НУКЛЕАРНА ТЕХНИКА
/
NUCLEAR ENGINEERING AND TECHNOLOGY

(НТ/NTI)

Posledica merenja brzih napona Kerovim efektom u polju gama zračenja

Nemanja Aranđelović, Dušan Nikezić, Dragan Brajović, Uzahir Ramadani

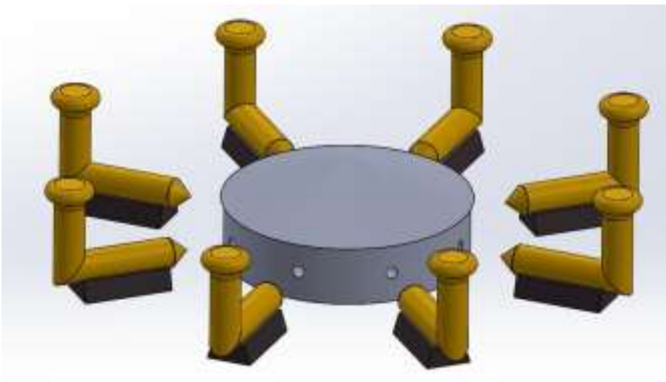
Apstract**—*****U ovom radu se razmatra mogućnost merenja elektronskog impulsa iz elektronskog generatora za zagrevanje plazme elektrooptičkom metodom. Eksperimenti se vrše primenom Kerovog efekta na modelu elektronskog generatora. Kerov efekat pokazuje izuzetno dobre karakteristike za merenje impulsa nanosekundne brzine. Međutim, dobijeni rezultati pokazuju da te njegove karakteristike znatno kvari gama zračenje u dinamičkom stanju kao i apsorbovana doza gama zračenja. Kada se tome doda i jednostavnost merenja kapacitivnom sondom može se zaključiti da Kerov elektrooptički efekat nije preporučljiv za merenje u fuzionim eksperimentima.***

Ključne reči**— nuklearna fuzija, elektronsko zagrevanje plazme, Kerov elektrooptički efekat, uticaj polja gama zračenja.***

I. Uvod

Rastuća potreba za energijom povećava napore za omogućavanje komercijalnog korišćenja nuklearne fuzije. Da bi do toga došlo potrebno je omogućiti zagrevanje plazme do temperatura koje su veće od praga za reakciju nuklearne fuzije. To se postiže injektovanjem energije u plazmu koja se nalazi u, takozvanoj, magnetnog boci. Prvobitno su rađeni eksperimenti sa laserskim injektovanjem energije u plazmu. Međutim, pokazalo se da plazma, pre postizanja temperature reakcije fuzije, počne da reflektuje laserske zrake čime se gubi veliki deo energije. Iz tog razloga se prešlo na čestično injektovanje energije u plazmu. To rešenje se pokazalo kao bolje, uz određene tehničke probleme koje treba rešiti [1-3].
Koncepcija čestičnog injektovanja energije u plazmu zasniva se na elektronskom generatoru, slika 1. Elektronski generator se sastoji od vertikalno postavljenog Marksovog generatora izolovanog uljem i horizontalnog talasovoda za oblikovanje elektronskog impulsa. Naime, elektronski generator treba da generiše elektronski impuls snage TW i širine 5 ns [4, 5]. Da bi se koncentrisalo dovoljno energije potrebno je da veći broj elektronskih generatora istovremeno injektuje elektronski impuls u plazmu. Iz zahteva za istovremenost injektovanja energije i nanosekunde širine impulsa javlja se problem džitera. Taj problem se rešava usavršavanjem okidanja Marksovog generatora primenom brzih troelektrodnih iskrišta [6-8]. Pored toga potrebno je meriti elektronski impuls na izlazu iz elektronskog generatora u cilju sinhronizacije okidanja svih generatora povratnom spregom. Merenje elektronskog snopa, zbog velike brzine, vrši se ili elektrooptičkim efektima ili brzim kapacitivnim sondama [9, 10].

Nemanja Aranđelović – Tehnološko-metalurški fakultet, Univerzitet u Beogradu, Karnegijeva 4, 11000 Beograd, Srbija (e-mail: snemi76@gmail.com).
Dušan Nikezić Institut za nuklearne nauke „Vinča“ - Institut od nacionalnog značaja za Republiku Srbiju, Univerzitet u Beogradu, Mike Petrovića Alasa bb., 1100 Beograd, Srbija (e-mail: dusan@vin.bg.ac.rs).
Dragan Brajović – Fakultet tehničkih nauka u Čačku, Univerzitet u Kragujevcu, Svetog Save 65, 32102 Čačak, Srbija (email: dragan.brajovic@vstss.com)
Uzahir Ramadani – Institut za nuklearne nauke „Vinča“ - Institut od nacionalnog značaja za Republiku Srbiju, Univerzitet u Beogradu, Mike Petrovića Alasa bb., 1100 Beograd, Srbija (e-mail: uzahir@vin.bg.ac.rs).



Sl. 1: Osnovni oblik elektronskog generatora.

Pošto se elektronski generator sa pratećom opremom nalazi u intenzivnom polju gama zračenja može da dođe do njegovog uticaja na tačnost merenja elektronskog snopa. Iz tog razloga je cilj ovog rada da se proveri uticaj gama zračenja i doze gama zračenja na efikasnost merenja elektronskog snopa (tj. njegovog električnog polja) primenom elektrooptičkog Kerovog efekta.

II. Kerov elektrooptički efekat

Kerov elektrooptički efekat je pojava dvojnog prelamanja svetlosti u jakom električnom polju. Pošto je ovaj efekat otkriven eksperimentalno, opisuje se fenomenološki uvođenjem takozvane Kerove konstante. Kerova konstanta povezuje faznu razliku Δϕ između regularnog i neregularnog talasa dvojno prelomljenog svetlosnog talasa sa električnim poljem, tj.:

$$\Delta\varphi = 2\pi B l E^2 \quad (1)$$

gde je $B=k/\lambda$ Kerova konstanta, l je dužina puta svetlosti kroz dielektrik u kom se vrši dvojno prelamanje i E je jačina električnog polja [11-14].

Izraz 1 omogućava merenje vrednosti električnog polja (ili napona) merenjem fazne razlike između regularnog i neregularnog talasa. Osobine i prednosti merenja električnog polja primenom Kerovog efekta nad standardnim postupcima tehnike visokih napona su: 1- veoma širok opseg visokonaponskih veličina koje se mogu meriti sa malom mernom nesigurnošću (1 %); 2- malo kašnjenje (oko 10^{-12} sekundi) step funkcije električnog polja; 3- pri korišćenju pravougaonih impulsa može se primeniti ista logika koja se koristi za jednosmerno električno polje; 4- dinamički opseg napona koji se može izmeniti sa zahtevanom tačnošću znatno prevazilazi 1 : 1000 (što je odgovarajući opseg klasične opreme); 5- primena Kerovog efekta nema probleme sa indukovanim naponima i prenaponima u galvanskoj vezi; 6- mogućnost merenja visokonaponskih veličina ekstremno visokih učestanosti; 7- mogućnost direktnih merenja u izolacionim uljima i drugim tečnim izolatorima i 8- mogućnost veoma precizne sinhronizacije optičkog i električnog signala [15-17].

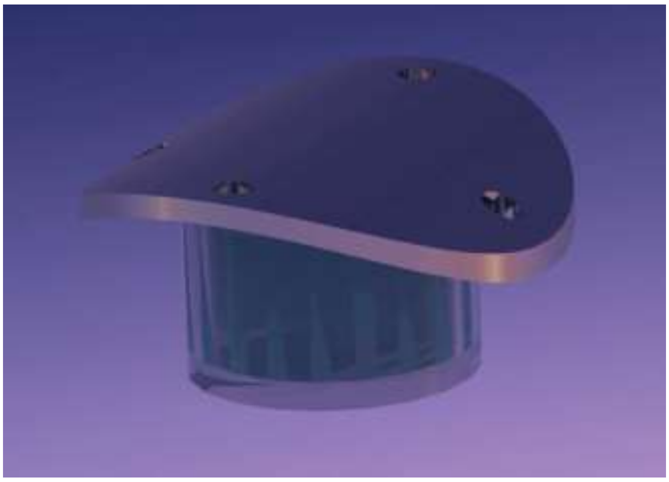
III. EKSPERIMENT I OBRADA EKSPERIMENTALNIH REZULTATA

Eksperimentalna provera dejstva gama zračenja i doze gama zračenja na mernu nesigurnost merenja pravougaonih naponskih impulsa vršena je na modelu horizontalnog dela elektronskog generatora, slika 2. U model sa slike 2 bili su ugrađeni polarizator, analizator i Kerova ćelija, slika 3. Kerova ćelija primenjivana u eksperimentu je bila zasnovana na tečnom dielektriku za dvojno prelamanje svetlosti. Primenjivane tečnosti i njihova Kerova konstanta su dati u tabeli 1.

Sl. 2. Model horizontalnog dela elektronskog generatora.

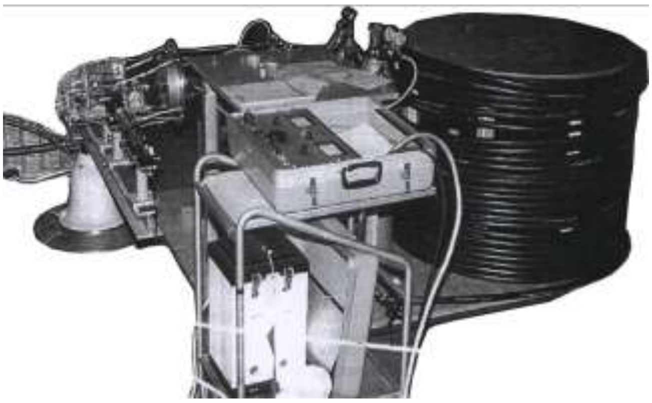
TABELA I
Kerove konstante primenjivanih tečnosti

TEČNOST	KEROVA KONSTANTA [m/V^2]
Nitrobenzen	$3.1\cdot10^{-12}$
Voda	$4.7\cdot10^{-14}$
Transformatorsko ulje	$1.8\cdot10^{-15}$



Sl. 3. Kerova ćelija koja se ugrađuje u horizontalni deo elektronskog generatora.

Kao izvor napona služio je visokonaponski kablovski generator, slika 4. Impuls iz kablovskog generatora je bio pravougaonog oblika sa veoma kratkim vremenom porasta i opadanja. Visokonaponski generator se sastojao od: 1- visokonaponskog transformatora; 2- ispravljača visokog naizmeničnog napona; 3- otpornika za ograničenje struje punjenja kabla; 4- koaksijalnog vodenog otpornika 50 Ω i 5- koaksijalnog visokonaponskog kabla dužine 60 m. Ovaj kablovski generator je generisao pravougaone impulse temene vrednosti 50 kV i trajanja 600 ns. Vremena uspona i opadanja čela i začelja su bila oko 3 ns.

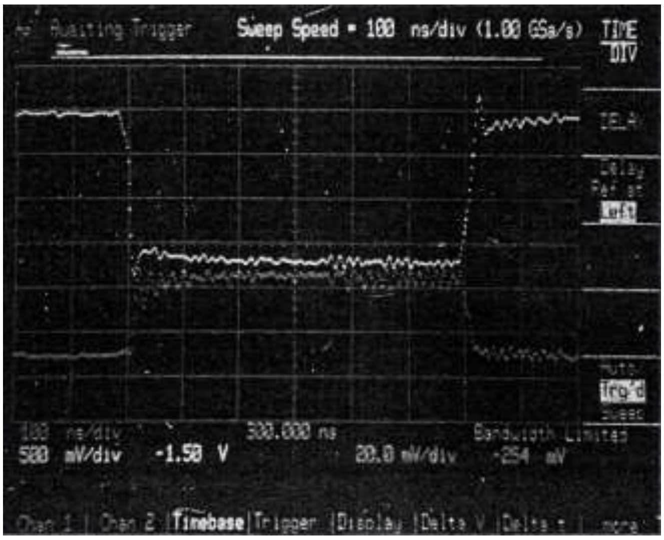


Slika 4: Visokonaponski kablovski generator.

Kao izvor svetlosti, tokom eksperimenta, korišćen je He-Ne laser. Ovaj tip lasera je jednostavan za rad i izvor je koherentne svetlosti. Osnovna talasna dužina ovog lasera je 632.82 nm.

