

Di Buono, Antonio, Cockbain, Neil, Green, Peter R. and Lennox, Barry (2020)
The effects of Total Ionizing Dose irradiation on supercapacitors deployed in
nuclear decommissioning environments. *Journal of Power Sources*, 479 . p.
228675.

Downloaded from: <http://insight.cumbria.ac.uk/id/eprint/7017/>

Usage of any items from the University of Cumbria's institutional repository 'Insight' must conform to the following fair usage guidelines.

Any item and its associated metadata held in the University of Cumbria's institutional repository Insight (unless stated otherwise on the metadata record) may be copied, displayed or performed, and stored in line with the JISC fair dealing guidelines (available [here](#)) for educational and not-for-profit activities

provided that

- the authors, title and full bibliographic details of the item are cited clearly when any part of the work is referred to verbally or in the written form
 - a hyperlink/URL to the original Insight record of that item is included in any citations of the work
- the content is not changed in any way
- all files required for usage of the item are kept together with the main item file.

You may not

- sell any part of an item
- refer to any part of an item without citation
- amend any item or contextualise it in a way that will impugn the creator's reputation
- remove or alter the copyright statement on an item.

The full policy can be found [here](#).

Alternatively contact the University of Cumbria Repository Editor by emailing insight@cumbria.ac.uk.



Perspective

The effects of Total Ionizing Dose irradiation on supercapacitors deployed in nuclear decommissioning environments[☆]



Antonio Di Buono^{a,b,c,*}, Neil Cockbain^{b,c}, Peter R. Green^{a,b}, Barry Lennox^{a,b}

^a Department of Electrical and Electronic Engineering, The University of Manchester, Sackville Street Building, Manchester, M13 9PL, United Kingdom

^b Centre for Innovative Nuclear Decommissioning (CINDe) Workington Laboratory, Workington, CA14 3YQ, United Kingdom

^c National Nuclear Laboratory, Central Laboratory, Sellafield Seascale, CA20 1PG, United Kingdom

HIGHLIGHTS

- Experimental tests on supercapacitors were carried out using a ⁶⁰Co irradiator.
- Evaluated if gamma radiation has effect on electrical properties of supercapacitors.
- Testing showed that supercapacitors exhibited no observable effect from irradiation.
- Tested devices are suitable for use in two specific decommissioning environments.

ARTICLE INFO

Keywords:

Radiation effects
Total Ionizing Dose
Supercapacitor
Wireless sensor network
Nuclear decommissioning environment

ABSTRACT

The effects of Total Ionizing Dose (TID) on electrical components is a key parameter to evaluate the life span of wireless sensor nodes for possible deployment in nuclear decommissioning environments. The aim of this study was to experimentally evaluate the effects of TID on capacitance, internal resistance and the self-discharge characteristic of 100 F supercapacitors. An automated test circuit was designed and assembled to charge and discharge the supercapacitors. The supercapacitors were irradiated using a Co-60 γ ray radiation source and the voltage across the supercapacitor terminals, charging current and discharging current were monitored and logged to calculate the capacitance during the irradiation process. Measurements of internal resistance and self-discharge characteristic were performed before and after the irradiation to examine the effects of exposure to γ radiation on these electrical properties. The experimental results show negligible effects on the capacitance of supercapacitors exposed to a maximum dose of 40 kGy. The internal resistance and self-discharge characteristics were not affected by TID up to 89 kGy. These results demonstrate that supercapacitors are a suitable technology to design an Energy Storage System to be deployed in the majority of nuclear decommissioning environments.

1. Introduction

One of the main challenges associated with the decommissioning of nuclear facilities is to reduce the cost associated with monitoring and surveillance operations. For example, the use of sensor networks to monitor waste storage facilities can reduce the cost and time of projects and dose exposure of the workers. In Ref. [1] the need to develop remote techniques to support the monitoring and characterization of areas with high radiation levels were identified. Wireless sensing systems can be deployed in nuclear environments to monitor the plant during

decommissioning operations and to replace legacy instrumentation. Early deployments of Commercial Off The Shelf (COTS) wireless instrumentation on the Sellafield site to monitor the pressure and temperature of steam lines have demonstrated the benefits associated with this technology [2]. The use of Wireless Sensor Networks (WSNs) in harsh environments is well documented in the literature [3–5], and [6].

Much research in recent years has focused on energy harvesting systems to reduce the battery replacement operations and hence extend the lifetime of WSNs powered by scavenging energy from the environment [7,8]. However, the solutions presented in the literature can

[☆] This document is the results of the research project funded by the Centre for Innovative Nuclear Decommissioning (CINDe) and partially through EPSRC (EP/P01366X/1: Robotics for Nuclear Environments).

* Corresponding author. School of Electrical and Electronic Engineering, The University of Manchester, Manchester, M139PL, United Kingdom.

E-mail address: antonio.dibuono@postgrad.manchester.ac.uk (A. Di Buono).

