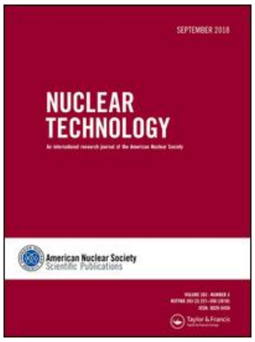

Taylor & Francis
Taylor & Francis Group

Nuclear Technology

ISSN: 0029-5450 (Print) 1943-7471 (Online) Journal homepage: https://www.tandfonline.com/loi/unct20

Estimation of Decay Heat in Ghana Research Reactor-1 Auxiliary Components Using ORIGEN-S: A Case Study

R. G. Abrefah & P. A. A. Essel

To cite this article: R. G. Abrefah & P. A. A. Essel (2019): Estimation of Decay Heat in Ghana Research Reactor-1 Auxiliary Components Using ORIGEN-S: A Case Study, Nuclear Technology, DOI: 10.1080/00295450.2019.1585736

To link to this article: https://doi.org/10.1080/00295450.2019.1585736

NUCLEAR TECHNOLOGY
© 2019 American Nuclear Society
DOI: https://doi.org/10.1080/00295450.2019.1585736

Technical Note

Estimation of Decay Heat in Ghana Research Reactor-1 Auxiliary Components Using ORIGEN-S: A Case Study

R. G. Abrefah[a,b]* and P. A. A. Essel[a]

[a]*University of Ghana, School of Nuclear and Allied Sciences, P.O. Box AE1, Atomic Energy, Accra, Ghana*
[b]*Nuclear Regulatory Authority, P.O. Box AE50, Accra, Ghana*

Received January 16, 2019
Accepted for Publication February 19, 2019

Abstract — *The high-enriched-uranium core of the Ghana Research Reactor-1 has been removed and replaced by low-enriched-uranium fuel. Some components of the reactor that were not transported to China as part of the Chinese take-back program will be managed and stored in Ghana. The amount of decay heat and activity in these components were estimated using the ORIGEN-S code in order to select the best waste management option and to protect the personnel that will handle these components. The results obtained showed relatively low decay heat and activity in the reactor components that were considered in this study.*

Keywords — *ORIGEN-S, decay heat, activity, waste storage strategy.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Following the shutdown and core removal of the Ghana Research Reactor-1 (GHARR-1), production of decay heat due to radiation effects will be retained in the core and other auxiliary parts of the reactor; the energy of the alpha, beta, or gamma radiation is converted into the thermal movement of atoms. Decay heat is the heat released as a result of radioactive decay. Decay heat occurs naturally from decay of long-lived radioisotopes that are primordially present from the Earth's formation.

Decay heat plays an important role in reactor heat generation during the relatively short time after the reactor has been shut down and nuclear chain reactions have been suspended. The decay of the short-lived radioisotopes created in fission continues at high power for a time after shutdown. The major source of heat production in a shutdown reactor is due to the beta decay of radioactive elements recently produced from fission fragments in the fission process. In a nuclear reactor, the fission of heavy atoms such as isotopes of uranium and plutonium results in the formation of highly radioactive fission products. These fission products radioactively decay at a rate determined by the amount and the type of radioactive nuclides present. Some radioactive atoms will decay while the reactor is operating, and the energy released by their decay will be removed from the core along with the heat produced by the fission process. All radioactive materials that remain in the reactor at the time of shutdown will continue to decay and release a significant amount of thermal energy.

If the reactor has had a long and steady power history, at the moment of reactor shutdown, decay heat from these radioactive sources is still 6.5% of the previous core power. About 1 h after shutdown, the decay heat will be about 1.5% of the previous core power. After 1 day, the decay heat falls to 0.4%, and after 1 week, it will be only 0.2% (Ref. 1). Because radioisotopes of all half-life lengths are present in nuclear waste, enough decay heat continues to be produced in spent fuel rods to require them to spend a minimum of 1 year, and more typically 10 to 20 years, in a spent fuel pool of water before being further processed. However, the heat produced during this time is still only a small fraction (less than 10%) of the heat produced in the first week after shutdown.[2]

If no cooling system is working to remove the decay heat from a crippled and newly shutdown reactor, the decay