Tokom merenja impulsa Kerovom ćelijom model horizontalnog dela elektronskog generatora je bio izložen dejstvu gama zračenja. Pri tome su vršena dva tipa merenja: 1- merenje pod dejstvom gama zračenja i 2- merenje nakon ozračenja Kerove ćelije pri čemu je data doza zračenja bila parametar merenja. Kao izvor zračenja korišćen je Co-60. Beta raspad radionuklida Co-60 prati fotonsko (gama) zračenje od 1.33 MeV i 1.17 MeV sa verovatnoćom emisije 1. Beta čestice koje se pri tome emituju nisu imale mogućnost da dopru do Kerove ćelije. Referentna merenja izvršena su u veličini kerma u vazduhu free-in-air pomoću referentnog mernog lanca, jonizacione komore i elektrometra, koji poseduje sledljivost do primarnog etalona. Prilikom dinamičnog merenja prototip horizontalnog dela elektronskog generatora postavljen je tako da je tokom merenja geometrija bila stalna. Doza koja je apsorbovana u Kerovoj ćeliji određivana je trajanjem ozračavanja na osnovu jačine doze određene jonizacionom komorom. Primenjene doze su iznosile: 20 Gy, 30 Gy, 40 Gy, 50 Gy, 60 Gy, 70 Gy, 80 Gy, 90 Gy, 100 Gy, 120 Gy, 140 Gy, 160 Gy, 180 Gy, 200 Gy, 300 Gy, 1000 Gy, 3000 Gy i 10000 Gy.

Merni postupak se sastojao u merenju impulsa iz kablovskog generatora Kerovom ćelijom. U postupku je vršena standardna konverzija fazne razlike regularnog i neregularnog talasa, slika 5 [18, 19]. Parametar merenja je bila vrsta dielektrika u Kerovoj ćeliji. Vršeno je po 50 snimanja napona iz kablovskog generatora dinamički i statički (za svaku dozu). Prilikom svakog merenja određivana je amplituda napona, vreme porasta, vreme opadanja i ripl na horizontalnom (temenom) delu napona. Takođe su statička merenja ponovljena (u istoj konfiguraciji) pet meseci nakon ozračenja. Merna nesigurnost tipa B postupka bila je 1.5 % [20, 21].



Sl. 5. Konvertovana fazna razlika regularnog i neregularnog talasa u naposnki impuls.

Statistička obrada eksperimentalnih rezultata se sastojala u sledećem: 1- primenom Šoveneovog kriterijuma čišćeni su statistički uzorci izmerenih slučajnih promenljivih od sumnjivih rezultata; 2- primenom χ^2 testa određena je statistička raspodela koja najbolje fituje dobijene statističke uzorke (testirane su Normalna raspodela i raspodela ekstremnih vrednosti); 3- momentnom metodom su određivana prva tri centralna momenta dobijenih raspodela i 4- određivana je merna nesigurnost tipa A za svaki statistički uzorak [22-24].

IV. Rezultati i diskusija

U tabeli 2 su date eksperimentalno dobijene vrednosti za merenje impulsa kablovskog generatora bez polja gama zračenja i sa poljem gama zračenja. Parametar eksperimentalnih rezultata su bile primenjene tečnosti u Kerovoj ćeliji.

TABELA II
EKSPERIMENTALNO DOBIJENE VREDNOSTI IMPULSA KABLOVSKOG GENERATORA BEZ I SA POLJEM GAMA ZRAČENJA

Tečnost	Amplituda		Vreme porasta		Vreme opadanja		Ripl		Merna nesigurnost tipa A	
Uslovi	bez γ	γ	bez γ	γ	bez γ	γ	bez γ	γ	bez γ	γ
Nitrobenzen	50 kV	46 kV	3 ns	3 ns	2 ns	2 ns	1 %	5 %	2 %	3.8 %
Voda	50 kV	41 kV	3 ns	3 ns	2 ns	2 ns	1.5 %	6 %	2.5 %	4.2 %
Trafo ulje	50 kV	43 kV	3 ns	3 ns	2 ns	2 ns	1 %	5 %	2.8 %	4.5 %

U tabeli 3 su date eksperimentalno dobijene vrednosti za merenje impulsa kablovskog generatora primenom Kerove ćelije ispunjene nitrobenzenom u zavisnosti od doze gama zračenja.

TABELA III
EKSPERIMENTALNO DOBIJENE VREDNOSTI IMPULSA KABLOVSKOG GENERATORA PRIMENOM KEROVE ĆELIJE ISPUNJENE NITROBENZENOM U ZAVISNOSTI OD PRIMLJENE DOZE GAMA ZRAČENJA

Doza [Gy]	Amplituda [kV]	Vreme porasta [ns]	Vreme opadanja [ns]	Ripl [%]	Merna nesigurnost tipa A [%]
20	50	3	2	1	2
30	50	3	2	1	2.2
40	49.3	3	2	1.2	2.2
50	48.8	3	2	1.4	2.25
70	47.8	3	2	1.4	2.32
80	46.4	3	2	1.52	2.37
90	45.8	3	2	1.6	2.46
100	45	3	2	1.65	2.62
120	44.1	3	2	1.76	2.84
140	43.2	3	2	1.88	2.93
160	42	3	2	2.2	3.1
180	40.8	3	2	2.4	3.4
200	39.4	3	2	2.7	3.7
300	35.2	3	2	3	4.5
1000	30	3	2	5.2	5.4
3000	27	3	2	6.8	5.6
10000	16	3	2	8	6.2

U tabeli 4 su date eksperimentalno dobijene vrednosti za merenje impulsa kablovskog generatora primenom Kerove ćelije ispunjene vodom u zavisnosti od doze gama zračenja.

TABELA IV
EKSPERIMENTALNO DOBIJENE VREDNOSTI IMPULSA KABLOVSKOG GENERATORA PRIMENOM KEROVE ĆELIJE ISPUNJENE VODOM U ZAVISNOSTI OD PRIMLJENE DOZE GAMA ZRAČENJA

Doza [Gy]	Amplituda [kV]	Vreme porasta [ns]	Vreme opadanja [ns]	Ripl [%]	Merna nesigurnost tipa A [%]
20	50	3	2	1	1.8
30	49.8	3	2	1.1	1.9
40	49.2	3	2	1.2	1.95
50	49.1	3	2	1.3	2.1
70	49.3	3	2	1.35	2.2
80	47.2	3	2	1.4	2.8
90	46.4	3	2	1.6	3
100	45.1	3	2	1.68	3.2
120	45	3	2	1.72	3.25
140	44.6	3	2	1.79	3.54
160	44.5	3	2	1.94	3.65
180	44.3	3	2	2.1	3.75
200	41.2	3	2	2.3	3.84
300	38.1	3	2	2.6	3.97
1000	33.8	3	2	2.9	4.2
3000	25.9	3	2	3.2	4.8
10000	16	3	2	5.4	5.9

U tabeli 5 su date eksperimentalno dobijene vrednosti za merenje impulsa kablovskog generatora primenom Kerove ćelije ispunjene trafo uljem u zavisnosti od doze gama zračenja.

TABELA V
EKSPERIMENTALNO DOBIJENE VREDNOSTI IMPULSA KABLOVSKOG GENERATORA PRIMENOM KEROVE ĆELIJE ISPUNJENE TRAFO ULJEM U ZAVISNOSTI OD PRIMLJENE DOZE GAMA ZRAČENJA

Doza [Gy]	Amplituda [kV]	Vreme porasta [ns]	Vreme opadanja [ns]	Ripl [%]	Merna nesigurnost tipa A [%]
20	49.8	3	2	1.8	2.1
30	49.8	3	2	2.1	2.15
40	48.2	3	2	2.3	2.25
50	48.1	3	2	2.35	2.38
70	47.8	3	2	2.39	2.41
80	47.6	3	2	2.41	2.43
90	47.1	3	2	2.43	2.46
100	47.0	3	2	2.47	2.49
120	46.8	3	2	2.49	2.52
140	46.1	3	2	2.52	2.54
160	46.0	3	2	2.55	2.59
180	45.7	3	2	2.59	3.12
200	45.1	3	2	3.2	3.21
300	44.9	3	2	3.6	3.28
1000	44.8	3	2	3.7	4.1
3000	44.0	3	2	4.1	4.9
10000	42.0	3	2	5.8	5.1

Na osnovu rezultata prikazanih u tabeli 2 se može zaključiti da Kerova ćelija u uslovima izloženosti dinamičkom gama zračenju menja neke od svojih karakteristika. Te promene su najviše izražene u slučaju da je tečnost u Kerovoj ćeliji trafo ulje, a najmanje izražene u slučaju da je tečnost u Kerovoj ćeliji nitrobenzen.

Dinamičko gama zračenje najviše utiče na ripl horizontalnog dela pravougaonog zračenja, a uopšte ne utiče na vreme porasta i opadanja pravougaonog impulsa. Pored toga dinamičko gama zračenje utiče na mernu nesigurnost tipa A merenja amplitude pravougaonog impulsa. Međutim, uticaj na ripl i amplitudu pravougaonog impulsa kablovskog generatora koje se pojavljuje kao posledica rada Kerove ćelije nisu značajne za sinhronizaciju rada elektronskih generatora. Osnovni uslov za sinhronizaciju elektronskih generatora je da vreme porasta i vreme opadanja impulsa budu konstantni, kao što jesu. Promene vrednosti amplitude pravougaonog impulsa, ripla i merne nesigurnosti tipa A takođe nisu od bitne važnosti za sinhronizaciju impulsa iz više elektronskih generatora pošto ne utiču na džiter. Što se tiče najvećeg uticaja gama zračenja na merenje Kerovom ćelijom kada je tečnost u ćeliji voda posledica je jednostavne strukture molekula vode i njene lake disocijacije.

Slična je situacija i sa primljenom dozom gama zračenja. Pošto primljena doza ne utiče na vreme porasta i opadanja impulsa može se zaključiti da primljena doza gama zračenja ne utiče na džiter. Ali prilikom velikih doza znatno opada amplituda pravougaonog impulsa, a to dovodi u pitanje ukupnu injektovanu energiju u plazmu. Najveći uticaj doza zračenja na amplitudu ima u slučaju da je Kerova ćelija ispunjena nitrobenzenom, a najmanji ako je Kerova ćelija ispunjena trafo uljem. To se može objasniti činjenicom što komponente nastale disocijacijom trafo ulja imaju približno istu vrednost Kerove konstante kao i trafo ulje. U slučaju nitrobenzena to nije slučaj. Manje opadanje amplitude sa povećanjem doze zračenja je proces rekombinacije atoma kiseonika i molekula vodonika tokom ozračivanja. Istim efektom se može objasniti i najveći stepen povratka prethodnih karakteristika Kerove ćelije sa vodom kao dielektrikom nakon vađenja iz polja gama zračenja. Naime, pokazalo se da je oporavak Kerove ćelije sa vodom kao dielektrikom nakon šest meseci neizloženosti gama zračenju stepena regeneracije 60 %. Regeneracija Kerove ćelije sa nitrobenzenom kao dielektrikom za isti period neizloženosti zračenju je samo 20 %. Ovako mali stepen regeneracije se objašnjava složenim molekulom nitrobenzena čije komponente disocijacije nemaju značajniju vrednost Kerove konstante. U slučaju Kerove ćelije punjene trafo uljem stepen regeneracije nakon šest meseci neizloženosti gama zračenju je oko 50 %. Međutim, velika vrednost ripla u ovom slučaju ukazuje da se ne radi o potpunoj regeneraciji trafo ulja već da u procentu oporavka učestvuju i komponente disocijacije koje imaju značajnu vrednost Kerove konstante.

Za razliku od ovih rezultata merenje uticaja neutronskog i gama zračenja na kapacitivnu sondu sa talasovodnim završnim otporom koja se takođe koristi za merenje impulsa elektronskog generatora pokazala je zanemarljiv efekat [25-27].