<https://doi.org/10.1016/j.jpowsour.2020.228675>

Received 29 January 2020; Received in revised form 7 July 2020; Accepted 17 July 2020

Available online 1 September 2020

0378-7753/© 2020 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

provide only an intermittent and limited power output, which is not adequate to meet the power requirements of typical sensor nodes [9]. In Refs. [10] supercapacitor technology was identified as a better energy storage device for WSN applications compared to battery technologies. Supercapacitors address a specific requirement to limit the use of rechargeable lithium batteries in nuclear decommissioning environments, and hence, reduce fire and explosion hazards [11,12]. Few researchers have investigated the effects of high radiation levels on the electrical properties of supercapacitors for deployment in nuclear decommissioning environments. Their tolerance to radiation is a fundamental parameter in providing a sufficient and predictable operational life span. However, several studies have investigated the damage that radiation can have on general electronic components [13]. Recent works have focused on the damage caused by Total Ionizing Dose [14–16]; Neutron Displacement [17–19] and Single Event Effects [17, 20,21]. Whilst there may be some neutron emissions in a nuclear decommissioning environment, it is the effects of Total Ionizing Dose (TID), produced by the energy deposited in the electronics by γ radiation, that will produce the most significant damage to electronic components [14].

Laghari et al. (1990) evaluated the radiation effects on the electrical properties of chemical double-layer capacitors exposed to γ radiation (TID of 75 kGy), thermal neutrons (fluence of 4.5×10^{14} n/cm²), and fast neutrons (fluence of 1.75×10^{13} n/cm²) in the reactor core. This study found that whilst the electrical properties of the capacitors were temporarily affected during irradiation, these properties fully recovered post-irradiation [22].

Further research has focused on the effects that radiation has on the capacitance and equivalent series resistance of supercapacitors. For example, Shojah-Adalan et al. described the effects of γ radiation and proton irradiation on three different supercapacitors, manufactured by Maxwell Technologies, with capacitance values of 10, 100, and 1200 F [23]. The capacitance and equivalent series resistance of these capacitors were measured following γ exposure of up to 2 kGy TID and proton TID of up to 20 kGy and found to be unaffected. However, the charging mechanism of one of the supercapacitors was damaged after exposure to 10 kGy.

Although this study demonstrated that capacitance and equivalent series resistance are not affected by TID effects, there has been limited research on capacitance measurements during irradiation and self-discharge properties of supercapacitors exposed to radiation levels typically experienced in nuclear decommissioning radioactive environments. The self-discharge characteristic is particularly relevant when the supercapacitor is being used for a long-term energy storage device in a wireless sensor system. In the present study, irradiation experiments were performed on Maxwell supercapacitors to evaluate the effect of TID on the capacitance during the irradiation. Also, the self-discharge and internal resistance characteristics were monitored, before and after the irradiations. The results provide valuable information to guide the design of energy storage systems for WSN. In particular, this work verifies the use of supercapacitors as a suitable technology for deployment in nuclear decommissioning environments.

2. Experimental methodology

The current investigation involves the experimental evaluation of TID effects on capacitance, internal resistance and self-discharge properties of COTS supercapacitors. BCAP0100 supercapacitors manufactured by Maxwell Technologies were selected to perform the experiments, using supercapacitors from lot number W170410702. To simulate the conditions that would be present in a nuclear decommissioning environment, the experiments were carried out at the Dalton Nuclear Facility using a ⁶⁰Co irradiator. The irradiator is a FTS Model 812 self-contained γ irradiator and emits two γ rays with energies of 1.17 and 1.33 MeV resulting in an average beam energy of 1.25 MeV [24].

Whilst in a decommissioning environment other γ emitters, such as ¹³⁷Cs are likely to be present, the energies of these γ rays will be lower, and hence they will have a slightly less damaging effect on electronic components. Consequently, ⁶⁰Co irradiators have become a standard γ ray radiation source to perform experiments to evaluate the effects of TID [25] and was therefore considered to be a suitable testing environment for this study. The MIL-STD-883K standard identifies uniform methods, controls and procedures for testing microelectronic devices suitable for use within military and aerospace environments. This standard suggests using a ⁶⁰Co γ ray source with a dose rate between 0.5 and 3 Gy/s [26].

Studies presented in Ref. [27] have shown that electronic components in nuclear decommissioning environments are exposed to different dose rates and total dose rates compared to other industrial applications. These findings need to be taken into account during the selection of dose rate and total dose to evaluate the effects of TID on components deployed in nuclear decommissioning environments.

The work presented in this paper focuses on two real-life scenarios: a medium level sludge storage facility with a dose rate of 4.5×10^{-1} Gy/h and hot spots in a Pressurized Water Reactor with a dose rate up to 2 Gy/h [28]. For both these cases γ ray radiation sources are the main challenge, and the contribution of neutron displacement damage is negligible.

A total of 9 supercapacitors were irradiated and analysed, by adapting the test method described by the British Standards (BS EN 62391) to evaluate electrical characteristics of fixed electric double-layer capacitors [29]. The availability of the irradiation facility limited the sample size of the experimental investigation.

