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Abstract

Nuclear energy's distinctive characteristics give rise to special educational requirements. These requirements are necessary to not only address the potential danger of nuclear proliferation, but also to build capacity for a secure nuclear fuel circle. In this paper, I assess the status of educational capacity in nuclear security both in response to, and in support of, Kenya's nuclear power program. I highlight the nuclear security educational infrastructure's key features in the context of nuclear power, noting the low capacity at Kenyan universities. I identify the steps required to ensure that the country's dynamic nuclear regulatory infrastructural framework is used effectively to build capacity in nuclear security. I then examine the link between nuclear security and nuclear forensics and discuss efforts toward developing educational capacity in nuclear security through forensics research at the University of Nairobi, emphasizing in-field nuclear forensics and management of nuclear and radioactive materials out of statutory control. Finally, I consider the research challenges and solutions, which include developing a National Nuclear Forensic Library as a database for illicit trafficking or incidents that involve nuclear and radioactive material. I conclude that, despite the challenges, progress is underway but can be accelerated by promoting broader stakeholder involvement and government buy-in for more comprehensive educational capacity building in nuclear security.

I. Introduction

A. Nuclear Security in the Context of Kenya's Nuclear Power Program

i. International Agreements

Developing a nuclear security infrastructure requires considerable effort, especially for a country new to establishing a nuclear power program. In consideration of this, Kenya is a state party to the Convention on the Physical Protection of Nuclear Material and its 2016 Amendment (CPPNM, 1979) **[*1*]**. The

Convention's scope encompasses physical protection of nuclear facilities and nuclear material in domestic use, storage, and transport. It also criminalizes theft and smuggling of nuclear material and the actual or threatened sabotage of nuclear facilities. States are required to minimize any radiological consequences of sabotage and prevent and combat related offenses. In this regard, Kenya voluntarily shares incidents involving radioactive material on IAEA's Incident and Trafficking Database (ITDB). Furthermore, by 2006, Kenya had already become party to the International Convention for the Suppression of Acts of Nuclear Terrorism **[*2*]**, the Convention on Nuclear Safety **[*3*]**, the Convention on Early Notification of a Nuclear Accident **[*4*]**, the Joint Convention on the Safety of Spent Fuel Management, and the Safety of Radioactive Waste Management **[*5*]**. These treaties, among other regulatory and legal provisions, whether signed or in progress, demonstrate Kenya's commitment to securely pursue peaceful uses of atomic energy, including nuclear power development.

ii. Developing Domestic Infrastructure

Following the National Economic and Social Council's (NESC) 2010 recommendation that nuclear power is the most viable option for meeting the country's energy needs while reducing carbon emissions **[*6*]**, Kenya incorporated nuclear power into its energy blueprint. Consequently, a nuclear energy programme implementing organization (NEPIO), now the Kenya Nuclear Electricity Board (KNEB), was established. KNEB's plans adhere to the IAEA Milestone approach and are currently in Phase 1 **[*7*]**. In the context of nuclear security, Kenya has established—via the radiation safety and protection regulatory agency (the Radiation Protection Board [RPB])—the national Nuclear Security Coordination Centre (NSCC), which brings together eighteen state stakeholders in nuclear energy. NSCC's overall objective is to promote a high level of nuclear security training and support services. The Integrated Nuclear Security Support Plan (INSSP) was recently finalized and provides a regular summary of the country's activities toward enhancing nuclear security.

B. Nuclear Security and Nuclear Power

Although a country could establish some degree of nuclear security knowledge without a nuclear power program—for example, by promoting international non-proliferation comprehensive nuclear security education expertise, which enables a country to more holistically manage all nuclear security issues—nuclear security expertise is best developed in the context of a nuclear power program. Approximately fifty countries have attempted to develop nuclear power, but the only ones that succeeded had some degree of expertise in nuclear security and were already engaged in building a reactor. These successful countries include Argentina, Mexico, Pakistan, South Korea, and Yugoslavia **[*8*]**. However, lack of educational capacity in nuclear security was the key impediment to the countries that failed to develop nuclear power **[*9*]**. Turkey, for instance, had plans to establish nuclear power as early as 1970. But it was not until the Triga research reactor at Istanbul Technical University was built in 1979 (the same year that Turkey ratified the 1970 Treaty on the Non-Proliferation of Nuclear Weapons [NPT] **[*10*]** and Additional Protocol [1981–2001]) **[*11*]** that its nuclear power program accelerated. An effective national nuclear security infrastructure ensures that nuclear and radioactive materials do not fall into the hands of parties who could use them for criminal or terrorist acts and prevents acts of sabotage against facilities and associated activities, even when in transit **[*12*]**. In order to ensure such security, educational capacity in nuclear security must be an essential part of a nuclear power program **[*13*]**. This paper assesses Kenya's status and development of educational capacity in nuclear security, with focus on demonstrating how it is both responding poorly to the country's new nuclear power program, while simultaneously providing the impetus for, among other similar stakeholder activities, the University of Nairobi to remedy the situation.