V. ZAKLJUČAK

Prethodno navedene osobine Kerovog elektrooptičkog efekta ga čine idealnim za merenje brzih naponskih impulsa. Međutim, rezultati prikazani u ovom radu pokazuju da Kerov efekat nije pogodan za merenje ako je Kerova ćelija ispunjena uobičajenim tečnostima, a treba da radi u polju gama zračenja. Naime, pokazuje se da gama zračenje ne utiče na regularni talas dvojnog prelamanja pošto njegovo prostiranje ne zavisi od indeksa prelamanja. Međutim, neregularna komponenta dvojnog prelamanja zavisi od indeksa prelamanja (tačnije njen indeks prelamanja zavisi od ugla upadnog zraka sa optičkom osom). Na taj način pravac kretanja neregularnog talasa postaje zavistan od indeksa prelamanja, a indeks prelamanja se menja usled pojave disocijacije molekula tečnosti usled zračenja. Na taj način dolazi do promenljive vrednosti fazne razlike između regularnog i neregularnog talasa. Ta razlika rezultira promenom amplitude izmerenog impulsa, njegovog ripla i merne nesigurnosti tipa A. Takvo ponašanje Kerove ćelije u polju gama zračenja čini je nepodesnom za merenje izlaznog elektronskog snopa elektronskog generatora koji se koristi za zagrevanje plazme. Ako se ovim osobinama doda i komplikovanost aparature za elektrooptička merenja može se zaključiti da je za ovaj tip merenja mnogo povoljnije koristiti brzu kapacitivnu sondu koja se pokazala rezistentna na dejstvo neutronskog i gama zračenja i koja daje zadovoljavajuće rezultate uz znatno jednostavniji merni sistem.

LITERATURA

[1] McCracken, G., Stott, P., Fusion, (2013) Fusion, 228 p, Elsevier Inc.
[2] Herman, R., (1990) Fusion: The Search for Endless Energy, Cambridge University Press, New York, NY. 527 pages. ISBN: 0-521-38373-0.
[3] Stankovic, K., Osmokrovic, P., Dolicanin, C., Vujisic, M., Vasic, A., Time enlargement law for gas pulse breakdown, (2009) Plasma Sources Science and Technology, 18 (2), art. no. 025028.
[4] Osmokrovic, P., Kusic, D., ArSic, N., Lazarevic, Z., Numerical and experimental design of three-electrode spark gap for synthetic test circuits, (1994) IEEE Transactions on Power Delivery, 9 (3), pp. 1444-1450.
[5] Osmokrović, P., Arsić, N., Vujisić, M., Stanković, K., Dolićanin, C., Reliability of three-electrode spark gaps, (2008) Plasma Devices and Operations, 16 (4), pp. 235-245.
[6] Avdic, S., Beganovic, A., Lagumdžija, A., Sadikovic, S., Pehlivanovic, B., Demirovic, D., Kadic, I., Comparative analysis of gamma dose rates measured by ion chamber in and around the historical sacral objects in Bosnia and Herzegovina, (2019) Nuclear Technology and Radiation Protection, 34 (2), pp. 157-164.
[7] Nedić, T.M., Janićijević, A.J., Stanković, K.D., Kartalović, N.M., Efficient replacement of the radioactive sources in the gas-filled surge arresters construction for the insulation co-ordination at the low voltage level, (2020) Nuclear Technology and Radiation Protection, 35 (2), pp. 130-137.
[8] S. B. Djekic, et al.: Passive and Active Shielding Against Electromagnetic Radiation, Nuclear Technology & Radiation Protection: Year 2020, Vol. 35, No. 4, pp. 331-338.
[9] D.C. Wunsch, *Kerr Cell Measuring System for High Voltage Pulses*, The Review of Scientific Instruments, Vol. 35, No. 7, July 1964.
[10] S. Newton, *Kerr Cell System for the Measurement of High Voltage Waveforms*, J.S. Instruments, Vol. 44, 1967.
[11] C.J.F. Böttscher, *Theory of Electric Polarization*, Dielectric in Static Fields, Vol. I, Elsevier, Amsterdam, 1973.
[12] Trifunović-Dragišić, V.Z., Stanković, M.D., Brajović, D.V., Kartalović, N.M., Estimation of the lifetime of solar cells in real conditions using accelerated aging under the influence of neutron and gamma radiation, (2019) Nuclear Technology and Radiation Protection, 34 (3), pp. 256-263.
[13] Fan, X., Chen, W., Zhang, Q., Chen, M., Wen, T., Zhang, X., Pei, Z., He, T., An electric field measurement method based on electro-optical modulation for corona discharge in air, (2019) Review of Scientific Instruments, 90 (8), art. no. 084704.
[14] Arbutina, D.S., Vasić-Milovanović, A.I., Nedić, T.M., Janićijević, A.J., Timotijević, L.B., Possibility of achieving an acceptable response rate of gas-filled surge arresters by substitution of alpha radiation sources by selection of electrode material and the electrode surface topography, (2020) Nuclear Technology and Radiation Protection, 35 (3), pp. 223-234.
[15] P. Osmokrović, I. Milovanović, M. Vujisić, K. Stanković, R. Radosavljević, „Experimental measurements of very fast transient voltages based on an electro-optic effect“, International Journal of Electrical Power & Energy Systems, Vol. 43, No. 1, pp. 408 – 417, 2012.
[16] Stanojević, N.Z., Djokić, J.V., Osmokrović, P.V., Research on water interconnections within the Šar mountains aquatorium by radioactive hydrogen isotope tritium, (2019) Nuclear Technology and Radiation Protection, 34 (4), pp. 392-398.
[17] H.M. Hertz, “Kerr effect tomography for nonintrusive spatially resolved measurements of asymmetric field distributions”, Applied Optics, Vol. 25, No. 6, pp. 914 – 921, March 1986.
[18] P. Osmokrović, D. Filipović, M. Pešić and Z. Lazarević, „Transient electric field measurement in the liquid dielectrics using computerized laser tomography“, *IEEE Transactions on Instrumentation and Measurement*, Vol. 56, No. 6, pp. 2538 – 2546, December 2007.
[19] M. Stojkanović, G. Djukić, K. Stanković, M. Vujisić and P. Osmokrović, ”Design Deployment and verification of the capacitive voltage divider for measuring fast transient occurrences in the nanosecond range“, Int. J. Elec Power, Vol. 43, pp. 1479-1486, 2012.
[20] Vulević, B., Osmokrović, P., Evaluation of uncertainty in the measurement of environmental electromagnetic fields, (2010) Radiation Protection Dosimetry, 141 (2), art. no. ncq158, pp. 173-177.
[21] P. Osmokrović, D. Petković and O. Marković, ”Measuring probe for fast transients monitoring in gas - insulated substations“, ETEP/IEEE Trans. Instrum. Meas., Vol. 46, pp. 36-45, 1997.
[22] Lazarevic, Z., Radosavljevic, R., Osmokrovic, P., A novel approach for temperature estimation in squirrel-cage induction motor without sensors, (1999) IEEE Transactions on Instrumentation and Measurement, 48 (3), pp. 753-757.
[23] Kaur, R., Shikha, D., Singh, S.P., Mehta, V., Environmental radon, its exhalation rates and activity concentration of ^{226}Ra, ^{232}Th, and40k in Northern India, (2020) Nuclear Technology and Radiation Protection, 35 (3), pp. 268-282.
[24] Polužanski, V.S., Žigić, A.D., Kovačević, D.S., Nikolić, B.D., Computer non-iterative data acquisition of particle trajectory in a spark chamber, (2019) Nuclear Technology and Radiation Protection, 34 (1), pp. 65-71.
[25] Kartalović, N., Stanković, K., Nikezić, D., Kovačević, U., Dose effect of gamma radiation on reliable voltage pulse measurement in nuclear fusion experiments, (2020) Radiation Effects and Defects in Solids.
[26] Pejović, M.M., Pejović, M.M., Jakšić, A.B., Stanković, K.D., Marković, S.A., Successive gamma-ray irradiation and corresponding post-irradiation annealing of pMOS dosimeters, (2012) Nuclear Technology and Radiation Protection, 27 (4), pp. 341-345.
[27] Osmokrovic, P., Stojanovic, M., Loncar, B., Kartalovic, N., Krivokapic, I., Radioactive resistance of elements for over-voltage protection of low-voltage systems, (1998) Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 140 (1-2), pp. 143-151.

ABSTRACT

In this paper, the possibility of measuring the electronic pulse from an electronic generator for plasma heating by electro-optical method is considered. The experiments are performed by applying the Kerr effect on an electronic generator model. Kerr effect shows very good characteristics for measuring nanosecond pulse rate. However, the results obtained show that these characteristics are significantly spoiled by gamma radiation in a dynamic state as well as by the absorbed dose of gamma radiation. When the simplicity of measuring with a capacitive probe is added to that, it can be concluded that the Kerr electro-optical effect is not recommended for measurement in fusion experiments.

Influence of gamma radiation on measurement fast pulse voltages by Kerr electro-optic effect

Nemanja Aranđelović, Dušan Nikezić, Dragan Brajović, Uzahir Ramadani

Radioactive Waste Management: Construction and Demolition Debris in Geopolymers

Ivana Jelić, Marija Šljivić-Ivanović, Tatjana Miljojčić, Milica Ćurčić and Slavko Dimović

Abstract — **Construction and demolition debris (C&DD) is one of the fastest-growing waste streams due to the global economic development and urbanization process. Therefore, developing more attractive and inexpensive methods and creating more valuable conventional and novel technologies that could more efficiently use these wastes and solve possible environmental problems, especially radioactive waste. The most widespread and economically viable solution for the reuse of C&DD today is civil engineering and the road industry. Also, there are several possible ways to use C&DD in geopolymers as recycled aggregates, activating components (precursors) depending on the composition, and as a hybrid system: with some aluminosilicate material that has better geopolymerization capacity or ordinary Portland cement. This use of C&D enables the synthesis of a wide range of matrices for the immobilization of radionuclides.**

Index Terms — **radionuclides; immobilization; geopolymers; environment; raw materials.**

I. Introduction

Construction and demolition waste (C&DW) is generated during the production of construction products or semi-final products, construction, demolition, and reconstruction. This waste accounts for the largest source of the solid waste stream in most countries worldwide [1-2]. According to European Environment Agency (EEA): "Construction and demolition waste (C&DW) comprises the largest waste stream in the EU, with relatively stable amounts produced over time and high recovery rates. Although this may suggest that the construction sector is highly circular, scrutiny of waste management practices reveals that C&DW recovery is largely based on backfilling operations and low-grade recovery, such as using recycled aggregates in road sub-bases" [3] as unbound aggregates or bound aggregates for concrete mixtures [4]. It is considered that construction is liable for climate changes (50%), increased energy consumption (40%), landfill waste generation (50%), air and water pollution, destruction of natural habitats, and negative impact on human health [5-7]. Thus, C&DW has an overall adverse environmental and economic impact, as well, on the construction sector, contributing to the emergence of additional costs. The main goal of C&DW management is to establish sustainable waste management, monitoring the quantities, types and composition of waste, waste generation, reduction of waste amount, separation and disposal of all types of construction waste, and its recycling and reuse.

Construction and demolition debris (C&DD), as one of the C&DW main fractions, occurs preferably after demolishing or reconstructing buildings (Fig. 1). It represents parts of walls, concrete, ceramic and roof tiles, carpentry, electrical parts, i.e. "discarded materials generally considered to be not water-soluble and non-hazardous in nature, including, but not limited to, steel, glass, brick, concrete, asphalt roofing material, pipe, gypsum wallboard, and lumber, from the construction or destruction of a structure as part of a construction or demolition project or from the renovation of a structure, and including rocks, soils, the tree remains, trees, and other vegetative matter that normally results from land clearing or land development operations for a construction project, including such debris from the construction of structures at a site remote from the construction or demolition project site" [8].

Fig. 1. Construction and demolition debris

This waste type is one of the fastest-growing waste streams due to the global economic development and urbanization process. The rapid progress of the market-oriented production

Ivana Jelić – Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia (e-mail: ivana.jelic@vin.bg.ac.rs).

Marija Šljivić-Ivanović – Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia (e-mail: marijasljivic@vin.bg.ac.rs).

Tatjana Miljojčić – Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia (e-mail: tatjana.miljojcic@vin.bg.ac.rs).

Milica Ćurčić– Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia (e-mail: milica.curcic@vin.bg.ac.rs).

Slavko Dimović – Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia (e-mail: sdimovic@vin.bg.ac.rs).

economy, industrialization, and population growth generate millions of tons of C&DD per year. This waste type counts the highest percentage of waste worldwide, approximately 75% [1].