The block diagram, displayed in Fig. 1, shows the automated measurement system that was designed to measure the capacitance and internal resistance whilst the supercapacitor under test is charged and discharged, following the adapted testing method. The constant current load was implemented using IRF510 MOSFET and LM10C operational amplifier/voltage reference. This sub-circuit was isolated from the supercapacitor's terminal block via relay 2. The charging and discharging current was monitored using two LT6105 precision current sense amplifiers. Both the voltages from the current sense amplifiers and the supercapacitor were connected to three different operational amplifiers OPA140 to buffer the signal.

Fig. 2 shows the block diagram of the circuit that was designed to perform the self-discharge experiments. The components to charge the supercapacitors is the same as described above. In addition, relay 4 was included between the supercapacitor and the operational amplifier OPA140 to isolate the supercapacitor from the data acquisition unit during the experiments and avoid any further discharge.

The methodology to evaluate the electrical characteristics used in this work was a modified version of BS EN 62391 adapted to the specific case of a supercapacitor of 100 F capacitance and maximum operating voltage of 2.7 V. A National Instruments USB-6009 data acquisition unit was connected to the charging and discharging circuit and to a laptop running LabVIEW software. LabVIEW software was designed to control the relays during the experiments and the logging of the voltage across the supercapacitor under test, charging current, and discharging current, was performed using a National Instruments Technical Data Management Streaming (TDMS) file. The data was graphically shown in real time with a sample period of 100 ms.

The measurement consists of three main stages: set the maximum voltage to 2.7 V and start to charge the supercapacitor with 1 A constant current, when the maximum voltage value is reached continue the constant voltage charging for 300 s and then discharging the supercapacitor using a constant current load set at 1 A.

3. Experimental results and discussion

Three supercapacitors were used in each experiment to evaluate the TID effects on capacitance and were mounted on a PCB and positioned

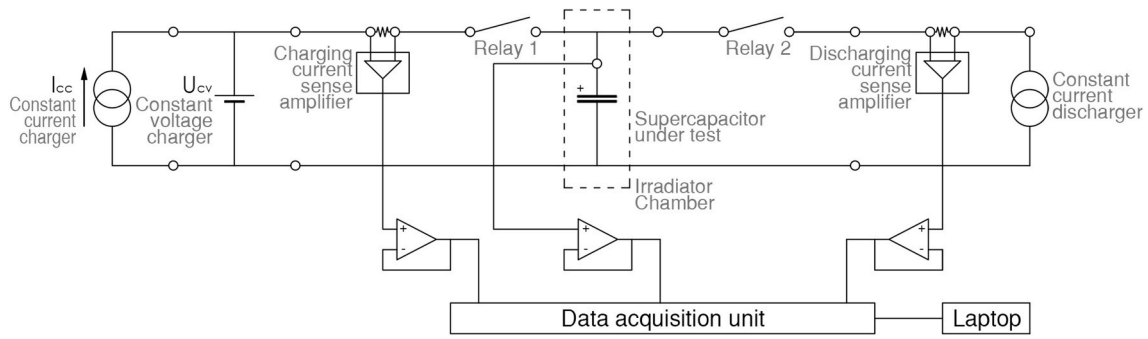


Fig. 1. Block diagram of capacitance and internal resistance measurement circuit.

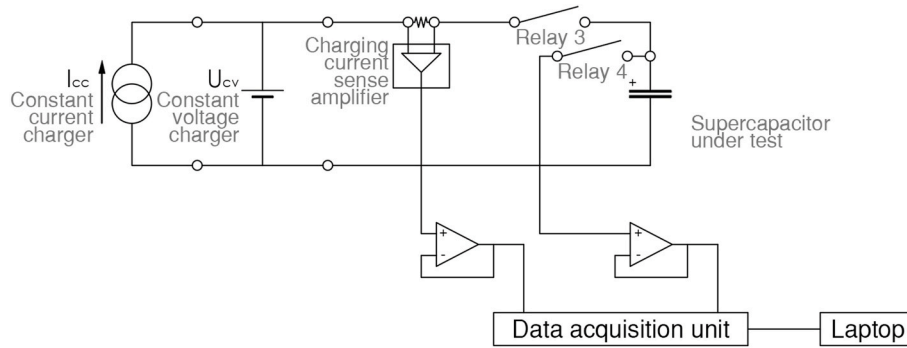


Fig. 2. Block diagram of self-discharge measurement circuit.

inside the irradiator chamber.

As shown in Fig. 3 (a) the device under test was connected to the charging and discharging circuit using two wires feeding through the irradiator access port. The advantage of having the charging and discharging circuit outside the irradiator is to limit the effects of TID on other components. For example, it has been demonstrated that operational amplifiers [30], power MOSFETs [31], and voltage regulators [32] are affected by γ radiation. Before mounting the supercapacitor inside the ionizing chamber, the dose rate was experimentally measured using an ionization chamber, with a result of 2.07 Gy/s, which is within the range suggested by the MIL-STD-883K standard.