International Journal of Nuclear Security, Vol. 4, No. 1, 2018

II. Framework for Capacity Building in Nuclear Security

A. Nuclear Security Training

In 2009, the IAEA recognized the need to establish and develop human resources for nuclear security in member states. Overseeing capacity building and human resource development to support the nuclear power program roadmap is among KNEB's mandates **[*14*]**. In collaboration with the IAEA, Kenya has hosted national and regional nuclear security training courses for border and other security personnel to improve illicitly-trafficked radioactive and nuclear material detection capability. IAEA has provided radiation-detection equipment support toward this initiative. In the context of IAEA's Emergency Preparedness and Review Mission to the country in 2015 **[*15*]**, Kenya developed a National Nuclear and Radiological Emergency Preparedness and Response Action Plan.

In terms of domestic capacity building in nuclear security, these efforts translate merely to basic skills in responding to nuclear and radiological emergencies. Nuclear security is a much broader discipline that relates to the prevention and detection of, and response to, theft, sabotage, unauthorized access and illegal transfer, or other malicious acts involving nuclear material, other radioactive substances, and their associated facilities **[*12*]**. In this context, the alarmingly scant educational capacity in nuclear security at Kenyan universities is easily noticeable.

B. Nuclear Security Education

None of Kenya's thirty-one universities with public charter currently have a nuclear security educational program. Before the advent of the country's nuclear power program, only Kenyatta University and the University of Nairobi (the country's oldest and largest university) had graduate programs in Applied Nuclear and Radiation Physics **[*16*]**. These graduate programs build on the normal, basic undergraduate Atomic and Nuclear Physics courses, and none offer Nuclear Chemistry or Radiochemistry. The University of Nairobi's Institute of Nuclear Science and Technology's 1979 mandate to train human resources in the multidisciplinary applications of nuclear science techniques is limited and, nearly forty years later, produces only a handful of graduate students (about five every year since its inception). No Kenyan university has a program in nuclear engineering. Furthermore, nuclear energy topics are noticeably absent in Law, Engineering, Economics, and other related courses. Considering the interdisciplinary characteristics of nuclear security, this narrowness contributes significantly to Kenya's educational capacity building problems.

Several IAEA conferences have highlighted nuclear security's need for human resource development programs. These include IAEA's International Conference on Human Resource Development for Introducing and Expanding Nuclear Power Programmes, held in Abu Dhabi, United Arab Emirates, 14-18 March 2010; and the International Conference on Human Resource Development for Nuclear Power Programmes: Building and Sustaining Capacity (Strategies for Education and Training, Networking and Knowledge Management), held in Vienna, Austria, 12–16 May 2014. Successive IAEA Nuclear Security Plans give high priority to assisting states in establishing nuclear security educational programs. The current Nuclear Security Plan for 2010-2013 **[*17*]** emphasizes the importance of considering existing capacities at international, regional, and national levels when designing nuclear security academic programs. As the responsibility of nuclear security rests wholly within each state, member states need educational infrastructure development strategies. This is best accomplished through a friendly partnership among university, industry, and government organizations that recognize the interdisciplinarity of nuclear energy. The goal of this collaboration should be to create, develop, and promote career pathways by adapting the existing programs to nuclear security needs. For this purpose, gap analysis and needs assessment are crucial. This study employs these methods to bridge the gap in a twofold way: (i) by pursuing generic capacity building in nuclear sciences to support government organizations in making knowledgeable nuclear power-related decisions; and (ii) by developing technical nuclear forensics professionals to help implement nuclear security.

i. Nuclear Forensics in Support of Nuclear Security

Nuclear forensics is the examination of nuclear or other radioactive materials, or of evidence that is contaminated with radionuclides, in the context of legal proceedings. Nuclear forensics can be utilized not only for a post-event investigation, but also for prevention of nuclear security events. For example, nuclear forensics can help identify previously unknown nuclear security gaps at both the facilities level and the state level, thus pointing out the existence of unaddressed deficiencies in materials accounting, control, and physical protection as well as highlighting the existent needs to improve a country's nuclear security regime **[*18*]**. In the case of an explosion, nuclear forensics can reconstruct key features of the nuclear device and can help identify its origins. Through rapid characterization of nuclear materials, nuclear forensics is thus a deterrent in itself against nuclear security threats, such as illicit trafficking and danger of terrorism utilizing improvised nuclear devices and/or radiological dispersal devices.