Since C&DD represents a significant part of the waste stream, it is aimed for necessarily waste reduction or recycling. C&DD presents a considerable amount of building materials that could be reused or renew, avoiding non-renewable raw materials depletion in the construction sector. This significant recovery and recycling potential is lost via a lack of waste collection facilities or poor recycling practices. Therefore, it is necessary to develop more attractive and low-cost methods and create more valuable conventional and novel technologies that could more efficiently use these wastes and solve possible environmental problems. Resource efficiency and the circular economy concept play an essential role in environmental and economic policy, as well as so-called "6R" principles in sustainable supply chain design (reduce, reuse, recycle, recover, redesign and remanufacture) [9].

Clean C&DD, without plastic, metal, rubber, and wood, is recycled into quality construction material, most often in the form of (unbound) aggregates. C&DD utilization is also increasingly popular in scientific research since it represents a sustainable and environmental-friendly solution. Waste materials utilization reduces the exploitation of non-renewable natural resources and the exploitation of various forms of energy to synthesize or modify natural raw materials or artificial materials. Availability and cost-effectiveness are of great importance for C&DD multipurpose utilization.

Benefits of C&DD reuse & recycling:

- Cost-benefit – lower disposal fees, less need to purchase new materials;
- Natural resources conservation;
- Slowing down the rate at which landfills reach capacity;
- Reducing methane emissions created when landfilled materials break down.

In particular, nowadays, there is a market for aggregates derived from C&DD, such as road base materials, drainage structures, and other construction projects, but its utilization potential is still under-used. Many studies have dealt with C&DD application possibilities in order to develop acceptable utilization techniques. A promising alternative recycling option appears to be offered by alkali-activated materials, i.e. geopolymers, incorporating C&DD as inert aggregates or partially reactive materials. Since geopolymers were shown substantial flexibility in various industrial wastes and by-products utilization, the use of C&DD in these binders has been extensively investigated, with encouraging results.

According to data, the immobilization of radionuclides in the waste-based geopolymers was rarely investigated, unlike very comprehensive research on heavy metals [13]. However, the advantage of these waste-based materials represents the possibility of using any waste containing aluminosilicate, which could be dissolved in an alkaline solution to obtain a matrix for immobilization of radionuclides.

II. C&DD UTILIZATION WORLDWIDE

As mentioned, the most widespread and economically viable solution for the reuse of C&DD today is the use in civil engineering and the road industry. Globally, there is a strong tendency to use recycled building materials exclusively in the same industry rather than expanding to other sectors.

The global demand for natural aggregates production of concrete is projected to grow by an average of 8% per year by 2022 [10]. Developing countries drive a significant portion of this demand as a result of their rapid industrialization and urbanization growth. The utilization of recycled aggregates (Fig. 2) from C&DD (concrete, bricks, tiles, plastics, etc.) could significantly help conserve natural resources and reduce waste disposal, which gains environmental and economic benefits. Though the incorporation of recycled aggregates from C&DD remarkably decreases the environmental impact and carbon footprint of concrete, the utilization of these aggregates in construction activities in developing countries is yet limited. The main reason is the lack of certainty in the properties of concretes or other construction materials with C&DD recycled aggregates under exploitation conditions. Thus, the use of recycled aggregates, manufactured from recycled products, to replace virgin aggregates and contribute to sustainable construction needs to be encouraged [11-12].

Fig. 2. Recycled Concrete Aggregates [11]

III. C&DD IN GEOPOLYMERS

Ordinary Portland cement (OPC), as the primary ingredient commonly used to prepare concrete binders, requires intensive energy in its production and produces a considerable amount of carbon dioxide and greenhouse gases. It is estimated that the cement industry contributes approximately 5% of global environmental pollution through carbon dioxide emissions [14]. With an estimated annual growth of 4% in cement production [15], carbon dioxide emissions will increase and cause additional environmental burdens [16]. Contrarily, geopolymer is featured with low greenhouse-gas emissions, less energy consumption, and reuse of waste materials, which is critical to future sustainability [17].

The standard procedure for radionuclide immobilization today is transformation into stable insoluble forms by matrix materials (solidification), most often in cement-based matrices.

The term geopolymer and its description as cement-free green cementitious material was coined nearly three decades back by Davidovits for alumino-silicate polymers formed in the alkaline environment [18]. Geopolymerization technology has been shown advantages in reusing various types of waste to produce new materials for many purposes. These so-called inorganic polymers have been proposed to utilize solid aluminosilicate waste and the development of new cementitious materials that could be made without OPC [19]. It is a novel family of building materials, a new material for coatings and adhesives, new binders for fiber composites, waste encapsulation, and new cement for concrete [20].

Geopolymers have attracted attention due to the simplicity of synthesis with low or zero greenhouse gas emissions [10,12]. Hence, the utilization of waste-based geopolymers could show many advantages such as usage of low-cost materials in production, e.g. slags, fly ash, clays, saving natural resources, ambient temperature production, and high compressive and flexural strengths, in particular as compared to cement [18-19]. All these characteristics are placing geopolymers in a category of eco-friendly and sustainable materials.

The chemical composition of geopolymer is somewhat similar to zeolites but with an amorphous microstructure. Unlike OPC/pozzolanic cement, geopolymers do not form calcium-silicate-hydrates (C-S-H) for matrix formation and strength but utilize the poly-condensation of silica and alumina precursors to attain structural strength. Davidovits [21] elucidated a structural model of the geopolymer and assumed an essentially monolithic polymer similar to organic polymers. (Fig. 3).

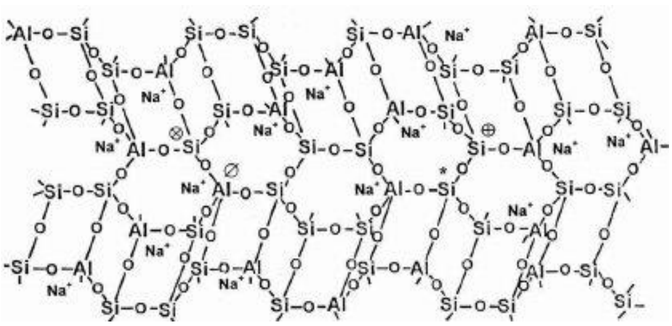


Fig. 3. Davidovits model of geopolymer structure [21]

Scientific publications provide a wealth of information relevant to productive C&DD usage in geopolymerization as processing technologies for value-added products.

Geopolymers based on C&DD differ in debris composition. Since its composition varies, there are many potential types of geopolymeric structures.

Fig. 4. Fly ash-based geopolymers [22]

Hence, there are several possible ways to use C&DD in geopolymers, as:

- recycled aggregates [4,23],
- activating component (precursors) [24-25] depending on the composition (e.g. bricks), and as
- hybrid system: with some aluminosilicate material with better geopolymerization capacity (e.g. metakaolin) or OPC [26].

The binary systems with OPC are synthesized due to the increase in geopolymer compressive strength in cases when it is assumed that geopolymerization will not be enough [26]. For example, this is the case with concrete debris, which is considered not to geopolymerize well due to its predominant participation of calcium carbonate in composition. Namely, the lack of aluminosilicate in almost pure concrete debris would lead to geopolymer non-creation. It was concluded that the addition of OPC in the geopolymerization processes contributed to the better mechanical behavior observed in the hybrid and binary systems. Although the use of cement is unfavorable from an energy point of view, this can affect the more significant usage of debris whose quantities are large, but geopolymerization is low.

However, it is more common for C&DD-based geopolymers to be synthesized with other aluminosilicates, especially waste-based material such as fly ash (Fig. 4) or other industrial waste: furnace slag, red mud, coal slag, etc. [4,27-29].

The stated utilization of C&DD allows the synthesis of a wide range of matrices for the immobilization of radionuclide.

IV. Conclusion

Recycling C&DD into sustainable and energy-efficient construction materials is a viable approach to relieve the stress of pollution and conserve virgin resources for the next generation. This study has reviewed the applications of C&DD as substitute materials in manufacturing sustainable geopolymer composites, specifically in the form of partial or even complete substitution of precursors or aggregates.

All results from cited studies suggest that waste-based geopolymers represent promising materials, but more thorough investigations are needed, especially for the utilization in radionuclide immobilization.

Acknowledgment

The research presented in this paper was done with the financial support of the Ministry of Education, Science and

Technological Development of the Republic of Serbia, within the funding of the scientific research work at the University of Belgrade, Vinca Institute of Nuclear Sciences (Contract No. 451-03-9/2021-14/ 200017).

REFERENCES

[1] V. A. Mymrin, K. P. Alekseev, R. E. Catai, R. L. S. Izzo, J. L. Rose, A. Nagalli, , C. A. Romano, "Construction material from construction and demolition debris and lime production wastes", *Constr. Build. Mater.*, vol. 79, pp. 207-213, 2015.

[2] O. Zimbili, W. Salim, M. A. Ndambuki, "Review on the usage of ceramic wastes in concrete production", *Int. J. Civ. Archit. Struct. Constr. Eng.*, vol. 8, pp. 91-95, 2014.

[3] EEA, Construction and demolition waste: challenges and opportunities in a circular economyhttps://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges

[4] M. Panizza, M. Natali, E. Garbin, S. Tamburini, M. Secco, "Assessment of geopolymers with Construction and Demolition Waste (CDW) aggregates as a building material", *Constr. Build. Mater.*, vol. 181, pp. 119-133, 2018.

[5] M. Medineckienė, Z. Turskis, Z. Kazimieras, E. Zavadskas, "Sustainable Construction Taking into Account the Building Impact on the Environment", *J. Environ. Eng. Landsc. Manag.*, vol. 18, no. 2, pp. 118-127, 2010.

[6] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, X. Zhang, "Carbon emission of global construction sector", *Renew. Sust. Energ. Rev*., vol. 81, pp. 1906-1916, 2018.

[7] United States Environmental Protection Agency (EPA), National Overview: Facts and Figures on Materials, Wastes and Recycling, https://www.epa. gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

[8] C&D Debris Recycling Study: Final Report, https://floridadep.gov/sites/default/files/CDreport5-8.pdf

[9] S. Sakai, H. Yoshida, Y. Hirai, M. Asari, H. Takigami, S. Takahashi, K. Tomoda, M. V. Peeler, J. Wejchert, T. Schmidt-Unterseh, A. Ravazzi Douvan, R. Hathaway, L. D. Hylander, C. Fischer, J. G. Oh, L. Jinhui, N. C. Chi, "International comparative study of 3R and waste management policy developments", *J. Mater. Cycles Waste Manag*., vol. 13, pp. 86-102, 2011.

[10] M. C. Collivignarelli, G. Cillari, P. Ricciardi, M. C. Miino, V. Torretta, E. C. Rada, A. Abbà, "The Production of Sustainable Concrete with the Use of Alternative Aggregates: A Review", *Sustainability*, vol. 12, no. 7903, 2020.

[11] K. McNeil, T. H. K. Kang, "Recycled Concrete Aggregates: A Review", *Int J Concr Struct Mater*, vol. 7, pp. 61-69, 2013.

[12] A. Noorul, M. Faisal, K. Muhammad, S. Gul, "Synthesis and characterization of geopolymer from bagasse bottom ash, waste of sugar industries and naturally available China clay", *J. Clean. Prod*., vol. 129, pp. 491-495, 2016.

[13] T. Cheng, M. Lee, M. Ko, T. Ueng, S. Yang, S. The heavy metal adsorption characteristics on metakaolin-based geopolymer. Appl. Clay Sci., vol. 56, pp. 90-96, 2012.

[14] R. M. Andrew, "Global CO_2 emissions from cement production", *Earth Syst. Sci. Data*, vol. 10, pp.195–217, 2018.

[15] G. H. Kusuma, J. Budidarmawan, A. Susilowati, "Impact of Concrete Quality on Sustainability", *Procedia Eng*., vol. 125, pp. 754-759, 2015.

[16] S. Dadsetan, H. Siad, M. Lachemi, M. Sahmaran, "Construction and demolition waste in geopolymer concrete technology: a review" *Mag. Concr. Res*., vol. 71, no. 23, pp. 1232-1252, 2019.

[17] Z. Tang, W. Li, V. W. Y. Tam, C. Xue, "Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials", *Resour Conserv Recy*, vol. 6, no. 100036, 2020.

