**Safeguarding Biodiversity and Future Generations: An Application of RESRAD Codes for Nuclear Emergency Planning and Response**

S. Bello 1\*, J. Simon 2, U.F Ahmad 3, A.S Aliyu 2, I. Godwin 4, Nasiru, A.M 5 and J.A, Yusuf 6.

1 Department of Physics, Umaru Musa Yar'adua University, Katsina.

2 Department of Physics, Ahmadu Bello University, Zaria.

3 Centre for renewable energy research, Bayero University Kano

4 Tomsk Polytechnic University, Lenin Ave, 30, Tomsk, Russia.

5 Department of Radiological safety, Nigerian nuclear regulatory authority

6 Health Physics and Radiation Biophysics section, Centre for energy research and training, Ahmadu Bello University, Zaria.

**Correspondence Email & Phone:** sbellojby@gmail.com; +2348166791940

Abstract – *The Chernobyl and Fukushima nuclear accidents have significantly impacted the public's perception of nuclear energy and its potential benefits. To fully harness nuclear technology's potential for contributing to the Sustainable Development Goals (SDGs), as highlighted by the IAEA bulletin of September 2016, we must restore public confidence in this energy source. Emergency preparedness and response is a cardinal principle of radiation protection, and the literature review indicates that most research and energy reactors worldwide have modelled hypothetical accident release scenarios. However, most of these models only considered respirable gaseous radionuclides released from the reactor core and failed to consider other possible exposure media, routes, and scenarios. In this paper, we propose a framework for using the RESRAD family of codes to improve emergency preparedness and response planning, especially in Africa, where site-specific data is lacking. By critically analysing related literature through a desk review, we demonstrate the application of these codes in biodiversity conservation, protecting people and the environment, and safeguarding future generations. Our proposed frameworks, if implemented, will build public confidence in nuclear energy projects in Africa, restoring public confidence and consequently help in solving the lingering energy crisis on the continent.*

**Keywords:** Nuclear accident, RESRAD, Nuclear power, radiological assessment, Africa.

I. Introduction

 Safeguarding biodiversity and future generation refers to taking actions to protect and preserve the variety of life on earth and ensuring that future generations can also benefit from a healthy and diverse environment. Nuclear energy has been shown to have many advantages but when an accident occurs, it can have devastating effects and irreparable harm to the environment and living things (Aghaie et al., 2019). During normal operations, nuclear reactors do not release remarkable amount of radionuclides to the environment but during accident, severe risks to the environment and living organisms are possible (Fairuz and Sahadath 2020). Siting a nuclear reactor for electrical power generation requires a safety analysis of the impacts it will have to the people and the environment during an incident or an accident no matter how worse it will be. The content of the safety analysis report includes radiological risk assessment of radiation doses and cancer risks under different severe accident release scenarios for proper nuclear emergency response planning. Three mile island, Chernobyl and Fukushima accidents made people doubt the safety of nuclear power plants and one of the key lessons learnt Lesson learnt from it is by the radiation protection community, is in the handling of the incident and the need to improve the public perception of nuclear safety and security in terms of reactor accident management on-site and off-site (Simonis et al., 2015; Nagataki et al., 2013; Evangeliou et al., 2014; Gonzalez et al., 2013 and Koo et al.., 2014). For the purpose of emergency preparedness and response, IAEA and national regulatory agencies require safety analysis reports with the postulations of accidents involving the release of radioactive substances into the environment, for existing and planned nuclear installations (Energy agency, 2000). Assessment of possible environmental radiological contamination risks in all nuclear installations facilitates; emergency response preparedness, development of mitigation strategies, advice stakeholders and decision makers and inform the public of the safety and security of such nuclear facilities (Simon et al., 2022). The data is needed for: creating documentation for safety and accident, safety analysis report, emergency preparedness and response, site permitting, consequences on the environment and society is used as feedback for the design and safety of the reactor and estimation of protection and mitigation measures in the environmental accidents. Some researchers studied actual accidents in the nuclear facility (Zhu et al. 2014; Mitrakos et al. 2016; Lebel et al. 2017; Park et al. 2017; Piguet et al. 2019; Bolshov et al. 2019; Kim et al. 2019; Mazur 2019; Al-Kloub et al. 2020; Aly et al. 2020; Andrade et al. 2020; Liland et al. 2020) using different models. However most of these researchers considered respirable gaseous radionuclides released from the reactor core and failed to consider other possible exposure media, routes, and scenarios. In this paper, we propose a framework for using the RESRAD family of codes to improve to extend the analysis to the other media for better emergency preparedness and response planning, especially in Africa, where site-specific data is lacking. The framework summarizes the key considerations for applying the RESRAD codes in safeguarding biodiversity and ensuring the protection of future generation especially in the context of Africa where site specific data is lacking. The work if implemented will help in building public confidence in nuclear energy projects in Africa and consequently pave way to the inclusion of nuclear energy in the energy mix.