For these reasons, nuclear forensics is an essential component of the IAEA nuclear security program, in direct relation to the Convention on the Physical Protection of Nuclear Material (CPPNM) **[*1*]**. Such essentiality is due to nuclear forensics' role in enabling cooperation and assistance in the event, or credible threat, of theft, robbery, or any other unlawful taking of nuclear material. Its involvement is geared toward the recovery of unlawfully taken nuclear material, the prosecution or extradition of alleged offenders, and the provision of assistance by member states in connection with criminal proceedings. CPPNM's scope extends to nuclear facilities and material in domestic use, storage, and transport. As such, nuclear forensics plays a role in the expanded cooperation among states, enabling rapid measures to locate and recover stolen or smuggled nuclear material, mitigate any radiological consequences of sabotage, and prevent and combat related offenses. Nuclear forensics also contributes to the Convention by assisting in the establishment of new nuclear smuggling, illicit trafficking, and sabotage offenses, as well as acts directly contributing to the commission of such offenses. These contributions are in line with the UN Security Council resolution 1373 and 1540 adopted under Chapter VII of the UN Charter in 2004 **[*19*]** and as such, states are obligated to adopt and enforce these measures and offenses.

III. Toward Nuclear Security Education at the University of Nairobi

Presently, Kenya's highest priority is developing measures to detect, deter, prevent, and combat illicit trafficking in nuclear and related (i.e., radioactive and radiological) materials. At the division of Applied Nuclear and Radiation Physics in the University of Nairobi's Department of Physics, we have responded to this by infusing our graduate academic courses with a technical focus (as opposed to policy focus) in nuclear security. Our strategy aligns closely with the ongoing establishment of a sustainable regulatory framework for the country's nuclear power program. Due to lack of qualified staff and requisite experimental facilities, it is not currently feasible to launch a full-fledged MSc Nuclear Security course, according to IAEA Nuclear Security Series No. 12 guidelines **[*20*]**. However, we have developed a new program that reforms the original one, which consisted of eight 40-hour courses in the first of two years **[*21*]**. In the previous program, during the first semester of year one, students took Advanced Nuclear Physics plus any three fundamental courses in advanced physics, such as Quantum Mechanics or Statistical Physics. In the second semester, students selected another four courses from among the following: Advanced Laboratory Techniques, Radiation Physics, Radiation Measurement and Spectroscopy, Radiation Protection and Dosimetry, and Applications of Radiation. In the second year of study, students began supervised thesis research on a relevant topic and received credits equivalent to eight taught courses.

International Journal of Nuclear Security, Vol. 4, No. 1, 2018

A. New Course Structure

The new program, targeting young graduates from engineering and natural sciences backgrounds, is composed of ten courses in year one, instead of the previous eight. In the first semester, Advanced Nuclear Physics is retained (but appropriately revised) and is taken along with another four fundamental courses, one of which is required to be Reactor Theory. The second semester's courses are categorized in five tracks, namely Nuclear Security and Safeguards, Health Physics and Radioprotection, Applied Radiometrics, Nuclear Science Techniques, and Applied Nuclear Physics.

Below are the details of the Nuclear Security and Safeguards track. The percentages shown in the parenthesis indicate how much IAEA Nuclear Security Series modules content is incorporated into the course. For instance, Nuclear Forensics and Attribution borrowed fully from NS 19 **[*22*]**, Methods and Instruments for Nuclear & Radioactive Material Measurements from NS 4 **[*23*]**, Threat Assessment from NS 6 **[*24*]**, and Nuclear and Radioactive Material Accountancy and Inventory Control from NS 13 **[*25*]**.

During the second semester of year one, students in the Nuclear Security and Safeguards track will take PHY-2, PHY-3, and PHY-7 plus any other two courses (following guidance) from the list below.

