodiodes, and Phototransistors, *International Journal of Photoenergy, 2013*, (2013), Article number 843174

[7] Dolićanin, E., Fetahović, I., Monte Carlo Optimization of Redundancy of nanotechnology Computer Memories in the Conditions of Background Radiation, *Nucl Technol Radiat, 33* (2018), 2, pp. 208-216

[8] Marjanović, N., *et al.*, Effect of Heavy Ion Bombardment on TiO_2 memristor Operation, *Radiation Effects and Defects in Solids, 166* (2011), Jan., pp. 1-7

[9] Vujisić, M., *et al.*, Radiation Hardness of COST EPROM and E2PROM, *Radiation Effects and Defects in Solids, 166* (2010), 5, May, pp. 362-369

[10] Osmokrović, P., *et al.*, Reliability of Three-Electrode Spark Gaps, *Plasma Devices and Operations, 16* (2008), 4, pp. 235-245

[11] Pejović, M. M., *et al.*, Experimental Investigation of Breakdown Voltage and Electrical Breakdown Time Delay of Commercial Gas Discharge Tubes, *Japanese Journal of Applied Physics, 50* (8 PART 1), art. no. 086001., 2011

[12] Stanković, K., *et al.*, Long-Term deconditioning of Gas-Filled Surge Arresters, *Radiation Effects and Defects in Solids, 171* (2016), 7-8, pp. 678-691

[13] Khan, A., *et al.*, Strategies for Improving Radiation Tolerance of Si Space Solar Cells; *Solar Energy Materials and Solar Cells, 75* (2003), 1-2, pp. 271-276

[14] Stanković, K., Alimpijević, M., Free-Electron Gas Spectrum Uniqueness in the Mixture of Noble Gases, *Contributions to Plasma Physics, 56* (2016), 2, pp. 126-133

[15] Veverka, A., *et al.*, About the Weibull Distribution Function, *Electrotech Obz, 66* (1977), 4, pp. 206-208

[16] Jeftenić, I., *et al.*, Aging of Stator Coil Inter Conductor Insulation of High Voltage Asynchronous Motor; *IEEE Transactions on Dielectrics and Electrical Insulation, 25* (2018), 1, pp. 352-359

V. Z. Trifunović, *et al.*: Estimation of the Lifetime of Solar Cells in Real ....
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 256-263

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[17] Kuending, J., *et al.*, Thin Film Silicon Solar Cells for Space Applications: Study of Proton Irradiation and Thermal Annealing Effects on the Characteristic of Solar Cells and Individual Layers; *Solar Energy Materials and Solar Cells, 79* (2003), 4, pp. 425-438

[18] Hauschild, W., Mosch, W., Statistical Techniques for High-Voltage Engineering, London, U.K.: Peregrinus

[19] Marjanović, N. S., *et al.*, Simulated Exposure of Titanium Dioxide Memristors to Ion Beams, *Nucl Technol Radiat, 25* (2010), 2, pp. 120-125

[20] Kartalović, N. M., *et al.*, The Determination of the Mean Value of the Non-Homogeneous Background Radiation and the Measurement Uncertainty Using Welch-Satterthwaite Equation, *Nucl Technol Radiat 32* (2017), 4, pp. 371-374

[21] Mann, N. R., *et al.*, *Methods for Statistical Analysis of Reliability and Life Data*, John Wiley & Sons, New York, USA, 1974

[22] Schwab, A. J., *High-Voltage Measurement Techniques*, M.I.T. Press, Cambridge, Mass., USA, 1972

**Весна З. ТРИФУНОВИЋ-ДРАГИШИЋ, Миленко Д. СТАНКОВИЋ,
Драган В. БРАЈОВИЋ, Ненад М. КАРТАЛОВИЋ**

ПРОЦЕНА ВЕКА ТРАЈАЊА СОЛАРНИХ ЋЕЛИЈА У РЕАЛНИМ УСЛОВИМА ПРИМЕНОМ УБРЗАНОГ СТАРЕЊА ДЕЈСТВОМ НЕУТРОНСКОГ И ГАМА ЗРАЧЕЊА

У раду су поступком дуготрајних испитивања биле подвргнуте монокристалне силицијумске ћелије. Ћелије су испитиване у добро контролисаним лабораторијским условима, и у реалним условима. У лабораторијским условима су коришћена бела светлост ветшачког сунца и монохроматска светлост жуте натријумове лампе. Циљ рада је био да се у лабораторијским условима постигне исти режим старења као и у реалним условима. То би омогућило да се дефинише лабораторијски алгоритам старења као и у реалним условима старења соларних ћелија и самим тим одреди њихов радни век комерцијалне експлоатације у урбаним срединама. Сложеним математичким методама, тј. коришћењем теорије времена трајања, установљено је да лабораторијско испитивање термичким неутронима доводи до тога да соларне ћелије у лабораторији старе аналогним механизмом којим старе соларне ћелије у реалним условима.

Кључне речи: соларна ћелија, старење, гама зрачење, зрачење брзим и термичким неутронима