Fig. 4 illustrates the voltage-time characteristics, charging and discharging current during the experiments to evaluate capacitance and internal resistance.

Capacitance was calculated according to the BS EN 62391 using the following equation:

$$C = I_d \frac{t_2 - t_1}{U_1 - U_2} \quad (1)$$

where:

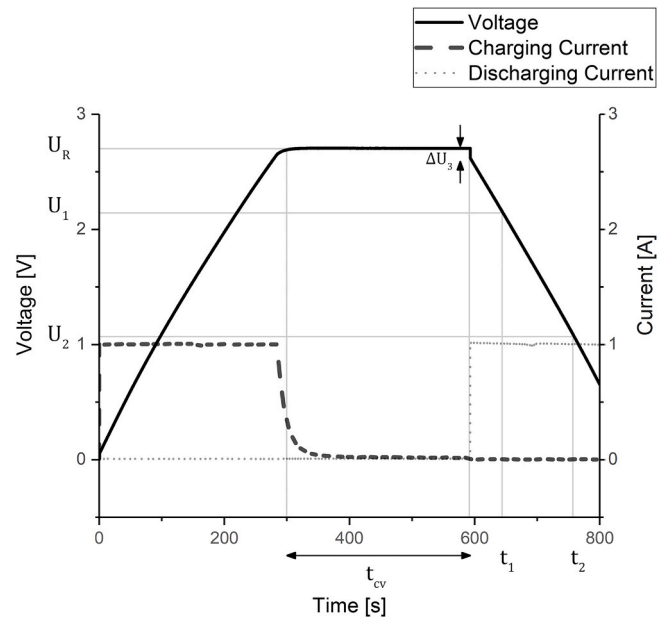


Fig. 4. Experimental measurement of voltage/time characteristics between supercapacitor terminals in capacitance and internal resistance experiments.

C is the capacitance of supercapacitor [F]

I_d is the discharge current [A]

U_1 is the measured start voltage [V]

U_2 is the measured end voltage [V]

t_1 is the time at which the terminal voltage of the capacitor reaches the value U_1 from the start of the discharge [s]

t_2 is the time at which the terminal voltage of the capacitor reaches the value U_2 from the start of the discharge [s];

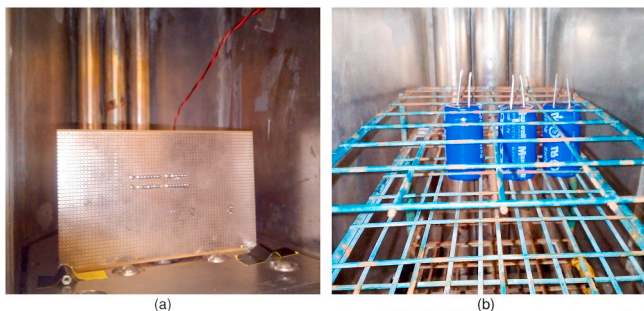


Fig. 3. Supercapacitor positioned inside the irradiator during capacitance test (a) and supercapacitors positioned using irradiator's rack (b).

Experiments to evaluate the internal resistance and self-discharging characteristics before and after irradiation were performed on two different groups of supercapacitors for a total irradiation time of 16 h and 4 h. Supercapacitors 4 to 9 were irradiated during two different irradiation tests, as shown in Fig. 3 (b).

Fig. 5 presents the results for capacitance measurements obtained using equation (1) to evaluate the effects of TID during the irradiation. As seen, similar behaviour was observed in all cases, with negligible effects up to a total dose of 40 kGy.

Although it is evident that the results are in good agreement with the manufacturer’s nominal value of 100 F with a 20% tolerance [33], additional experiments were carried out to estimate other potential sources of measurement error during the experiments. For example, the temperature of the irradiation chamber was measured to increase from ambient room temperature to 40 °C during the first two hours of irradiation. As a result, the effect of temperature on the capacitance of supercapacitor was investigated. Supercapacitors 1 to 3 connected to the charging and discharging circuit by two wires were placed inside an oven, following the same experimental arrangement developed for irradiation experiments. The voltage across the supercapacitors, the charging current and discharging current were monitored for 5 h to evaluate capacitance changes during the test. A second evaluation was completed to assess if the results of capacitance measurements were affected directly by the tolerances and self-heating effects of the components employed in charging and discharging circuits. Supercapacitors 1 to 3 were charged and discharged in the laboratory environment at ambient temperature for five hours, and then the capacitance was calculated to evaluate if the initial calculated value had undergone any change during the experiment.

Fig. 6 illustrates the comparison between the effects of TID, temperature and test circuit components. As can be seen in the figure, the three plots are very similar. All the experiments show a variation of the initial capacitance value compared to the value calculated after 5 h within the range 1.3%–2.2%. This result demonstrates the small changes in the capacitance values were unlikely to be the result of irradiation. To the best knowledge of the authors, the results of TID effects on capacitance during the irradiation are novel. The 3 supercapacitors did not show any temporary changes to the capacitance during the irradiation test, this result could suggest that the dielectric constant of the electrolyte is not affected.