[18] J. Davidovits, "Geopolymers", *J. Thermal Anal*., vol. 37, pp. 1633-1656, 1991.

[19] J. L. Provis, "Geopolymers and other alkali activated materials: why, how, and what?", *Mater.Struct*., vol. 47, pp. 11-25, 2014.

[20] R. Cioffi, L. Maffucci and L. Santoro "Optimization of geopolymer synthesis by calcinations and polycondensation of a kaolinitic residue Resources", *Resour Conserv Recycl*, vol. 40, pp. 27-38, 2003.

[21] J. Davidovits, "Solid phase synthesis of a mineral block polymer by low temperature polycondensation of aluminosilicate polymers", IUPAC International Symposium on Macromolecules Stockholm; Sept. Topic III, New Polymers of high stability, 1976.

[22] S. Thokchom, P. Ghosh, S. Ghosh, "Performance of Fly ash Based Geopolymer Mortars in Sulphate Solution", J. Eng. Sci. Technol, vol. 3, no. 1, pp. 36-40, 2010.

[23] Z. Abdollahnejad, M. Mastali, M. Falah, T. Luukkonen, M. Mazari, M. Illikainen, "Construction and Demolition Waste as Recycled Aggregates in Alkali-Activated Concretes", *Materials*, vol.12, no. 4016, 2019.

[24] O. Şahin, H. İlcan, A. T. Ateşli, A. Kul, G. Yıldırım, M. Şahmaran, Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing", *Cem Concr Compos*, vol. 121, no. 104088, 2021.

[25] D. Kioupis, A. Skaropoulou, S. Tsivilis, G. Kakali, "Valorization of Brick and Glass CDWs for the Development of Geopolymers Containing More Than 80% of Wastes", *Minerals,* vol.10, no. 672, 2020.

[26] A. Vásquez, V. Cárdenas, R. A. Robayo, R. M. de Gutiérrez "Geopolymer based on concrete demolition waste", Adv Powder Technol, vol. 27, no. 4, pp. 1173-1179, 2016.

[27] N. M. Azad, S. M. Samindi, M. K. Samarakoon, "Utilization of Industrial By-Products/Waste to Manufacture Geopolymer Cement/Concrete", *Sustainability*, vol. 13, no. 2, pp. 873-879, 2021.

[28] S. R. Zedan, M. R. Maha, A. A. Doa, M. H. Aya, "Effect of demolition/construction wastes on the properties of alkali activated slag cement", *HBRC*, pp. 331-336, 2017.

[29] B. A. Ionescu, A Lzrescu, "A Review Regarding the Use of Natural and Industrial by-products in the Production of Geopolymer Binders", *Mater. Sci. Eng*., vol. 877, no. 012033, 2020.

A Strategic Means of Hybrid Warfare

Milica Ćurčić, Slavko Dimović, Ivan Lazović

*Abstract***—The modern security environment is undergoing a profound transformation. This transformation has been shaped by the emergence of new patterns of conflict and cooperation among state and non-state actors as well as the spread of globalization and new technologies. Also, the development of a new breed occurred, characterized by a combination of warfare methods and usage of different means of warfare. In the constellation of new wars, a hybrid wars stand out as a war that combines different strategies of warfare to achieve synergistic effects. The aim of the article is to analyze and describe characteristic of both non-state and state hybrid warfare, as well as the key elements that constitute strategic means of hybrid warfare. The usage of information weapons, cyber sphere and psychological means, in combination with conventional weapons of war, become main features of modern conflict. Modern technologies are the main factor that influenced and transformed warfare and their usage permeates every activity in hybrid war.**

***Index Terms* — Hybrid warfare, war, means of warfare, security, strategy, new technologies**

I. Introduction

Clausewitz's observation that war is "a merely continuation of policy by other means" [1] has become an incontestable maxim among security experts. During history, war occurred among centralized, hierarchically ordered, territorialized states in which big armies confronted each other on the battlefield, using similar strategies, tactics, and weapons. The war is still present in international relations, but with different forms and characteristics.

The nature of warfare is changing and as Williams noticed, there are three issues important to discuss: how useful is the concept of 'total war' for thinking about developments in warfare? What is the relationship between war and globalization; specifically, has globalization given rise to a 'new' type of warfare? What changes can be identified in the way advanced industrialized democracies in the West are waging war today compared to earlier historical periods? [2]

The post-cold war period is characterized by the emergence of non-state actors, new threats that are combined with globalization factors and the usage of sophisticated technology. In order to find a new analytical framework for understanding the nature of modern wars, new paradigms had been constructed. Those concepts are seeking to understand an ambiguous border between war and peace because from the perspective of modern wars, wartime, peacetime and crisis do not exist as separate phases [3]. In a more practical way, the main dilemma arises from questions of how it is possible for a weaker actor to win a war against a significantly stronger and more powerful enemy and how a stronger actor should oppose to a weaker one in an asymmetric conflict.

One of the basic characteristics of modern wars is the use of new means of warfare that avoid predictability and linear military operations. Technological progress has conditioned changes in all spheres of life, including conflict, wars and military operations. The new technologies allow the possibility to achieve strategic goals by unconventional and cognitive effects (technologies of social influence and manipulation, cyber sphere, information weapon, possibilities of significant damage of control system of a state) [4]. Those technologies appear to be increasingly adaptive and sophisticated, able to outpace state-based militaries in the dialectic and competitive learning cycle inherent to wars [5]. Technological advancements have furthered weapons and platform development, but also introduced new capabilities and vulnerabilities in the security arena, that additionally increase the complexities of contemporary conflicts.

II. Hybrid War as a New Form of Warfare

The security architecture of the modern world focuses on threats such as terrorism and radicalization, nonproliferation of WMD, securitization of migration, cyber and ecological threats etc. Most of these threats are dominantly posed by different non-state actors. Also security agendas introduce new types of wars that cannot be defined as conventional, traditional or classical wars. In order to clarify the different types of war in a contemporary security environment, as well as their basic characteristics, a number of scholars have attempted to define new types of war. In the literature we can find terms Unconventional war [6-8], Irregular war [5, 9], Fourth Generation of War [10-11], Unrestricted War [12] Compound War [13] and Asymmetric War [14-16]. All this approaches of modern war in different ways are pointing at the blurring of subjects, objects and dynamics in contemporary conflicts.

The following variables are most commonly used to determine the characteristics of modern wars: the main protagonists and units of analysis of war - states or non-state actors; the primary motives of actors (ideology, territorial secession, religion etc.); the spatial ranges: interstate, regional, or global; the technological means of violence – weapons and strategies of war; the social, material, and human impact of conflict, including patterns of human victimization and forced

Milica Ćurčić – Department of Physical Chemistry, "Vinca" Institute of Nuclear Sciences - National Institute of Republic of Serbia, University of Belgrade, Belgrade, Serbia (e-mail: milica.curcic@vin.bg.ac.rs).

Slavko Dimović – Department of Radiation and Environmental Protection "Vinca" Institute of Nuclear Sciences - National Institute of Republic of Serbia, University of Belgrade, Belgrade, Serbia (e-mail: sdimovic@vin.bg.ac.rs).

Ivan Lazović – "Vinca" Institute of Nuclear Sciences - National Institute of Republic of Serbia, University of Belgrade, Belgrade, Serbia (e-mail: ivan.lazovic@vin.bg.ac.rs).

human displacement; the influence of the political, economic and social structure on conflict [17].

The „hybrid war" emerged as the newest kind of war during the first decade of the 21st century by key scholars who focused on "the blending or blurring character of conflict" [18]. This term was first used in 2006 to describe the strategy that Hezbollah used in the Lebanon war. Mixing an organized political movement with decentralized armed cells employing adaptive tactics in ungoverned zones, Hezbollah affirms an emerging trend. Highly disciplined, well-trained, distributed cells can contest modern conventional forces with an admixture of guerrilla tactics and technology in densely packed urban centers [19]. In this conflict Hezbollah conducted several technological surprises on Israeli forces. Hezbollah's fighters bypassed the complex surveillance system used by Israel to monitor its border with Lebanon led to the kidnapping of two Israeli soldiers and the killing of eight. The firing of a Noor anti-ship cruise missile (an Iranian version of the Chinese C-802) resulted in the loss of four Israeli sailors and the crippling of an Israeli missile ship. Two Merkava IV tanks were destroyed and their crews killed or wounded, probably by a combination of Raad anti-tank missiles (the Iranian version of the Russian Sagger AT-3) and advanced improvised explosive devices (IEDs) [20].

This case demonstrated the ability of a non-state actor to deconstruct the vulnerability of not only a powerful state, but Western-style militaries [21]. The increased number of actors, who innovatively combine different models of war, capacities and weapons in order to achieve strategic goals, has created fertile ground for the introduction of concept which explains characteristics of modern warfare. In that manner, hybrid war is becoming the dominant discourse in discussions of modern warfare as well as accepted and promoted by politicians, military experts and theorists as the basic concept of modern military strategies [22].

The term 'hybrid warfare' was introduced in theory by Frank Hoffman, a former US Marine officer, to influence on ingrained and outdated beliefs in the US military about the utility of military force in the post-Cold War environment. In Hoffman's view, hybrid warfare was a suitable analytical construct to explain the success of a relatively weak opponent, such as the Taliban, Al Qaeda, or Hezbollah, against the vastly technologically and numerically superior militaries both in Afghanistan and Iraq and in the 2006 Lebanon war against Iraq and Israeli forces [23]. Hoffman define hybrid war as a type of war that "incorporate a range of different modes of warfare, including conventional capabilities, irregular tactics and formations, terrorist acts including indiscriminate violence and coercion and criminal disorder. Hybrid war can be conducted by both states and variety of non-state actors" [18].

What makes a war "hybrid" and divers from other modern war is coordinated fusion of different modes of warfare, both military (use of force) and non-military (violence, irregular tactics, criminal disorder, terrorist acts), to achieve synergistic effects in the physical and psychological dimensions of conflict within the main battle space [18].

The evolution of hybrid warfare has two phases so far. The first phase is called non-state hybrid war, as it involves the action of non-state actors that combines conventional forces, whose actions are regulated by the rules and norms of law and traditional military custom, with unconventional forces that conduct operations of guerrilla warfare, terrorist activities and criminal activities. Characteristics of this phase of hybrid war are: non-state exhibit increased levels of military sophistication as they successfully develop modern weapons systems (such as anti-ship missiles, UAVs), new technologies (cyber, secure communication, sophisticated command and control), and tactics (combined arms) that are traditionally considered to be outside range of such actors. Non-state actors expanded the battlefield beyond the purely military realm and show the growing importance of non-military tools by including elements of information warfare (e.g. controlling the battle of the narrative and online propaganda, recruitment and ideological mobilization [24].

The second phase of the evolution of the term hybrid war called state hybrid war begins with the Ukrainian crisis and the Russian annexation of Crimea in 2014. Russian operations demonstrate that hybrid warfare can be conducted with great success by state actors. The main characteristics of Russian operation in Crimea as a prototype of the second phase of hybrid warfare are:

- non-declaration of the state of war;
- non-contact clashes between highly maneuverable interspecific fighting groups;
- annihilation of the enemy's military and economic power by short-time precise strikes in the strategic military and civilian infrastructure;
- massive use of high-precision weapons and special operations, robotics, and weapons that use new physical principles (direct-energy weapons – lasers, shortwave radiation, etc);
- use of armed civilians;
- simultaneous strike on the enemy's units and facilities in all of the territory;
- simultaneous battle on land, air, sea, and in the informational space.
- use of asymmetric and indirect methods;
- management of troops in a unified informational sphere [25]. Usage of non-military means, especially the use of information surprised Ukraine and represented significant factors for the realization of Russian plans in Crimea and announced future trends in warfare.

This transformation of used means surprised even Hoffman, whose definition of hybrid warfare is limited to a combination of tactics related to violence and irregular way of warfare between state and non-state actors. His definition did not recognize non-violent and non-military instruments like diplomatic, economic and financial activities, subversive political acts such as the creation or secret use of trade unions and non-governmental organizations as a front of actions, or information and propaganda operations through the use of fake websites and newspaper articles [22].

As Figure 1 shows hybrid warfare differs from other types of war in their initiation and prosecution, involve various sphere of social action, employee different strategies and means. Hybrid warfare is directed towards the whole society with the aim of destabilization and polarization. In this type of war, not only the military weaknesses are essential but also those that only society can generate: ethnic tensions, weak and corrupt institutions, economic or energy dependence. Based on these weaknesses, hybrid war applies on the full spectrum of activities ranging from media propaganda to terrorism through irregular and unassumed warfare [26].