PHY-1: Nuclear Energy and Nuclear Fuel Circle (85% from NS 3)
PHY-2: Fundamentals of Nuclear Security (75% from NS 1)
PHY-3: Nuclear Forensics and Attribution (NS 19)
PHY-4: Crime Scene Investigation and Forensic Techniques (NS 12)
PHY-5: Threat Assessment (NS 6)
PHY-6: Methods and Instruments for Nuclear & Radioactive Material Measurements (NS 4)
PHY-7: Nuclear and Radioactive Material Accountancy & Inventory Control (NS 13)
PHY-8: Fundamentals of Nuclear Energy Management

The thesis research pursued in the second year will focus on the student's track, but emphasize our current research strengths:

(i) Nuclear forensics and attribution methodologies in support of nuclear security
(ii) Analysis and modeling of nuclear traces and dynamics in complex ecosystems
(iii) Size-resolved radiogenic characterization of atmospheric aerosols and hot particles

The above courses are also intended to enrich our recently developed undergraduate-level Nuclear, Radiation & Health Physics track, where we have tailored experiments focusing on modern microscopy, fundamentals of image formation with applications in nuclear sciences, detector electronics and digital signal and image processing. Furthermore, our course development recently assisted the University of Nairobi's School of Medicine in starting their MSc Forensic Science program. We suggested and developed two 20-hour course modules in their new curriculum, namely Elements of Nuclear Security and Nuclear Forensic Radioanalytics.

Ideally, the new program will both motivate and prepare students for careers in nuclear security. The new course recognizes the interdisciplinary dimensions of nuclear security and adapts the existing program to the emerging needs of the nuclear power program. The promotion of safeguards, safety, and a security culture are integral to the program. However, challenges continue to exist in designing a proper curriculum and identifying appropriate teaching and assessment methods to promote student learning in this exciting area **[*26*]**. Examples of the challenges include a lack of qualified staff to sustain a graduate program which can be accredited and which favorably benchmarks with similar programs in nuclear security elsewhere; the narrowed breadth of the program to fit into our nascent research line in nuclear forensics; and the initial restriction of the program to mostly physics (and related) graduate students, given the interdisciplinary character of nuclear security. However, these challenges are expected to reduce as the program matures and generates enough graduates versed in nuclear security to become faculty, and as research capacity in nuclear security expands beyond nuclear forensics. Furthermore, the gradual maturing of Kenya's nuclear power program will compel infrastructural development in nuclear security, thus providing a partner, as well as stakeholder, to our educational efforts.

B. Nuclear Forensics as a Nuclear Security Education Tool

The Nuclear Security and Safeguards track is strongly supported by a relatively new research line in nuclear forensics. We consider nuclear forensics research as a means to both foster scientific innovation in nuclear security and to support non-proliferation by enabling the identification of high-confidence nuclear forensic signatures. The research aims to support the nuclear security infrastructure necessary for the country's safe handling of nuclear materials and to promote its nuclear power program. Building a nuclear forensics workforce requires a scientific education primarily in physics or chemistry with specialization in radiochemistry, health physics, nuclear physics, etc., followed by hands-on experience working with nuclear material and analytical techniques. Our research group is composed of three faculty, one PhD student, and five MSc students from various backgrounds (physics, chemistry, and nuclear science).

Nuclear forensics—normally pursued to support criminal investigation of illegal use, transfer, or disposal of nuclear and radioactive materials—probes the relationship between the materials' origin and intended use **[*27*]**. Thus, nuclear forensics is a useful tool in the nuclear fuel cycle. The nuclear forensic signatures of interest include isotopic (U, Pu, Th, Co, O, Pb, Sr, Nd, S) chemical (compound, rare-earth element patterns, trace metal, ionic) impurities as well as microstructural information on the materials. As materials move through the nuclear fuel cycle, these nuclear forensic signatures are created, modified, and destroyed; therefore, each step provides information that can be used to constrain the source **[*28*]**. In our research, we emphasize the science behind the detection and attribution of the materials. As trace evidence and microanalysis are ubiquitous in nuclear forensics, we have developed multimodal, machine-learning-enabled nuclear forensic analytical and imaging spectrometry methodologies for this purpose, utilizing chemical (metal, molecular), isotopic, and structural signatures of the analyzed nuclear and radioactive materials to support national nuclear security concerns.