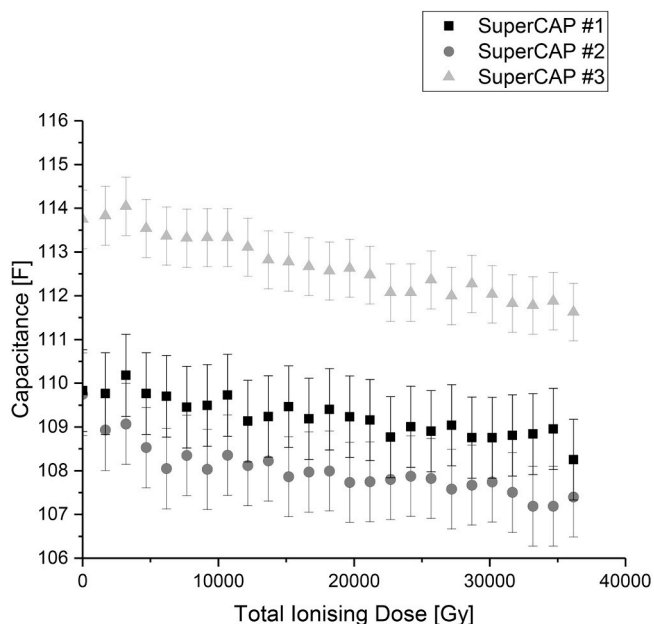


Fig. 5. Total Ionizing Dose effects on capacitance characteristic.

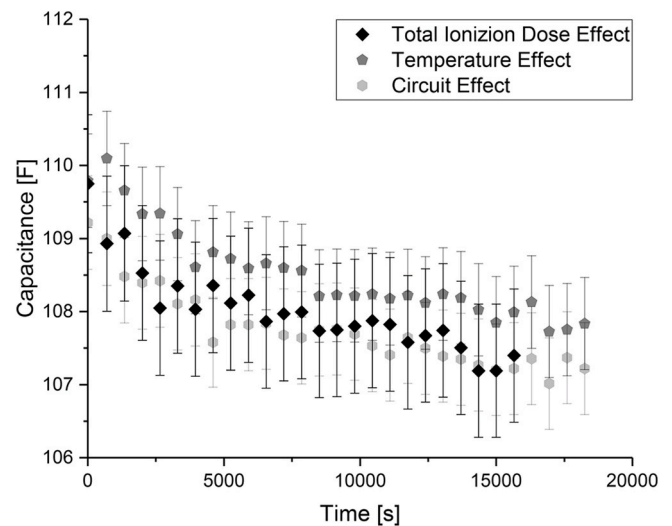


Fig. 6. Comparisons of TID, temperature and circuit effects on capacitance characteristic.

Internal resistance was calculated according to BS EN 62391 using the following equation:

$$R = \frac{\Delta U_3}{I_d} \tag{2}$$

where:

R is the internal resistance of supercapacitor [Ω]

ΔU_3 is the difference of voltages between the calculation start voltage and the set value of constant voltage charging [V]

Table 1 shows the results for the internal resistance irradiation test with a TID up to 29 kGy and 89 kGy. The findings on irradiation effects for the internal resistance of supercapacitors extends to those in literature, confirming that no effects have been observed up to a dose of 89 kGy.

Fig. 7 shows the voltage between the supercapacitor terminals measured during this study to evaluate the self-discharge characteristic of the supercapacitors. The supercapacitor was charged at 1 A constant current up to the rated voltage of 2.7 V, then continuing to charge at 2.7 V constant voltage for 300 s and at the end disconnecting the supercapacitor from the circuit. During the experiments, the voltage across the terminals of supercapacitor was monitored every 12 h for 72 h.

The self-discharge parameter was calculated according to the following equation:

$$U_{s-d} = U_{end} - U_R \tag{3}$$

where:

U_{s-d} is the self-discharge characteristic [V]

Table 1
Internal resistance before and after irradiations.

Supercapacitor under test	TID[kGy]	R[Ω]	
		Irradiated	Non Irradiated
SuperCAP#4	27	0.045	0.046
SuperCAP#5	29	0.045	0.047
SuperCAP#6	29	0.045	0.046
SuperCAP#7	83	0.045	0.045
SuperCAP#8	89	0.047	0.047
SuperCAP#9	89	0.047	0.048