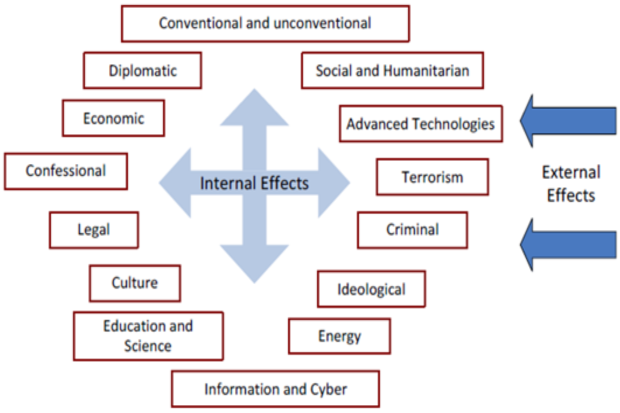


Fig 1. Hybrid warfare spheres [4]

III. The Impact of New Technologies on Hybrid Warfare

At the strategic level, the hybrid theory of warfare can be seen as the employment of information operations and diplomacy in conjunction with cyber and electronic operations to weaken an opponent or to sow the seeds of chaos in relation to an adversary [27]. In addition to traditional wars, hybrid wars are not declared and, therefore, cannot be completed in the classical sense of military conflicts. This is a permanent war of variable intensity across multiple sectors, with cascading impacts and synergistic destructive manifestations, in which the entire population of the country is involved. An essential feature of this concept is the diminished role of military content, more precise usage of armed struggle. Unlike the classic war conflicts, in which concepts based on the mass use of armed force were dominated, minimized often disguised military hard power is the most significant novelty in the history of warfare introduced by hybrid warfare [28].

Through the use of innovative technologies, it became possible to shift conflict from predominantly overt and forceful (kinetic) means to less obvious strategies focused on the structural vulnerabilities of adversaries, including achieving cognitive advantage over them [4]. Widespread usage of new technologies should provide reduction of hard military power to minimum creating a distorted image of the real attacker. In that way, modern technologies were the main factor that influenced and transformed warfare.

Hybrid war in Ukraine shows that the main battlefield is human mind so the most important elements of modern war become information and psychological means. Wide-ranging, multidimensional and by employing multifactorial information, hybrid warfare in Ukraine included applying of highly technological samples of weapons and military hardware. Y. Danyik et all in the paper [4] identifies some of the most important areas of information technology involved in hybrid warfare:

1. electronic warfare systems and complexes;
2. modern information and communication systems;
3. innovative weapon control systems;
4. integrated reconnaissance-strike complexes;
5. innovative software;
6. complexes for conducting information-psychological activities and actions in cyber space
7. environmental control and space systems;
8. robotic systems (especially unmanned aircraft complexes).

All modern country are highly depended on various information infrastructure and information-based resources including complex management systems and infrastructures involving the control of electric power, money flow, air traffic, oil and gas, and other information-dependent item [29]. The development and use of new, and especially information technologies is a determinant of the state development, but also the most important means in the application of measures and countermeasures in hybrid warfare.

Ukrainian hybrid war demonstrates the complexity of strategy that includes military and nonmilitary means relying on new technologies at every stage of operation. Moscow employed methods that blended conventional and irregular combat, economic coercion, sponsorship of political protests, and the now notorious disinformation campaign [30]. Also, different technologies were use simultaneously as a part of strategically design campaign with main goal of undermining public confidence in the government. Bērziņš, identified eight phases of Russian hybrid strategy:

1. non-military means (encompassing information, moral, psychological, ideological, diplomatic and economic measures);
2. special operations carried out by media, diplomatic channels, top government and military agencies to mislead political and military leaders (can include leaking false data, orders, directives, and instructions);
3. intimidating, deceiving and bribing government and military officers with the objective of making them abandon their service duties;
4. use of destabilizing propaganda to increase discontent among the population (can be further enhanced by the arrival of ‘volunteers’, escalating subversion);
5. establishment of no-fly zones over the targeted country, imposition of blockades, extensive use of private military contractors and armed opposition;
6. commencement of military action, immediately preceded by large-scale reconnaissance and subversive missions of all types (including special operations forces; space, radio, radio engineering, electronic, diplomatic and secret service intelligence; and industrial espionage);
7. targeted information, electronic warfare and aerospace operations along with continuous air-force harassment, combined with the use of high-precision weapons launched

from various platforms (long-range artillery and weapons based on new physical principles, including microwaves, radiation, radiological and ecological disasters and non-lethal biological weapons);

8. crushing the remaining points of resistance and destroying surviving enemy units by using special operation units. [25]

Those are phases of war that Russians refer as "new generation of warfare" directed against Western influence in the world. While the Chinese concept of 'unrestricted warfare' was aimed at identifying ways to counter the West's overwhelming hard and soft power through asymmetric means, the Russians concept of warfare is the answer on tolls that Western use: liberalism, international institutions, non-governmental organizations, and strategic communication [30]. Hybrid warfare, or new generation of war demonstrated tremendous success by usage of a sophisticated blend of psychological warfare, cyber - attacks, strategic communication, disinformation campaign and covert troops. The further risks also arise from the circumstances that nuclear states do not directly confront each other by traditional means. The doctrinal turnover that includes strategic means of hybrid warfare, as well as military modernization of states, creates a new kind of security dilemma. In that sense, nuclear security based on the concept of nuclear deterrence should be reconsidered in the context of hybrid warfare. Hybrid warfare ignores a key concept that builds nuclear deterrence as a viable strategy including concepts of stability, preparedness, clarity and rationality.

IV. Conclusion

Warfare is sui generis a socio-historical phenomenon with a pronounced technological component. Definition of war modified with the change of social circumstances and due to technological progress. In the last two decades, this definition expanded to incorporate non-state actors, cyber warfare and usage of non-military means. The blending of all used means of waging the war is what distinguishes hybrid war from other historical forms. The mind becomes the main battlefield of the 21st century which puts focus on information and psychological means of warfare. In the further transformation of hybrid war, the tendency will be on in developing strategies and means how to first defeat adversary mentally by the usage of non-military means. The main goal of modern warfare is the reduction of hard military power and defeating the enemy in the short term without human losses, which hybrid warfare perfectly demonstrates.

Acknowledgment

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia, as the part of theme "Fundamental and applied aspects of electrocatalysis in energy systems and green technologies", within the program Energy and energy efficiency, which are realized in the "Vinča" Institute of Nuclear Sciences - National Institute of Republic of Serbia, University of Belgrade, Belgrade, Serbia.

References

[1] C. V. Clausewitz, "On War", Oxford University Press, Oxford, 2007.
[2] P. D. Williams, "On War", *In Security Studies – An Introduction.* Routledge, London and New York, pp. 151-170. 2008.
[3] G. Razma, "Modern Warfare Paradigm: Reconsideration of Combat Power Concept. Journal of Security and Sustainability Issues. Vol. 8, No.3, pp. 435-452. 2019.
[4] Y. Danyik, T. Maliarchuk, C. Briggs. "Hybrid War: High-tech, Information and Cyber Conflict". *The Quartely Journal*, Vol. 10, No. 2, pp.5-24. 2017.
[5] F. G. Hoffman. "Complex Irregular Warfare: The Next Revolution in Military Affairs". *Orbis*, Vol. 50, No. 3, pp. 395-411, 2006.
[6] YA. C. Janos, "Unconventional Warfare: Framework and Analysis", *World Politics*, Vol. 15, No. 4, pp. 636-646, 1963.
[7] K. Knorr, "Unconventional Warfare : Strategy and Tactics in Internal Political Strife", *The Annals of the American Academy of Political and Social Science*, Vol 341, Issue 1, pp. 53-64, 1962.
[8] D. Kilcullen, "The Evolution of Unconventional Warfare". *Scandinavian Journal of Military Studies*, Vol. 2, No. 1, pp. 61–71. 2019.
[9] C. S. Gray, "Irregular Warfare: One Nature, Many Characters", *Strategic Studies Quarterly*, Vol. 1, No. 2, pp. 35-57, 2007.
[10] W. S. Lind, K. Nightengale, J. F Schmitt, J. W. Sutton, Gary I. Wilso, "The Changing Face of War, Into the Four Generation", *Marine Corps Gazette*, 1989.
[11] W. S. Lind, "Understanding Fourth Generation of War", *Military Review*, 2004.
[12] Q. Liang, W. Xiangsui, *Unrestricted Warfare*. Beijing, PLA Literature and Arts 1999.
[13] T. Huber, "Compound Warfare: A Conceptual Framework", *Compound Warfare: That Fatal Knot*, U.S. Army Command and General Staff College Press, Kansas, 2002, 1-11.
[14] D. Buffaloe, *Defining Asymmetric Warfare*, The Institute of Land Warfare, Virginia, 2006.
[15] A. Lele, "Asymmetric Warfare: A State vs Non-State Conflict", *OASIS*, No. 20, 2014, 97-111.
[16] M. Ćurčić, Asymmetric Threats in Security Studies in *Asymmetry and Strategy - Thematic Collection of Articles*. Strategic Research Institute and National Defence School, Belgrade, pp. 17-31, 2018.
[17] E. Newman, "The 'New Wars' Debate: A Historical Perspective Is Needed. *Security Dialogue*. Vol. 35, No. 2, pp. 173–189. 2004.
[18] F. G. Hoffman, Conflict in the 21st Century – The Rise of Hybrid Wars, Potomac Institute for Policy Studies, Arlington, Virginia, 2007
[19] F. G. Hoffman, "Lessons from Lebanon: Hezbollah and Hybrid Wars", Foreign Policy Research Institute, E-notes, 2006. Internet: https://www.fpri.org article/2006/08/lessons-from-lebanon-hezbollah-and-hybrid-wars/ Access: 29.05.2021
[20] G. Ben-Ari, "*Technological Surprise and Technological Failure in the Current Lebanon Crisis*". Center for Strategic and International Studies. Wachington D.C. 2006.
[21] M. Vračar, M. Ćurčić, "The Evolution of European Perception of the term „Hybrid Warfare", *Vojno delo*, Vol. 1, pp. 5-21. 2018.
[22] M. Ćurčić, "Hibridni ratovi u savremenom bezbednosnom okruženju" *U Hibridno ratovanje - dilema koncepta savremenh sukoba*, Beograd, Srbija, 2018, 47-62.
[23] B. Renz, "Russia and 'hybrid warfare". *Contemporary Politics*. pp. 1-18. 2016.
[24] E. Reichborn-Kjennerud, P. Cullen, *What is Hybrid Warfare*, Policy Brief No.1. Norwegian Institute of International Affairs, 2016.
[25] J. Berzins, J. *Russia's New Generation Warfare in Ukraine: Implications for Latvian Defense Policy*, Policy Paper No. 2, Riga, National Defense Academy of Latvia, 2014.
[26] M. M. Neag, "A New Typology of War – The Hybrid War", *Revista Academiei Forţelor Terestre*, No. 1, pp. 15-20, 2016.
[27] A. C. Fox. *Hybrid Warfare: The 21st Century Russian Way of Warfare*. School of Advanced Military Studies United States Army Command and General Staff College Fort Leavenworth. Kansas. 2017.

[28] M. Vračar, “Razmatranje adekvatnog teorijsko-epistemološkog pristupa u istraživanju fenomena hibridnog ratovanja“. *Vojno delo*, No. 7, str. 292-307. 2017.

[29] R. C. Molander, A. S. Riddile, P. A. Wilson, *Strategic Information Warfare – A New Face of War*. National Defense Research Institute. 1996.

[30] S. Hadjitodorov, M. Sokolov, “Blending New-generation Warfare and Soft Power: Hybrid Dimensions of Russia-Bulgaria Relations“. *Connections: The Quarterly Journal*. No. 1, pp. 5-20, 2018.