---

*E-mail: adibola2001@yahoo.com

heat may cause the core of the reactor to reach unsafe temperatures within a few hours or days, depending upon the type of core. These extreme temperatures can lead to minor fuel damage [e.g., a few fuel particle failures (0.1% to 0.5%)] in a graphite-moderated gas-cooled design[3] or even major core structural damage (partial meltdown) in a light water reactor[4,5] or liquid-metal fast reactor. Chemical species released from the damaged core material may lead to further explosive reactions (steam or hydrogen), which may further damage the reactor.[6]

Moreover, radioactive isotopes will eventually decay to stable material. However, while they are decaying, they emit radiation (α, β^-, β^+, and γ). Some isotopes decay in hours or even minutes, but others decay very slowly. Those high-level wastes are hazardous to humans and other life forms because of their high radiation levels. For example, 10 years after removal from a reactor, the surface dose rate for a typical spent fuel assembly exceeds 10 000 rems/h, whereas a fatal whole-body dose for humans is about 500 rems (if received all at one time). Furthermore, if constituents of these high-level wastes were to get into groundwater or rivers, they could enter into food chains. Although the dose produced through this indirect exposure is much smaller than a direct exposure dose, there is a greater potential for a larger population to be exposed. That is the reason why nuclear wastes must be stored in a way that provides adequate protection for very long times.

Heat production due to delayed neutron–induced fission or spontaneous fission is usually neglected. Activation of light elements in structural materials plays a role only in special circumstances and is usually excluded from decay heat analyses.

It is important to know precisely the amount of decay heat in the core and other parts of the reactor. GHARR-1 is set to convert from high-enriched-uranium (HEU) fuel to low-enriched-uranium fuel. The HEU fuel pins will be transported back to their home of origin. However, other components like the end plugs, control rod guide tube, grid plates, shim tray, and top shim plates will all be handled by personnel of GHARR-1. Subsequently, these components will be stored in a stainless steel cask. It is imperative to determine the decay heat and radioactivity emanating from these parts to secure the safety of staff.

II. GHANA RESEARCH REACTOR-1

GHARR-1 is a commercial miniature neutron source reactor (MNSR) similar to the Canadian SLOWPOKE research reactor in design.[7] GHARR-1 is a 30-kW tank-in-pool reactor, producing a peak or maximum thermal neutron flux in the core and its inner irradiation channels of 1×10^{12} n/cm^2·s. The reactor is designed to be compact and safe and has made valuable contributions in the nuclear power industry. It is used mainly for research and development in reactor and nuclear engineering, neutron activation analysis, production of short-lived radioisotopes, human resource development for Ghana's nuclear program, and education and training.

At present, GHARR-1's core consists of fuel assembly HEU (UAl_4 alloyed) fuel elements arranged in ten concentric rings about a central control rod guide tube which houses the reactor's only control rod. The control rod's reactivity worth is about 7 mk, providing a core shutdown margin of 3 mk of reactivity. The small core has a low critical mass. However, its relatively large negative temperature coefficient of reactivity is capable of boosting its inherent safety properties. The small size of the core facilitates neutron leakage and escape in both axial and radial directions. To minimize such loses and thereby conserve neutron economy, the core is heavily reflected on the side and underneath the fuel cage by a thick annulus and slab of beryllium alloy material.[7] Figures 1 and 2 show the pictorial details of GHARR-1.

III. THEORY

ORIGEN-S was employed to estimate the decay heat as well as the radioactivity in the auxiliary components removed from the reactor. In determining the time dependence of nuclide concentrations, ORIGEN-S solves for the formation and disappearance of a nuclide by radioactive disintegration and neutron transmutation. Mathematically,

$$\frac{dN_i}{dt} = Formation\ Rate - Destruction\ Rate - Decay\ Rate\ . \tag{1}$$

The time rate of change of the concentration for a particular nuclide N_i in terms of these production and removal processes can be written as

$$\frac{dN_i}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j + \Phi \sum_{k=2}^{m} f_{ik}\sigma_k N_k - (\lambda_i + \Phi\sigma_i)N_i (i = 1, 2, \ldots . m)\ , \tag{2}$$