Advances in photonics, especially in optics and imaging spectrometry that enable material analysis at microscale resolution, enable the development of such rapid nuclear forensic analysis methods. As a result of the nuclear renaissance, nuclear proliferation is a growing danger that is further complicated by possibilities of terrorism through the utilization of improvised nuclear devices and/or radiological dispersal devices. Such risk places a critical challenge on the existing nuclear forensics analysis methods, which are usually radiochemical or radiometric and costly, to cope with tasks that demand rapid, direct, and minimally invasive characterization of nuclear and radioactive materials, especially if they are of limited size and/or concealed. This underscores the need to develop new methods and improve on the existing ones, for nuclear materials and post-detonation debris analysis. Analytical capability for micro-size samples is an especially powerful tool for monitoring undeclared nuclear activity, verifying nuclear safeguards, responding to nuclear anthropogenic releases, and analyzing materials from radiological crime scenes. For these purposes, we employ X-ray fluorescence spectroscopy, laser-scanning microscopy, laser Raman microspectrometry, and laser-induced breakdown/ablation molecular isotopic spectroscopy (LIBS/LAMIS) **[*29–31*]**.

While the advantage of combining the above techniques is clear, the interpretive challenges of high-dimensional data **[*32*]** complicate the identity and distribution of nuclear forensic signatures. Incorporating machine learning broadens the techniques' applicability by enabling mining (management, analysis, and visualization of large data sets) and extraction of useful information embedded in the spectra as well as images that are acquired from the instruments while providing greater versatility. For instance, genetic algorithms hybridize deductive models and evolve predictive rules applicable to nuclear forensics attribution, revealing unexpected information. Machine learning further enables amplified analytical sensitivity. The major advantage of machine learning is its ability to represent multivariate data into few dimensions in a graphical interface **[*33, 34*]**, allowing us to use data fusion to derive robust forensic attributions. Our research results are the first systematic nuclear forensics data in the country and will help guide the development of a national nuclear forensic library (NNFL). An NNFL is an essential facility for any country with a nuclear power program and, in Kenya, will bolster response capability to nuclear security events through a broad spectrum of signatures and methods that contribute to nuclear non-proliferation.

C. Leveraging International Partnerships

Forging international links is key to creating a global, nuclear-secure regime. Since 2013, when the University of Nairobi became a member, the activities of the International Nuclear Security Network (INSEN) **[*35*]** have been an important catalyst for our efforts. INSEN's mission is to enhance global nuclear security by developing, sharing, and promoting excellence in nuclear security education. In line with its mission, INSEN assisted in the development of the previously-mentioned new courses at the University of Nairobi via production of teaching materials, professional development opportunities for faculty, and global networking of staff **[*36*]**. Further international cooperation includes the International Science Program's (ISP) support of our nuclear forensics research line. ISP assists lower-income countries in building and strengthening their domestic research capacity and postgraduate education in the basic sciences. ISP funded the purchase of our key research equipment through the grant "Advancing Integrated Machine Learning Enabled Microphotonic Approaches to Multifunctional Disease Diagnostics and Nuclear Forensic Analysis (2017-19)." Our efforts in the nuclear forensics research group have also been supported by The World Academy of Sciences (TWAS) for the Advancement of Science in Developing Countries, which supports sustainable prosperity through research, education, policy, and diplomacy **[*37*]**. In this context, TWAS helped three MSc students pursue research in nuclear forensics at our research group under the grant "Development of Machine Learning Enabled Laser Based Spectrometry and Imaging Approaches for Direct Rapid Nuclear Forensics Analysis and Attribution (2014-16)."

These collaborative efforts and bilateral agreements align with Kenya's commitment to pursue its nuclear power program through international involvement. As such, Kenya has received IAEA support with two national technical cooperation projects in energy planning and for 49 fellowships in nuclear energy fundamentals since 2012. IAEA has especially supported Kenya's quest to foster international partnerships in the development of indigenous capacity, such as the annual training programs created by Texas A&M University's Nuclear Power Institute. Since 2012, these programs, developed in cooperation with the IAEA, have offered supportive training in Nuclear Power Plant Technology.

In the same context, Kenya has signed several memorandums of understanding (MoU) with established nuclear power countries, namely Slovakia, China, Republic of Korea, and Russia. These MoUs aim at enhancing collaboration in the development of Kenya's nuclear power program. Consequently, more than 400 Kenyans have benefited from trainings, fellowships, scientific visits, and technical meetings related to nuclear power, and also through the Masters in Nuclear Engineering at the Kepco International Nuclear Graduate School (KINGS) in the Republic of Korea.