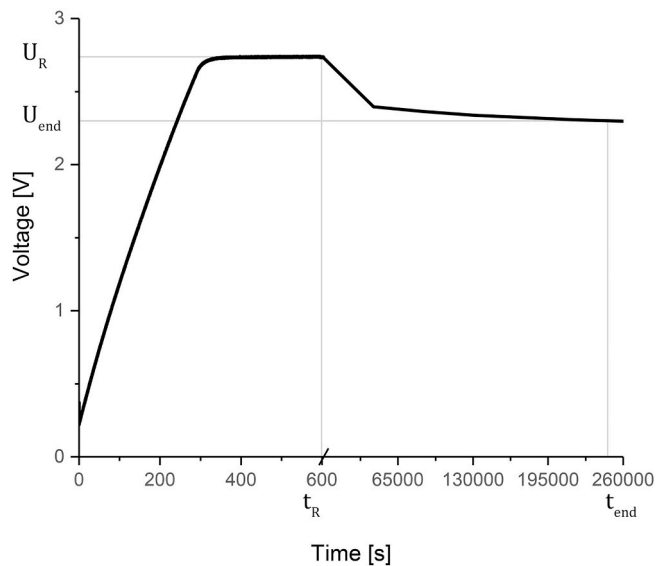


Fig. 7. Experimental measurement of voltage/time characteristics between supercapacitor terminals in self-discharge characteristic experiments.

Table 2
Self-discharge characteristic before and after irradiations.

Supercapacitor under test	TID [kGy]	Self-Discharge[V]	
		Irradiated	Non Irradiated
SuperCAP#4	27	0.0496	0.481
SuperCAP#5	29	0.0442	0.413
SuperCAP#6	29	0.0450	0.396
SuperCAP#7	83	0.554	0.531
SuperCAP#8	89	0.583	0.518
SuperCAP#9	89	0.565	0.523

U_{end} is the voltage between open capacitor terminal at the end of the experiment [V]

U_R is the rated voltage [V]

Finally, the results on the self-discharge characteristic of supercapacitors are reported in Table 2. The self-discharge characteristic is a fundamental parameter to evaluate the energy stored by the supercapacitor exposed to γ radiation during deployment. The values present the changes in voltage before and after the irradiation calculated with equation (3). The voltage increase in the supercapacitor after irradiation at 27 kGy and 89 kGy ranged from 0.015 V to 0.065 V.

4. Conclusion

This paper has investigated the effect of TID on the electrical properties of supercapacitors to determine their suitability for use in two specific nuclear decommissioning environments. The first set of experiments evaluated the effects of gamma radiation on capacitance when the devices were irradiated with a dose of 40 kGy, with a second experiment examining whether the internal resistance and self-discharging abilities of the supercapacitors changed before and after being irradiated with a dose of 89 kGy. The results of these experiments indicated that the electrical properties of the supercapacitors showed no observable effects both during and after irradiation.

The TID that the supercapacitors were exposed to in the experiments is relatively high for a nuclear decommissioning environment, and it can therefore be concluded that the particular supercapacitors that were tested could have an operational life span up to 10 years within a

medium level sludge storage facility and up to 2 years if deployed close to a hot spot in a Pressurized Water Reactor under decommissioning.

CRedit authorship contribution statement

Antonio Di Buono: Conceptualization, Methodology, Investigation, Writing - original draft. **Neil Cockbain:** Conceptualization, Supervision, Writing - review & editing. **Peter R. Green:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Barry Lennox:** Supervision, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work has been supported by the Centre for Innovative Nuclear Decommissioning (CINDe), United Kingdom, which is led by the National Nuclear Laboratory, in partnership with Sellafield Ltd and a network of Universities that includes the University of Manchester, Lancaster University, the University of Liverpool and the University of Cumbria, partially through EPSRC (EP/P01366X/1: Robotics for Nuclear Environments), United Kingdom. In addition, the author would like to take this opportunity to acknowledge the support of Ruth Edge and Kevin Warren at The University of Manchester Dalton Cumbrian Facility (DCF), a partner in the National Nuclear User Facility, the EPSRC UK National Ion Beam Centre and the Henry Royce Institute.