where

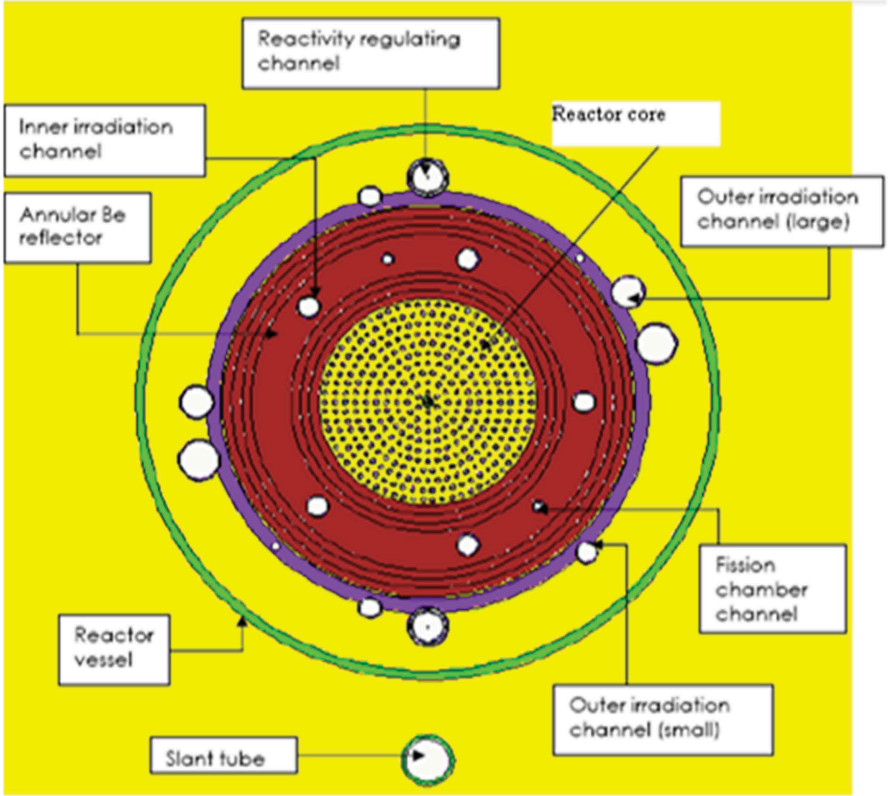

Fig. 1. GHARR-1 core configuration showing fuel region.

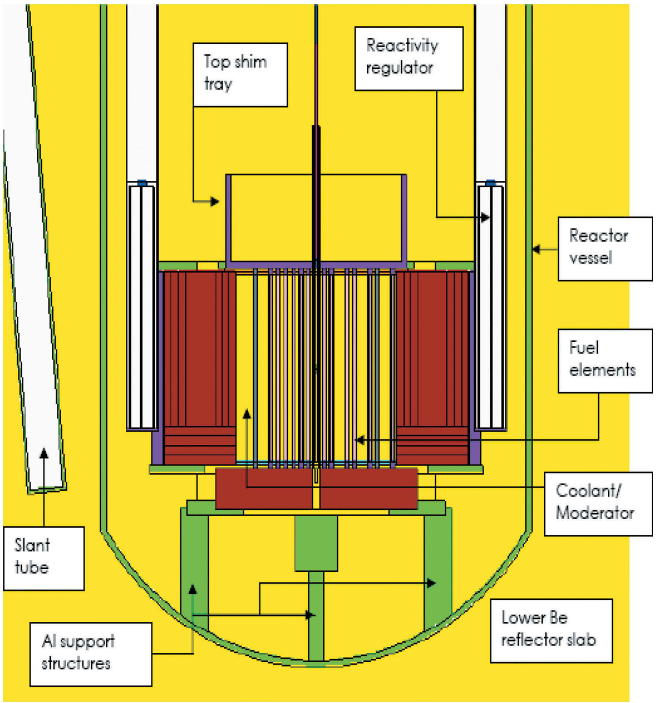

Fig. 2. MCNP plot of vertical cross section of GHARR-1.

N_i = atom density of nuclide i

λ_i = radioactive disintegration constant of nuclide i

σ_i = spectrum-averaged neutron absorption cross section of nuclide i

Φ = space- and energy-averaged neutron flux

l_{ij} = branching fractions of radioactive disintegrations from other nuclides j

f_{ik} = branching fractions for neutron absorption by other nuclides k that lead to the formation of species i.

Equation (2) is written for a homogeneous medium containing a space- and energy-averaged neutron flux Φ, with one-group, flux-weighted average cross sections σ_i representing the reaction probabilities.