The progress of Kenya's collaborative efforts in the development of nuclear power depends on the endorsement of an Act of Parliament on peaceful uses of atomic energy. This Act should be followed by the creation of a Nuclear Energy Corporation for planning, designing, constructing, operating, maintaining, and managing nuclear power plants. Furthermore, there is a need to create a Nuclear

Regulatory Authority with responsibility for safety, security, and safeguards. KNEB has already established an Inter-Ministerial Working Group, which—under the guidance of IAEA—has developed a Draft National Nuclear Regulatory Bill (2015) and Nuclear Policy **[*38*]**, providing optimism for the future.

IV. Conclusion and Prospects

This paper has assessed the status of education capacity in nuclear security both in response to, and in support of, Kenya's nuclear power program. The nuclear security educational infrastructure's key features have been highlighted in the context of nuclear power. The low levels of nuclear security educational capacity at Kenyan universities have been recognized and appropriate strategies identified for remedying the situation, namely the current effort at the University of Nairobi toward developing educational capacity in nuclear security and research in nuclear forensics. The link between nuclear forensics and nuclear security has been examined in detail. It has been argued that the multimodal photonic microanalytical approach to nuclear forensics research is enabling the identification of a comprehensive combination of nuclear forensic signatures to manage nuclear materials out of statutory control. However, more rapid progress will require stronger involvement of stakeholder networks extending to all sectors of the nuclear fuel cycle. I propose a National Working Group on Education and Knowledge Management in Nuclear Security in Kenya to identify a course of action and the steps required to ensure effective use of the country's infrastructure for nuclear security education. In this regard, the Kenya Nuclear Electricity Board should serve as a think tank to bring all stakeholders together to discuss the plans. KNEB is the promoter of the country's nuclear power program and therefore it must fulfill its role in increasing and sustaining political buy-in and government investment in nuclear security initiatives. This will improve national capacity to build a nuclear power plant earlier than projected.

V. Works Cited

1. IAEA, "Convention on Physical Protection of Nuclear Material and Amendment thereto" (1979).

2. IAEA, International Convention for the Suppression of Acts of Nuclear Terrorism (2005).

3. IAEA, Convention on Nuclear Safety (1994).

4. IAEA, Convention on Early Notification of a Nuclear Accident (1986).

5. IAEA, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (1997).

6. K. Achola, The Past, Present and future of Kenya's Power Sector. *Kenya Eng.* (2013), (available at http://www.kenyaengineer.co.ke/the-past-present-and-future-of-kenya-s-power-sector/).

7. IAEA, *Milestones in the Development of a National Infrastructure for Nuclear Power* (International Atomic Energy Agency, 2015), *IAEA Nuclear Security Series No. NG-G-3.1*.

8. N. Ponomarev-Stepnoi, Nuclear Power of the 21st Century. *Nucl. Eng. Des.* **173**, 21–31 (1997).

9. N. Li, C. Dale, K. Kern, S. Scott, in *Proceedings of 2009 International Congress on Advances in Nuclear Power Plants* (Tokyo, Japan, 2009), vol. 43 of *Report Number INIS-JP-123*.

10. IAEA, Treaty on the Non-Proliferation of Nuclear Weapons (1970).

11. IAEA, Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards (1981).

12. IAEA, *Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control* (International Atomic Energy Agency, 2011), *IAEA Nuclear Security Series No. 15*.

13. Sustainable Nuclear Energy Technology Platform, Working Group on Education, Training and Knowledge Management (ETKM), "Nuclear Education and Training: Key Elements of a Sustainable European Strategy" (Sustanable Nuclear Energy Technology Platform, Brussels, Belgium, 2010), (available at http://hdl.voced.edu.au/10707/208796).

14. *Kenya Nuclear Science & Technology Bill* (2011).

15. IAEA, Reviewing Emergency Preparedness Across the African Region. *Int. At. Energy Agency* (2015), (available at https://www.iaea.org/newscenter/news/reviewing-emergency-preparedness-across-the-african-region).

16. H. K. Angeyo, "Approaches to Education and Training for Kenya's Nuclear Power Program" (Conference Presentation, International Atomic Energy Agency (IAEA) International Conference on Human Resource Development for Nuclear Power Programs: Building and Sustaining Capacity, Vienna, Austria, 2014).