References

- [1] S.J. Palethorpe, B. Bowen, J.J. Hastings, P.E. Mort, G. Askew, *Technical Challenges, Needs and Opportunities in Decommissioning of the Sellafield Site*, 2013. Technical Report.
- [2] T.S. Nobes, C. Murphy, Deciding to use wireless control and instruments in the UK nuclear industry, *Meas. Contr.* 47 (2) (2014) 58–64.
- [3] H.H. Khalili, P.R. Green, D. George, G. Watson, W. Schiffrs, Wireless sensor networks for monitoring gas turbine engines during development, in: 2017 IEEE Symposium on Computers and Communications (ISCC), July 2017, pp. 1325–1331.
- [4] E. Sisinni, P. Archetti, M. Manenti, E. Piana, High availability wireless temperature sensors for harsh environments, in: 2012 IEEE Sensors Applications Symposium Proceedings, Feb 2012, pp. 1–6.
- [5] M.C. Scardelletti, J.L. Jordan, G.E. Ponchak, C.A. Zorman, Wireless capacitive pressure sensor with directional rf chip antenna for high temperature environments, in: 2015 IEEE International Conference on Wireless for Space and Extreme Environments, WISEE, Dec 2015, pp. 1–6.
- [6] T.G. van Kessel, M. Ramachandran, L.J. Klein, D. Nair, N. Hinds, H. Hamann, N. E. Sosa, Methane leak detection and localization using wireless sensor networks for remote oil and gas operations, in: 2018 IEEE SENSORS, Oct 2018, pp. 1–4.
- [7] K.Z. Panatik, K. Kamardin, S.A. Shariff, S.S. Yuhani, N.A. Ahmad, O.M. Yusop, S. Ismail, Energy harvesting in wireless sensor networks: a survey, in: 2016 IEEE 3rd International Symposium on Telecommunication Technologies (ISTT), Nov 2016, pp. 53–58.
- [8] J.A. Paradiso, T. Starner, Energy scavenging for mobile and wireless electronics, *IEEE Pervasive Computing* 4 (1) (Jan 2005) 18–27.
- [9] R. Ge, Z. Lin, N. Gong, J. Wang, Design and performance analysis of energy harvesting sensor networks with supercapacitor, in: 2017 IEEE 60th International Midwest Symposium on Circuits and Systems, MWSCAS, Aug 2017, pp. 64–67.
- [10] A. Othman, Energy storage system options in intelligent wireless sensor network, in: 2017 International Conference on Military Technologies (ICMT), May 2017, pp. 772–778.
- [11] J. Goodenough, Y. Kim, Challenges for rechargeable li batteries, *Chem. Mater.* 22 (3) (2 2010) 587–603.
- [12] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, C. Chen, Thermal runaway caused fire and explosion of lithium ion battery, *J. Power Sources* 208 (2012) 210–224 [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378775312003989>.
- [13] *Handbook of Radiation Effects*, second ed. Oxford: Oxford University Press.
- [14] D.M. Fleetwood, Total ionizing dose effects in mos and low-dose-rate-sensitive linear-bipolar devices, *IEEE Trans. Nucl. Sci.* 60 (3) (June 2013) 1706–1730.
- [15] H.J. Barnaby, M. McClain, I.S. Esqueda, Total-ionizing-dose effects on isolation oxides in modern cmos technologies, *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 261 (1) (2007) 1142–1145, the Application of

- Accelerators in Research and Industry. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0168583X07006696>.
- [16] Z. Hu, Z. Liu, H. Shao, Z. Zhang, B. Ning, M. Chen, D. Bi, S. Zou, Total ionizing dose effects in elementary devices for 180-nm flash technologies, *Microelectron. Reliab.* 51 (8) (2011) 1295–1301 [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S002627141100103X>.
- [17] E. Normand, Single-event effects in avionics, *IEEE Trans. Nucl. Sci.* 43 (2) (April 1996) 461–474.
- [18] M.B. Yazdi, M. Schmeidl, X. Wu, T. Neyer, A concise study of neutron irradiation effects on power mosfets and igbts, *Microelectron. Reliab.* 62 (2016) 74–78 [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0026271416300555>.
- [19] V. Kilchytska, J. Alvarado, N. Collaert, R. Rooyackers, O. Militaru, G. Berger, D. Flandre, Effect of high-energy neutrons on mufgts, *Solid State Electron.* 54 (2) (2010) 196–204, selected Full-Length Extended Papers from the EUROSOI 2009 Conference. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0038110109003621>.
- [20] J. Liu, F. Ma, M. Hou, Y. Sun, J. Quan, Y. Zhou, Y. Zhong, J. Fan, Z. Chen, F. Feng, Heavy ion induced single event effects in semiconductor device1this subject was supported by the Chinese academy of sciences.1, *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 135 (1) (1998) 239–243 [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0168583X97005983>.
- [21] X. Du, S. Liu, D. Luo, Y. Zhang, X. Du, C. He, X. Ren, W. Yang, Y. Yuan, Single event effects sensitivity of low energy proton in xilinx zynq-7010 system-on chip, *Microelectron. Reliab.* 71 (2017) 65–70 [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0026271417300379>.
- [22] J.R. Laghari, A.N. Hammoud, Effect of nuclear radiation on the electrical properties of chemical double layer capacitors, *IEEE Trans. Nucl. Sci.* 37 (2) (April 1990) 1072–1075.
- [23] S. Shojah-Adalan, R. Wilkins, H.U. Machado, B.A. Syed, S. McClure, B. Rax, L. Scheick, M. Weideman, C. Yui, M. Reed, Z. Ahmed, Susceptibility of "ultracapacitors" to proton and gamma irradiation, in: 2003 IEEE Radiation Effects Data Workshop, July 2003, pp. 89–91.
- [24] L. Leay, W. Bower, G. Horne, P. Wady, A. Baidak, M. Pottinger, M. Nancekievill, A. Smith, S. Watson, P. Green, B. Lennox, J. LaVerne, S. Pimblott, Development of irradiation capabilities to address the challenges of the nuclear industry, *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 343 (2015) 62–69 [Online]. Available, <http://www.sciencedirect.com/science/article/pii/S0168583X14009094>.
- [25] J. Shen, W. Li, Y. Zhang, Assessment of tid effect of fram memory cell under electron, x-ray, and co- 60 γ ray radiation sources, *IEEE Trans. Nucl. Sci.* 64 (3) (March 2017) 969–975.
- [26] "MIL-STD-883K", Defense Logistics Agency, Tech. Rep, March 2003.
- [27] M. Nancekievill, S. Watson, P.R. Green, B. Lennox, Radiation tolerance of commercial-off-the-shelf components deployed in an underground nuclear decommissioning embedded system, in: 2016 IEEE Radiation Effects Data Workshop (REDW), July 2016, pp. 1–5.
- [28] L.P. Houssay, Robotics and Radiation Hardening in the Nuclear Industry, Ph.D. dissertation, State University System of Florida, 2000.
- [29] BSEN62391-1:2016, Fixed Electric Double-Layer Capacitors for Use in Electric and Electronic Equipment, 2016.
- [30] F. Irom, S.G. Agarwal, M. Amrbar, Compendium of single-event latchup and total ionizing dose test results of commercial and radiation tolerant operational amplifiers, in: 2014 IEEE Radiation Effects Data Workshop (REDW), July 2014, pp. 1–8.
- [31] R.D. Pugh, A.H. Johnston, K.F. Galloway, Characteristics of the breakdown voltage of power mosfets after total dose irradiation, *IEEE Trans. Nucl. Sci.* 33 (6) (Dec 1986) 1460–1464.
- [32] A.T. Kelly, P.C. Adell, A.F. Witulski, W.T. Holman, R.D. Schrimpf, V. Pouget, Total dose and single event transients in linear voltage regulators, *IEEE Trans. Nucl. Sci.* 54 (4) (Aug 2007) 1327–1334.
- [33] Maxwell Technologies, 2.7 V 100 F ultracapacitor cell [Online]. Available: http://www.maxwell.com/images/documents/2_7_100F_ds_3001959_datasheet.pdf.