Standard and validated method for determination of tritium on Liquid scintillation spectrometer

Marija Janković, Nataša Sarap, Gordana Pantelić, Jelena Krneta Nikolić, Milica Rajačić, Dragana Todorović, Ivana Vukanac

***Abstract*—Tritium concentrations in water samples were analyzed. The aim is to compare methods: standard method (direct method): according to ASTM D 4107-08 and validated method: which applies electrolytic enrichment. Low level tritium concentration in natural waters required measurement after enrichment. One set of samples, which contain 16 samples including spike water were enrichment and compared with 4 samples measured by direct method. For this analysis liquid scintillation spectrometer was using. In general, analysis with enrichment is more applicable for samples with low activity. Also, validated method with enrichment reduced minimum detectable concentration.**

***Index Terms*—tritium, liquid scintillation spectrometer, water samples, enrichment.**

I. Introduction

Tritium (^{3}H), radioactive isotope of hydrogen, has half life of 12.3 years. ^{3}H has low beta energy with maximum of 18 keV and a mean energy of 5.7 keV. Its origin is naturally, from the upper atmosphere (stratosphere) where arises by interaction between fast neutron and nitrogen atoms, and artificially (produced from the nuclear reactor, atmospheric thermonuclear tests, nuclear weapons testing, nuclear reactors, fuel reprocessing plants, heavy water production facilities and commercial production for medical diagnostics, radiopharmaceuticals, luminous paints, sign illumination, self-luminous aircraft, airport runway lights, luminous dials, gauges and wrist watches) [1]. It can enter in hydrological cycle from precipitation and can enter in surface water and groundwater. From that reason, monitoring of tritium in natural water is necessary.

In water samples, tritium can be measured directly, after distillation, or after electrolytic enrichment of samples. Based on the fact that nowadays, concentration of tritium in natural water is low, it is necessary to concentrate the samples through enrichment. In the case of the assumption that the concentration is high, enrichment is not required.

This paper presents the comparison between different preparations of water samples which means using of standard method – direct method and validated method – method with electrolytic enrichment.

II. The Method

Total number of 15 water samples were collected in order to analyze tritium concentrations: 1 drinking water, November 2020, 9 precipitations (3 from referent meteorological station Zeleno Brdo in Belgrade (ZB), September, October and November 2020; 3 from station in Vinča Institute of Nuclear Sciences Site Center (CS), September, October and November 2020; 3 from station in Vinča Institute of Nuclear Sciences Meteo stub (MS), September, October and November 2020), 5 surface water (Sava, September and October 2020; Danube, October 2020; Mlaka Creek in Vinča Institute of Nuclear Sciences, October and November 2020).

Approximately 300 ml of each composite monthly sample are distilled to remove dissolved salts and organic impurities. The various ions that are naturally found in water (Cl^-, SO^{-4}, CO_3, Mg^{++}, Na^+, K^+, etc.) could interfere with the electrolysis process [2].

In the case where the direct method is applied the ASTM D 4107-08 standard method [3] is used. After preliminary distillation an aliquot of 8 ml of distillated samples is mix with 12 ml scintillation cocktail ULTIMA GOLD LLT in polyethylene vial (volume of vial is 20 ml).

In the case where validated method is applied [4], preliminary distillated samples must be enriched. Enrichment unit contains electrolytic cells, constant current supply unit and cooling unit. In one electrolysis run, a set of 16

Marija Janković, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: marijam@vinca.rs).

Nataša Sarap, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: natasas@vinca.rs).

Gordana Pantelić, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: pantelic@vinca.rs).

Jelena Krneta Nikolić, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: jnikolic@vinca.rs).

Milica Rajačić, University of Belgrade, Radiation and Environmental Protection Department, National Institute of the Republic of Serbia, University of Belgrade, Vinča Institute of Nuclear Sciences, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: milica100@vinca.rs).

Dragana Todorović, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: beba@vinca.rs).

Ivana Vukanac, University of Belgrade, Radiation and Environmental Protection Department, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11001 Belgrade, Serbia (e-mail: vukanac@vinca.rs).

electrolytic cells is connected in series and connected to a direct current source. Each enrichment run contains 16 samples, including 1 spike water (water of known tritium activity concentration used for enrichment factor determination). Each cell contains 250 ml of initial volume of the distillated sample. As an electrolyte, Na_2O_2 is used. In order to achieve approximately 10-15 ml of final volume of the samples, system works on 5 A. The enrichment operated with 5 A current could enrich approximately 1.7 g of water samples per hour. This means 5 days is necessary to enrich from 250 ml to 10-15 ml of water samples according to Faraday's factor.

An enrichment samples must be distilled again to remove electrolyte. After the second distillation an aliquot of 8 ml of the samples mix with 12 ml scintillation cocktail ULTIMA GOLD LLT in polyethylene vials.

For both methods, standard and validated, ultra-low-level liquid scintillation counter Quantulus 1220 is used. Measuring time of each sample is 300 min. Beside the samples, *dead water DW* (tritium free water) is also measured for background, as well as water of known tritium activity (*BEFORE BE*). *BEFORE*, after enrichment calls *SPIKE SW* water. Their ratio determines cell enrichment factor.

Counting efficiency is determined according to standard method [3]. For determination of efficiency, standard tritium solution ^{3}H 9031-OL-548/13 Czech Metrology Institute Type: ERX with activity 5.060 MBq on day 1.10.2013 is used. The tritium measurement uncertainty is expressed as the expanded measurement uncertainty for the factor k=2, which corresponds to a normal distribution with a confidence level of 95 %.

Minimum detectable activity (*MDA*) is measured using the following equation:

$$MDA = \frac{2{,}71 + 4{,}65\sqrt{R_b t_b}}{60 \varepsilon V t_b} \quad (1)$$

where R_b is background count rate (cps), t_b is background counting time (min), ε is efficiency (%) and V is volume of the *DW* (l). In case with enrichment, above equation is further divided by the electrolysis enrichment factor *Z*.

III. Section Title (e.g. Main Results)

For 15 natural water samples, validated method with electrolytic enrichment was performed in order to determined tritium activity. The obtained results are presented in Table 1. 1 drinking water, 9 precipitation samples and 5 surface water samples were analyzed. For the results shown from one electrolysis, it took 695 Ah to reduce initial volume of the samples to 13 ml (5.8 days at 5A). Calculated enrichment factor, *Z*, for this electrolysis is 13.2. Calculated *MDA* for this electrolysis is 0,23 Bq/l for background counts of 0.035 cps. Efficiency obtained by calibration of the spectrometer is 27.9 %.

Results for tritium activity in drinking water and precipitation from the reference meteorological station Zeleno Brdo are similar regardless of the month of sampling. Results obtained for precipitation at two locations in Vinča Institute of Nuclear Sciences, CS and MS are higher than results obtained for precipitation at ZB. This is in accordance with earlier results for tritium activity in precipitation for these locations [5-7]. In surface water samples, obtained results are different in relation to precipitation. Results for Sava and Danube are similar with values obtained for precipitation at MS. On the other hand, results for Mlaka Creek at location in Vinča Institute of Nuclear Sciences present higher values than surface water in Belgrade outside the Institute. These results are in accordance with previously results [5-7].

TABLE I
TRITIUM ACTIVITY CONCENTRATIONS IN WATER SAMPLES

Sample	Location	^{3}H (Bq/l) with enrichment	^{3}H (Bq/l) without enrichment
Drinking water	Belgrade	0.7 ± 0.2	
Precipitation	ZB IX 2020	1.2 ± 0.2	
	ZB X 2020	0.8 ± 0.2	5.4 ± 1.9
	ZB XI 2020	0.8 ± 0.2	
	CS IX 2020	3.1 ± 0.3	
	CS X 2020	3.0 ± 0.3	
	CS XI 2020	3.0 ± 0.3	
	MS IX 2020	1.6 ± 0.2	
	MS X 2020	1.7 ± 0.2	
	MS XI 2020	1.7 ± 0.2	
Surface water	Sava IX 2020	1.4 ± 0.2	
	Sava X 2020	1.2 ± 0.2	5.0 ± 1.9
	Danube X 2020	1.7 ± 0.2	5.0 ± 1.9
	Mlaka X 2020	5.4 ± 0.5	9.5 ± 2.0
	Mlaka XI 2020	5.4 ± 0.5	

For 4 samples: one precipitation, ZB, X 2020, and 3 surface water, Sava, X 2020, Danube, X 2020 and Mlaka Creek, X 2020 direct method for tritium analysis is performed. Results are presented in Table 1. As can be seen from the Table, values obtained for these samples which were measured directly are higher than values obtained for the same samples which were measured after enrichment. For this method, calculated *MDA* is 2.9 Bq/l for background counts of 0.033 cps. Efficiency is the same, 27.9 %.

For low level tritium activity it is evident that it is better to apply validated method, which also reduces the detection limit. In case it is certain that the activity of tritium is high the standard direct method can be applied. Especially because it is necessary to take into account that in case of expected high tritium values, contamination of the electrolysis system may occur.

In Serbia, legislation defines permitted values for tritum activity only for drinking water (100 Bq/l) [8]. In relation to this allowed value, all analyzed samples meet the criteria given by rulebook.

IV. Conclusion

Comparing standard and validated method for tritium determination in natural water samples, it can be concluded that validated method with electrolytic enrichment is more applicable for samples with low level tritium concentrations. Standard – direct method gives higher values and can be acceptable for expected high values of tritium. Method with enrichment also reduced minimum detectable activity. Liquid scintillation counting has proven to be irreplaceable in environmental tritium monitoring and for analysis of low level activity.

Acknowledgment

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

References

[1] "Investigation of the Environmental Fate of Tritium in the Atmosphere," in Part of the Tritium Studies Project, Info 0792, Canada, Minister of Public Works and Government Services Canada, Canadian Nuclear Safety Commission, 2009, Canada nuclear regulator, ISBN 978-1-100-13928-9

[2] Singh, A. Hussain, S.D. Khobragade "Analysis of isotope element by electrolytic enrichment method for ground water and surface water in Saurashtra region, Gujarat, India" Cogent Engineering, vol. 3, no. 1, 2016. DOI: 10.1080/23311916.2016.1164789

[3] ASTM D 4107-08 Standard Test Method for Tritium in Drinking Water

[4] Tecnical Procedure Note 19, Isotope Hydrology Lab., Procedure and Technique Critique for Tritium Enricment by Electrolysis at the IAEA Laboratory, IAEA 1976.

[5] M.M.Janković, D.J. Todorović, Z.Keleman, N.R. Miljević, "The measurement of tritium in water samples with electrolytic enrichment using liquid scintillation counter" Nuclear Technology & Radiation Protection, 27 (3) (2012), 239-246

[6] M.M. Janković, B.Ž. Janković, D.J. Todorović, Lj.M. Ignjatović, "Tritium concentration analysis in atmospheric precipitation in Serbia" Journal of Environmental Science and Health, Part A, 47(2012) 669-674.

[7] M.M. Janković, D.J. Todorović, "Examining the Relationships Between the Activities of ^{3}H in Precipitationand ^{137}Cs in Ground-Level Air in Belgrade City Area" Water Air & Soil Pollution, 223 (7) (2012) 4471-4483.

[8] Rulebook on Limits of Radionuclides Contentin Drinking Water, Foodstuffs, Feeding Stufffs, Medicines, Product for General Use, Construction Materials and Other Goods to be placed on Market (Official Gazette RS 36/18

HPGe detector efficiency optimization for the atypical measurement geometry of simulated aerosol filters

Jelena Krneta Nikolić*, Ivana Vukanac, Milica Rajačić, Dragana Todorović, Gordana Pantelić and Marija Janković

Abstract — **Gamma spectrometry is widely used method of choice for measurement of environmental samples conducted during monitoring of the environment and contamination control, as well as measurement of radionuclide content in various materials. However, one of the main challenges in this method of spectrometry is the determination of detection efficiency for different energies, different source-detector geometries and different composition of samples. This task is defined as an efficiency calibration of the detector. When using a commercial calibration sources is not possible, or the available sources are not adequate, the optimization of the efficiency calibration has to be performed.**

In this paper, the results of the optimization of efficiency calibration for the atypical geometry and composition of the simulated aerosol samples, measured within the Proficiency tests organized by International Atomic Energy Agency (IAEA), performed using EFFTRAN efficiency transfer software, will be presented and discussed.

Index Terms— **gamma spectrometry; efficiency calibration, EFFTRAN; optimization**

I. Introduction

Gamma spectrometry is one of the mostly often used measurement methods for determining the radionuclide content in various samples. It is a non-destructive method which can be applied for a wide range of environmental samples measured within the framework of a monitoring, as well as for contamination control.