The elements of the transition matrix a_{ij} are the first-order rate constants for the formation of nuclides i from nuclides j. The solution in terms of these rate constants is written as

$$N_i = N_i(0) + t\sum_j a_{ij}N_j(0) + \frac{t}{2}\sum_k \left[a_{ik}t\sum_j a_{kj}N_j(0)\right] + \frac{t}{3}\sum_m \left\{ai_m \times \frac{t}{2}\sum_k \left[a_{ik}t\sum_j a_{kj}N_j(0)\right]\right\} + \ldots\ , \tag{3}$$

where the range of indices j, k, and m is 1 to M for an $M \times M$ matrix $\mathbf{A}$.

ORIGEN-S performs a flux-correction calculation to obtain an estimate of the average flux over the irradiation time interval t.

The time-dependent linear Boltzmann transport equation is given as

$$\Psi(r,v) = \int\left[\int\Psi(r',v')C(v' \rightarrow v,r)dv' + Q(r',v)\right] \times T(r' \rightarrow r,v)dv' \ , \tag{4}$$

where

$\Psi(r,v)$ = particle collision density
$Q(r',v)$ = source term
$C(v' \rightarrow v,r')$ = collision kernel, change velocity at fixed position r'
$C(r' \rightarrow r,v)$ = transport kernel, change in position r at a fixed velocity v
$\Psi(r,v) = \dfrac{\Psi(r,v)}{\sum(r,|v|)}$ = angular flux
$v(r,|v|) = \displaystyle\int_{\vec{\Omega}} \frac{\Psi(r,v)}{\sum(r,|v|)} d\vec{\Omega}$ = scalar flux, where $v = |v|\vec{\Omega}$
$\overrightarrow{d\Omega}$ = solid angle.

The source term for the Boltzmann equation is

$$Q(r,v) = \left\{\begin{array}{l} S(r,v) \\ S(r,v) + \displaystyle\int\Psi(r,v')F(v' \rightarrow v,r)dv' \\ \dfrac{1}{\kappa}\displaystyle\int\Psi(r,v')F(v' \rightarrow v,r)dv' \end{array}\right\} , \tag{5}$$

where

$S(r,v)$ = fixed-source term
$F(v' \rightarrow v,r)$ = creation operator (due to fission); particles at (r,v') create particles at (r,v)
κ = eigenvalues.[8,9]

IV. METHODOLOGY

The ORIGEN-S deck is divided into blocks (each block contains important information that helps in depleting the core). The core depletion takes into consideration the composition of decay nuclides and fission products as well as light elements as a result of burnup. Key parts of the input deck include the nuclide identity, the composition of the nuclide, and the desirable results as well as specific desirable neutron and gamma energies (that is, all these pieces of information are vital and used to set up the input deck). The nuclide composition and continuous nuclide feed rate were specified for nuclides of interest.

The cutoff fraction was overridden to give way for the output summary table. Two vectors were set up in the deck, and the nuclide concentration data in one vector were moved into the other vector depending on the calculation of interest. The decay and cross-section libraries were specified so that the code works with those selected data. The code was instructed to control the printing of only relevant input data libraries. The deck was also set up to track the photon production rate in 39 energy groups. Since the code was written for nuclear power plants, the code was instructed to read nuclide identifiers for replacement decay and cross-section data cards in order to suit the MNSR.

The average burnup, flux, and specific power for an irradiation was calculated. Neutron flux and power were specified for irradiation of a single interval. Decay of a single interval was also specified.

The table type to be printed (element, nuclides, or summary) was specified for actinides, light elements, and fission products. The power history of GHARR-1 used was 15 kW. It was assumed to operate for 4 h/day, 4 days/week, 4 weeks/month, and 11 months/year. A cumulative number of operating days were used. The decay time in steps of ten was used in order to monitor the short-lived radionuclides. The average of running power, especially the historic operation, was determined and used. Near the end of life of the fuel, finer detail depletion is desirable, but the historic operation would have lost its entire short-lived isotope; hence, coarse detail depletion is more convenient (20 years, 10 months, 10 weeks, 1 week, and the last 5 days to the core removal).

The succession of neutron flux values (neutron per centimeter square per second) on the regions considered (end plugs, control rod guide tube, grid plates, shim tray, and top shim plates) during the different time intervals of reactor operation was used. Since there is no fuel in these areas, no fission power can be defined, so the neutron flux obtained from MCNP tallies on these regions is used instead to determine their activation.