Antonio Di Buono is a PhD doctoral student at Centre for Innovative Nuclear Decommissioning, which is a partnership between Sellafield Ltd, the National Nuclear Laboratory and the Universities of Manchester, Liverpool, Lancaster and Cumbria. He received his Master of Science in Nuclear Engineering at the University of Pisa. His research interests are in the field of nuclear decommissioning and waste management, in particular his current research is focused on the wireless sensor network technologies for nuclear environments. He is involved in the activities of the European Nuclear Society-Young Generation Network and he is representative of YGN in the High Scientific Council of the European Nuclear Society.



Neil Cockbain was born in Cockermouth, Cumbria, UK in 1966. Graduating from the University of Central Lancashire, Neil has been employed by National Nuclear Laboratory since 1987 with over 31 years' of experience in software/systems engineering. Neil has been supporting various parts of Sellafield site, including THORP and Magnox plants, on physical and chemical instrumentation. Neil has a thorough knowledge in several Instrumentation areas, including image processing, software engineering, computer hardware and interfacing, and electrical control systems. He is experienced in all aspects of project life-cycle, including specification, development, construction, testing, installation, commissioning and support. Modifications and corrections to 'Special Instruments' follow the full 'V' model life cycle. During the time working in 'Special Instruments' Group at BNFL Neil has worked on real-time, embedded systems with varying safety significance. From 2002, Mr. Cockbain works in the NNL Instrumentation & In-situ Analysis team at the Central Laboratory, Sellafield, as a Senior Research Technologist, on a number of diverse projects and bespoke systems. Also being an industrial supervisor for a number of CINDE PhD's students in areas of wireless and underwater acoustic communication for POCO and decommissioning.



Peter Green is Professor of Wireless Communications in the School of Electrical and Electronic Engineering. Following graduation from the University of Cambridge in 1985, Peter worked in the aerospace industry developing embedded control systems for commercial and military gas turbine engines. He joined the School of Electrical and Electronic Engineering at The University of Manchester in 1991, and is a member of the Communication Systems Research Group. Peter's research is concerned with the design, implementation and evaluation of wireless and network communication systems, with a focus on applications in harsh environments. His research resulted in early examples of the deployment of wireless sensor network technologies in the process and nuclear industries. Collaboration with Rolls-Royce has developed techniques for experimentally evaluating the performance of wireless sensing techniques in gas turbine engines and pioneered the use of Software Defined Radio (SDR) in the aerospace sector.



Barry Lennox is Fellow of the Royal Academy of Engineering and Professor of Applied Control and Nuclear Engineering Decommissioning in the School of Electrical and Electronic Engineering at The University of Manchester. He is Director of the £12 M EPSRC Robotics and Artificial Intelligence for Nuclear (RAIN) Robotics Hub and Research Director of the Dalton Cumbrian Facility. His expertise is in applied control and its use in robotics and process operations and he has considerable experience in transferring leading edge technology into industry. He leads the £5 M EPSRC Programme Grant, Robotics for Nuclear Environments and leads the robotics work within the EPSRC TORONE project.