17. IAEA, "Nuclear Security Plan 2010-2013" (Board of Governors General Conference Report GOV/2009/54-GC(53)/18, IAEA, 2009).

18. V. Fedchenko, The Role of Nuclear Forensics in Nuclear Security. *Strateg. Anal.* **38**, 230–247 (2014).

19. United Nations, "UN Security Council Resolution 1540" (Resolution S/RES/1540, United Nations Security Council, 2004).

20. *Educational Programme in Nuclear Security: Technical Guidance* (International Atomic Energy Agency, 2010), *IAEA Nuclear Security Series No. 12*.

21. H. K. Angeyo, New Master Programme and New Supporting Research Line in Nuclear Forensics in Kenya (2017).

22. *Establishing the Nuclear Security Infrastructure for a Nuclear Programme: Implementing Guide* (International Atomic Energy Agency, 2013), *IAEA Nuclear Security Series No. 19*.

23. *Engineering Safety Aspects of the Protection of Nuclear Power Plants against Sabotage: Technical Guidance* (International Atomic Energy Agency, 2007), *IAEA Nuclear Security Series No. 4*.

24. *Combating Illicit Trafficking in Nuclear and Other Radioactive Material: Technical Guidance Reference Manual* (International Atomic Energy Agency, 2007), *IAEA Nuclear Security Series No. 6*.

25. IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities, Revision 5* (International Atomic Energy Agency, 2011), *IAEA Nuclear Security Series No. 13*.

26. C. Hobbs, M. Moran, *Developing Educational Courses in Nuclear Security: A Handbook* (King's College London, 2014).

27. M. Robel, M. J. Kristo, M. A. Heller, in *50th Annual Meeting* (Tucson, AZ, 2009; https://e-reports-ext.llnl.gov/pdf/374432.pdf), vol. LLNL-CONF-414001.

28. L. Borg, I. Hutcheon, "Forensic Analysis of Samples from the Nuclear Fuel Cycle" (LLNL-TR-636458, Lawrence Livermore National Laboratory, 2013), (available at https://e-reports-ext.llnl.gov/pdf/755525.pdf).

29. H. K. Angeyo, B. Bhatt, A. Dehayem-Massop, J. N. Malaba, J. N. Onkangi, B. Wanyonyi, "Nuclear Forensics Utilizing Machine Learning Enabled Peak-Free LIBS and LAMIS" (Conference Presentation, 9th Euro-Mediterranean Symposium, Pisa, Italy, 2017).

30. J. N. Onkangi, H. K. Angeyo, D. M. Mania, "Utility of Machine Learning-Enabled LIBS in Forensic Analysis of High Level Nuclear Waste" (Conference Presentation, 9th Euro-Mediterranean Symposium, Pisa, Italy, 2017).

31. J. M. Webwile, H. K. Angeyo, A. Dehayem-Massop, "Quantitative Raman Microspectrometry of Uranium in Individual Aerosols over a Model Nuclear Atmosphere" (Conference Presentation, 9th Euro-Mediterranean Symposium, Pisa, Italy, 2017).

32. V.-D. Hodoroaba, M. Radtke, L. Vincze, V. Rackwitz, D. Reuter, X-ray Sscattering in X-ray Fluorescence Spectra with X-ray Tube Excitation – Modelling, Experiment, and Monte-Carlo Simulation. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At.* **268**, 3568–3575 (2010).

33. C. K. Egan, S. D. M. Jacques, R. J. Cernik, Multivariate Analysis of Hyperspectral Hard X-ray Images. *X-Ray Spectrom.* **42**, 151–157 (2013).

34. R. R. Meglen, Examining Large Databases: A Chemometric Approach Using Principal Component Analysis. *J. Chemom.* **5**, 163–179 (1991).

35. International Atomic Energy Agency, "Educational Programme in Nuclear Security," *IAEA Nuclear Security Series No. 12* (IAEA, Vienna, Austria, 2010), (available at http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1439_web.pdf).

36. APS/AAAS, "Nuclear Forensics - Role, State of the Art, and Program Needs" (ISBN 978-0-87168-720-3, American Physical Society and American Association for the Advancement of Science, Washington, DC, 2008).

37. A Surge of Innovation: The state of science in the Arab Region. *World Acad. Sci. Newsl.* **29** (2017).

38. The Energy Bill - Government of the Republic of Kenya (2015).