V. RESULTS AND DISCUSSION

Predictably, the decay heat decreased as the time increased for all the components that were considered.

The results are generally minimal for all the components that were considered. However, the decay heat from the control rod guide tube fell within the lowest range probably because the reactor was shut down for about 6 months prior to core removal. The amount of time (180 days) allowed for cooling could also be linked to the shutdown time before core removal. Figure 3 presents the decay heat results obtained from the five components that were considered in this work.

The amount of radioactive materials present in the reactor at the time of shutdown could be attributed to the power levels at which the reactor operated. Again, the duration of operation is also very relevant. GHARR-1 is operated at half-power (15 kW) at most times in order to compensate for loss of reactivity. The low levels of decay heat could also be explained by the fact that over the period that the reactor was shut down, the amounts of unstable fission products and actinides that decay to produce heat are greatly reduced. Fissions induced by delayed neutrons and reactions induced by fission neutrons are nonexistent thereby reducing the sources of decay heat.

Radioactivity naturally decays over time, so radioactive waste has to be isolated and confined in appropriate disposal facilities for a sufficient period until it no longer poses a threat. The time radioactive waste must be stored depends on the type of waste and radioactive isotopes. Figure 4 outlines the results for radioactivity as obtained in the control rod guide tube, end plugs, grid plates, shim tray, and top shim plates.

The activity of the top beryllium shim plate recorded the highest values while the control rod guide tube recorded the lowest activity. The relatively high activity at the beryllium shim plates could be attributed to the ability of the beryllium to react with both alpha particles and gammas to produce neutrons. Generally, the activities also reduced with time for all the components. The activity levels may be a result of the decay of the parent radionuclides. There is initially a fast decrease in activity as the short-lived radionuclides with short half-lives decay into more stable nuclides. However, the trend begins to slow down after the fifth day when most of the short-lived nuclides might have decayed. The low temperature in the shutdown reactor could also account for the activity levels. The low-temperature level will retain the density of the moderator thereby reducing the level of activity measured in the reactor.

VI. CONCLUSION

Consequent to operating a reactor power history of 15 kW, the reactor was estimated to operate for 11 months in 1 year, 4 weeks in 1 month, 4 days in 1 week, and 4 h every day. At the end of the irradiation period, the core was allowed to cool for 180 days. The decay heat and activity of the radionuclides were estimated for the control rod guide tube, end plugs, grid plates, shim tray, and top shim plates, respectively. This study was to ascertain the amount of decay heat associated with these components that were not going to

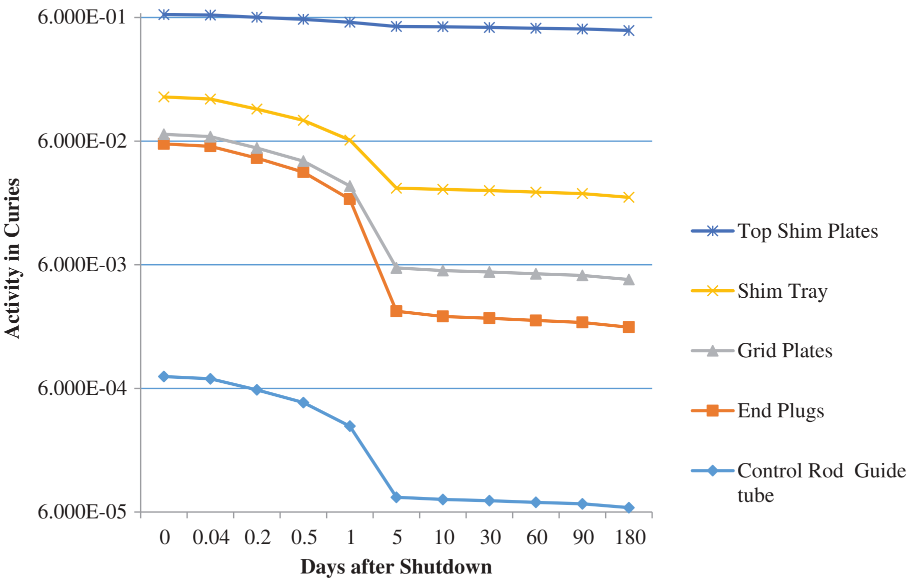

Fig. 3. Graph of reactive decay in units of curie from 0 to 180 days after shutdown.