This method is based on the interaction of gamma rays emitted from the sample with the active volume of the detector. Semiconductor detectors and among them, high purity germanium (HPGe) detectors, are mostly used due to their high sensitivity and good energy and time resolution. The result of a gamma spectrometric measurement is represented by the spectrum of photons originating from the source, that are collected by the multichannel analyzer (MCA) and the number of photons detected is proportional to the activity of the given radionuclide. The main challenge in this method of measurement is the determination of the detection efficiency which is dependent not only on the type of the detector and the energy of the emitted gamma photons, but also on the type of the measured sample: its geometry and chemical composition, the sample – detector geometry and the presence of the absorber. This task is defined as an efficiency calibration of the detector [1].

The most often used approach to the efficiency calibration is a direct measurement of different calibration sources containing γ-ray emitters and subsequent fitting of obtained results to a parametric function, thus obtaining the efficiency curve – a functional dependence of the efficiency with respect to the energy. Different sample types require different calibration curves. Due to that, this approach requires a large number of calibration sources, produced to mimic the real measured samples to the largest possible degree, which may not be available. This problem is especially pronounced when environmental samples are of interest due to their diversity in composition and structure [2].

When the sample of the atypical geometry or composition is presented, an optimization of the calibration curve using the means available in the laboratory has to be performed. One of the methods of optimization is the efficiency transfer using some type of software. The software calculates the efficiency transfer factors with which the original efficiency for a given energy needs to be multiplied in order to obtain the efficiency in the special case of the measured sample [3]. One of these software is EFFTRAN [4], a user friendly software that calculates efficiency transfer factors and coincidence summing correction factors for cylindrical samples.

In this paper, the results of the efficiency calibration for the atypical geometry and composition of the simulated aerosol samples, measured within the Proficiency tests organized by International Atomic Energy Agency (IAEA), performed using EFFTRAN efficiency transfer software,

Jelena Krneta Nikolić is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: jnikolic@ vin.bg.ac.rs).

Ivana Vukanac is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: vukanac@ vin.bg.ac.rs)

Milica Rajačić is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: milica100@ vin.bg.ac.rs)

Dragana Todorović is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: beba@ vinca.bg.ac.rs)

Gordana Pantelić is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: pantelic@ vin.bg.ac.rs)

Marija Janković is with the University of Belgrade, Institute for Nuclear Sciences Vinča, National Institute of Republic of Serbia, Radiation and Environmental Protection Department Mike Petrovića Alasa 12-14, Vinča 11000 Belgrade, Serbia (e-mail: marijam@ vin.bg.ac.rs)

will be presented and discussed.

II. Main Results and Discussion

A. Efficiency transfer

The calculations of the efficiency transfer factors are based on the assumption that the detector efficiency for the special case of measured sample can be obtained by multiplying the reference efficiency (obtained by measuring the commercial or laboratory calibration source) by the efficiency transfer factors. In order to calculate these factors, a set of partial differential equations needs to be solved. For the purpose of the efficiency transfer, in our laboratory, EFFTRAN software is often used. It is organized as an user friendly Excel file with three modules. The software performs the needed calculations using a Monte Carlo integration, given the specific data are provided.

The data that the software requires are the detector characteristics (crystal material, diameter and length, thickness of the dead layer, housing geometry and composition, material of the window and window to crystal gap,) and the characteristics of both calibration sample used for the reference calibration curve and the measured sample (the diameter, filling height and thickness of the container, chemical composition and density of the sample matrix). . Because the model of the sample, as well as the detector crystal, can be constructed from cylinders only, the only complex operation required in the code is the calculation of the path length traversed through a cylinder of given dimensions by a gamma photon originating from an arbitrary location [4].

The choice of the reference efficiency plays a significant role in the final result, therefore it has to be chosen with care. This is especially important when the geometry of the measured sample differs significantly from the calibration source used for the efficiency calibration of the detector. Also the definition of the calibration source as well as the measured sample has to be performed as precise as possible, especially the chemical composition which has the largest influence on transfer factors. The final result of the calculation is the efficiency for the measured sample which is dependent on the reference efficiency used. The measurement uncertainty of the calculated efficiency is determined according to the following equation:
[5]:

$$u(\varepsilon) = \sqrt{(u(\varepsilon_{ref}))^2 + (u(C))^2 + (u_D)^2 + (u_S)^2} \quad (1)$$

where *u(ε)* represents the combined measurement uncertainty of the efficiency for the measured sample, $u(\varepsilon_{ref})$ is the relative uncertainty of the reference efficiency value which has to be calculated, *u(C)* is the uncertainty of the transfer factors calculated by the program as a statistical uncertainty of the Monte Carlo integration (≈ 1.2%), u_D is the uncertainty associated with the geometry of the detector and u_S is the uncertainty associated with the characteristics of the sample. The, for the measurement uncertainty of the measured activity, this component is combined with other contributions to obtain the total combined measurement uncertainty.

B. Results and Discussion

As it was said in the previous section, the final efficiency for the measured sample is dependent on the reference efficiency used. It is therefore crucial to perform some sort of validation of the results, when a choice of different reference efficiency is available.

In this investigation, the efficiency for an atypical geometry and composition has been calculated using three different reference efficiencies. The measured samples were simulated aerosol filters containing different artificial radionuclides, printed on a cellulose filter paper, diameter 43 mm, thickness of 1mm. These samples were measured within the World-Wide Open Proficiency test IAEA-TEL-2019-03, World-Wide Open Proficiency test IAEA-TEL-2020-03 and World-Wide Open Proficiency test IAEA-TEL-2020-05, organized by International Atomic Energy Agency (IAEA) during the year 2019 and 2020 [https://nucleus.iaea.org/sites/ReferenceMaterials/Pages/Interlaboratory-Studies.aspx]. The simulated aerosol filters contained Cs-134, Cs-134 (IAEA-TEL-2019-03 and IAEA-TEL-2020-05) and Ag-110m and Se-75 (IAEA-TEL-2020-03).

Three existing efficiency calibration curves were used for the reference efficiency: spiked charcoal in cylindrical geometry of 100 ml filled to a full, spiked mineralized grass in cylindrical geometry of 100 ml filled with 6.03g of matrix, and 50 ml vial, filled with 4.22g of aerosol [6]. The charcoal efficiency curve was used as it has the similar composition and density, the grass had the closest measurement geometry and the aerosol was used because it is readily used for the measurement of the prepared aerosol filters in the laboratory.

The simulated aerosol filters were measured on 2 p-type HPGe detectors. The duration of the measurement was 5100 s, 60000 s and 240000 s for the filter from IAEA-TEL-2019-03, IAEA-TEL-2020-03 and IAEA-TEL-2020-05 respectively. After the measurement, the activity of the present radionuclides was calculated using the grass matrix reference efficiencies (as it was the closest with the respect to the measurement geometry) in order to obtain the uncorrected results. Then the efficiency transfer was performed using EFFTRAN and the calculated transfer factors were applied in order to obtain the corrected result. Both uncorrected and corrected results were compared to the target value provided by the IAEA in the final report of the said Proficiency tests.

The uncorrected results, the corrected results and the target value for one simulated aerosol filter from each Proficiency test are presented in the Table I

TABLE I

THE RESULTS OF THE SIMULATED AEROSOL FILTER MEASUREMENTS USING DIFFERENT EFFICIENCIES AND THE TARGET VALUE, THE RESULTS WERE GIVEN WITH THE APPROPRIATE MEASUREMENT UNCERTAINTY, COVERAGE FACTOR 1

IAEA-TEL-2019-03					
Element	**Uncorrected result [Bq/sample]**	**Charcoal to filter efficiency transfer [Bq/sample]**	**Grass to filter efficiency transfer [Bq/sample]**	**Vial to filter efficiency transfer [Bq/sample]**	**Target value [Bq/sample]**
Cs-137	17.8 ± 0.7	9.6 ± 0.5	12.7 ± 0.6	13.1 ± 0.6	**13.02 ± 0.40**
Cs-134	21 ± 2	15 ± 1	20 ± 2	21 ± 2	**20.28 ± 0.61**
IAEA-TEL-2020-03					
Se-75	51 ± 2	23.5 ± 1.1	31 ± 2	29 ± 1	**31.3 ± 1.5**
Ag-110m	57 ± 2	30 ± 2	35 ± 2	35 ± 2	**35.1 ± 3.0**
IAEA-TEL-2020-05					
Cs-137	47.7 ± 0.8	25 ± 1	31 ± 1	29 ± 1	**28.6 ± 1.5**
Cs-134	27 ± 1	16.1 ± 0.7	20.4 ± 0.9	19.1 ± 0.9	**20.5 ± 1.1**

As it can be seen from the Table I, the uncorrected results differ significantly from the ones obtained using the efficiency transfer, although the composition of the mineralized grass (mainly cellulose and carbon) and the geometry were similar. Also, the transfer from the reference efficiency with the coal matrix produced the results that are significantly lower than the target value, meaning that the obtained efficiency is significantly overestimated. This can be explained by the large difference between the geometry of the reference efficiency which has greater diameter and sample height and therefore is the most diverse from the measured sample. Contrary to that, the transfer from the other two reference efficiency curves produced the results that are in agreement with the target values. For the elements that have multiple gamma lines, the coincidence correction factors were obtained using also EFFTRAN software. As it can be seen, the values for Cs-134, Se-75 and Ag-110m which are corrected for the coincidence summing effect and efficiency transfer from the grass reference efficiency proved to be the closest to the target value. For Cs-137, which has only one gamma emission and do not require coincidence summing correction, better results are obtained by transferring the aerosol reference efficiency. There is a local minimum at the energy of 661 keV in all efficiency curves regardless of the matrix of the calibration source. This leads to underestimation of the efficiency for this energy, which in turn produces an underestimated transferred efficiency. The recommendation for this energy is to use the efficiency obtained directly from the calibration source measurement, rather than from the calibration curve. Also, it is evident that the aerosol calibration source, although it closely represents the real aerosol samples, is not the best choice for the simulated aerosol filters which have an atypical geometry and composition. The mineralized grass calibration source proves to be the best reference calibration for the efficiency transfer since its diameter is very close to the diameter of the measured sample and more important, its thickness and chemical composition are virtually the same.

All the results obtained by using the efficiency transfer from the grass and aerosol matrix are acceptable, while none of the uncorrected results are acceptable. This obviously proves that the efficiency transfer has to be performed with the adequate reference calibration curve.

III. CONCLUSION

In this paper we presented the optimization of the efficiency calibration of HPGe detectors for the measurement of the simulated aerosol filters, measured within three Proficiency tests organized by IAEA. In case of the atypical geometry and composition of the measured sample, the efficiency transfer is inevitable, since the uncorrected activities are not in agreement with the target values, although the calibration source used for the efficiency calibration is of the similar geometry and composition. The choice of the reference efficiency curve for the efficiency transfer should be based on the similarities between the thickness and composition of the calibration source and the measured sample, since this choice produces the best results.

ACKNOWLEDGMENT

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

REFERENCES

[1] G. Gilmore, "*Practical Gamma-ray Spectrometry, Second edition*, New York, USA Wiley, 2008,

[2] M.J. Daza, B. Quintana, M. Garcia Tavalera, F. Fernandez, *"Efficiency calibration of a HPGe detector in the 46.54-2000 keV energy range for the measurement of environmental samples"*, Nucl. Instr. Method. A, vol. 470, pp. 520–532, 2001

[3] L. Moens, J. De Donder, X. Lin et al., *"Calculation of the absolute peak efficiency of gamma-ray detectors for different counting geometries"*, Nucl. Instr. Method, vol. 187, pp. 451-472, 1981

[4] T. Vidmar, *"EFFTRAN – A Monte Carlo Efficiency Transfer Code For gamma-ray spectrometry"*, Nucl. Instr. Method. A, vol. 550,pp. 603-608, 2005

[5] *IAEA-TECDOC-1401*, "*Quantifying uncertainty in nuclear analytical measurements"*, Vienna, Austria, IAEA, 2004

[6] J. Krneta Nikolic, M. Rajacic, D. Todorovic, M. Jankovic, N. Sarap, G. Pantelic, I. Vukanac, *"Semiempirical Efficiency Calibration in Semiconductor HPGe Gamma-Ray Spectroscopy"*, Journal of