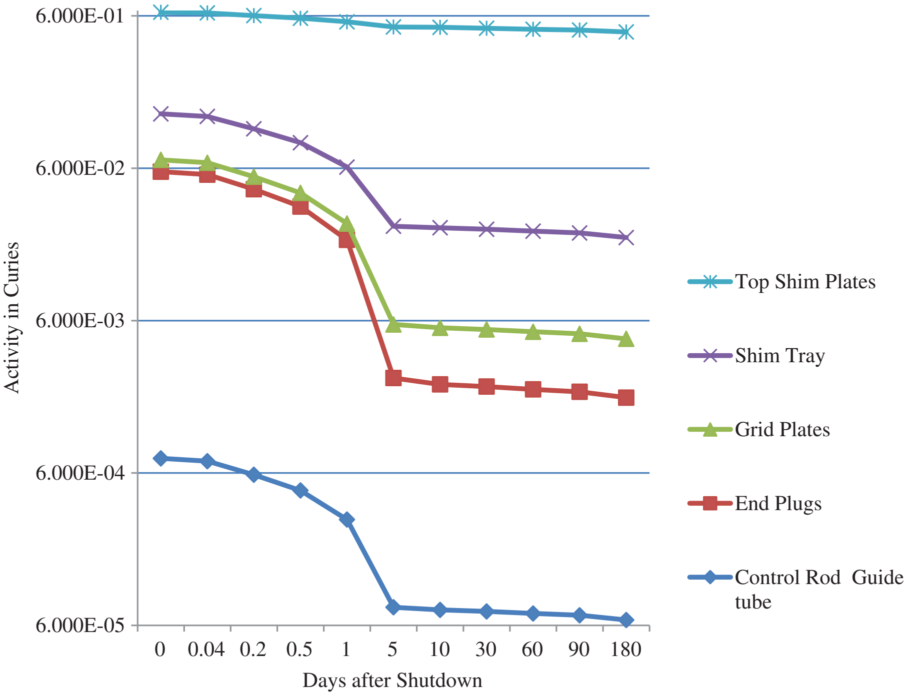

Fig. 4. Graph showing activity in units of curie from 0 to 180 days after shutdown for various components.

be transported to China as part of the take-back program of the Chinese HEU MNSR (so that the results will inform proper handling and storage of these components in Ghana). The results showed that the decay heat levels of all the components that were considered were relatively low compared to other reactors.[2] The activity levels were considerably low. Results from the work will assist in choosing the right waste management strategy for the HEU reactor components.

ACKNOWLEDGMENT

We give special thanks to the staff of the Nuclear Engineering Department of Argonne National Laboratory for their unflinching support.

References

1. “Spent Fuel,” Argonne National Laboratory (Apr. 2011); https://www.ne.anl.gov/pdfs/nuclear/nuclear_fuel_yacout.pdf (current as of Jan. 26, 2013).
2. M. RAGHEB, “Decay Heat Generation in Fission Reactors,” in “Probabilistic, Possibilistic, and Deterministic Safety Analysis, Nuclear Applications,” p. 20, University of Illinois Urbana-Champaign (2011); http://mragheb.com/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Title-Preface.pdf (current as of Jan. 26, 2013).
3. “Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors,” IAEA TECDOC 978, International Atomic Energy Agency (Nov. 2007).
4. “Report of the President’s Commission on the Accident at Three Mile Island, The Need for Change: The Legacy of TMI”; http://large.stanford.edu/courses/2012/ph241/tran1/docs/188.pdf (Oct. 30, 1979) (current as of Jan. 26, 2013).
5. M. HOLT, R. J. CAMPBELL, and M. B. NIKITIN, “Fukushima Nuclear Disaster,” Congressional Research Service (Jan. 18, 2012).
6. “Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience, Report of the Chernobyl Forum Expert Group ‘Environment,’” International Atomic Energy Agency (2006).
7. E. H. K. AKAHO et al., “Safety Analysis Report for Ghana Research Reactor-1,” GAEC-NNRI-RT-26, Ghana Atomic Energy Commission (1995).
8. R. BREWER, “Criticality Calculations with MCNP5: A Primer,” LA-UR-09-00380, Los Alamos National Laboratory (2009); https://www.mragheb.com/npre%20457%.
9. L. L. CARTER and E. D. CASHWELL, “Particle Transport Simulation with the Monte Carlo Method,” ERDA Critical Review Series, TID-26607, Energy Research and Development Administration (1975).