**II. Brief about the RESRAD software**

 RESRAD is a Computer model in the form of a software for the estimation of radiation doses and Cancer risks associated with residual radioactivity in soil or any other material. It is a very helpful tool for specific evaluation of environmental contaminants for a real or hypothetical exposure scenario. The RESRAD codes were developed by the US DOE and US NRC to evaluate radiologically contaminated sites (Yu et al., 1999, 2000, 2001 and 2007). The code is used to derive clean up criteria or derived concentration guideline levels (DCGLs) and estimate radiation dose or risk from residual radioactive material under various scenarios using appropriate parameters. The latest version of the code contains 92 principal radionuclides and 153 associated radionuclides. The codes allow the user to specify most of the environmental bioaccumulation and transfer factors as well as exposure related factors such as ingestion and inhalation factors which narrows down the calculation, to site specific for better reliability of the outputs. However, lack of data through reliable exposure handbooks and/or publications in Africa hinders its optimal utilization. The question that begs for answer is how can we in Africa utilize these codes despite the lack of site specific data and still obtain realistic results? The codes have default values for almost all the parameters and also have default probability distribution for most uncertain and sensitive parameters.  The default conversion factors for ingestion and inhalation were based on EPA’s FGR 11 and 13 (Eckerman et al., 1988). The codes are incorporated with other codes depending on the intended purpose. For example, for receptors located at the boundary of the contaminated sites, RESRAD-OFFSITE is used based on its incorporation with the atmospheric dispersion model links (CAP 88 computer code) (Parks 1997) and the groundwater transport model (Yu et al., 2001). RESRAD ONSITE is used for radiological risk assessment of receptors living on site of the contamination. If one is interested in the radiological risk assessment of workers and the public for recycling of materials containing traces of radioactivity RESRAD-RECYCLE is the preferred option (Yu et al., 2001). The code is adaptable to specific exposure situations and is readily available for free over the internet to any member of the public (<http://evs.anl.gov/resrad>).

It is a very dynamic model that not only accounts for radiological decay and ingrowth, but also project impacts to ground water over time. The default period of evaluation is 1000 years. When the risk assessor enters the parent radionuclide activity concentration, RESRAD automatically   assigns value to the daughter. The risk assessor should consider the appropriate concentration of each of these radionuclides based on the site knowledge or reasonable rules of thumb. If the site data is not available for each radionuclide, concentrations should be estimated else risks will be underestimated. The default assumptions can be that all radionuclides in a series are present at the same concentration (secular equilibrium). This assumption may be typically   conservative, but may not be depending on the age and process history of the radioactively contaminated soil. RESRAD   always makes default assumption about the relative concentrations of series radionuclides. It is up to the user to change the default assumptions to match the site.

**III. Determination of core inventory and source term for use in the RESRAD code**

Hypothetical accidents are normally considered based on two most likely accident scenarios that might likely occur during the lifetime of a nuclear reactor that is; design basis accident and beyond design basis accident. The beyond design basis accident (BDBA) scenario is considered in an emergency planning purposes because it is always more severe than the design basis accidents (DBA). Example of DBA include: total station blackout, heavy earthquake causing the reactor to collapse, off site power source was cut off and emergency diesel generator failed, reactor pressure vessel leaked water thereafter they remained uncovered with water which resulted in core meltdown and subsequent releases of radioactive material to the surrounding atmosphere (IAEA –TECDOC-1844). Other causes of nuclear reactor accidents include reactivity transients, loss of flow accidents and loss of coolant accidents. To use RESRAD codes for the radiological assessment following a hypothetical or real accident, the source term (activity concentration) of the radionuclides of interest should be generated. Depending on the RESRAD code type to be used, the activity concentration generated should be converted to the appropriate units of the RESRAD inputs, for example, the gaseous radionuclides activity concentrations are usually provided in Bq/m3 and some RESRAD codes such as OFFSITE and ONSITE utilizes concentrations in Bq/g. There are many soft wares that can be used to calculate the source term. For instance, Origen 2.1 can be used for inventory calculations. SCALE for Triton can also be used for depletion analysis (with codes like KENO VI Performing the Neutron transport using Monte Carlo Computational technique), depending on the RESRAD code type to be used, the solid, liquid or gaseous fission products can be selected to get the inventory (Simon et al., 2022). Once the core inventory is obtained, transfer factors from IAEA Tech docs can be used to obtain the source term in Becquerel and finally the activity concentration. Alternatively, where possible, the information of the activity concentrations of the radionuclides can obtained via experimentation or a sophisticated model (source term) or time series of information.

**IV. Application of RESRAD in safeguarding Biodiversity and future generation**

The code is applicable in safeguarding biodiversity, present and future generations due to its ability to effectively carry out the following for any given time from now up to 100,000 years:

1. Calculate the derived concentration guides (concentrations that will comply with dose or risk based clean up or release requirements of a regulator).
2. Calculate the annual effective dose or lifetime cancer risks to workers and the members of the public resulting from exposures to residual radioactivity in soil or any other material.
3. Calculate concentrations of radionuclides in various media (groundwater, air, surface water) resulting from exposures to residual radioactive material in soil.
4. Support cost benefit analysis that can help in the clean-up decision making process.

To safeguard biodiversity and future generation, radiation total effective dose equivalent (the sum of the external and internal radiation dose) and cancer risk is used. The dose limits/constraints used as the basis for the guidelines depends on the requirements of the regulations and the selection of the land use scenario. For compliance demonstration, US DOE and US NRC use 0.25 mSv/year as the general constraint for soil clean up or site decontamination. The controlling principle is that the annual effective dose received by members of the public from residual radioactive materials predicted by a realistic but reasonably conservative analysis of the actual or likely future use of the site and calculated as the total effective dose equivalent should not exceed the dose constraint of 0.25mSv/year. In Africa, most of our nuclear regulatory agencies have adopted the threshold dose of 1 mSv/year recommended by ICRP for members of the public in their basic safety standards as against the US NRC 0.25 mSv/year recommendation, due to social and economic considerations. The 1 mSv/year is for all the pathways and sources combined (excluding background and medical exposures). Therefore potential doses from residual radioactivity must be well below the primary dose limit. It is worth noting that, even the ICRP recommends establishing dose constraints lower than 1 mSv/year dose limit, hence it is consistent with DOE that set 0.25 mSv/year. However, the 0.25 mSv/year DOE guidance ensures that the final dose limit  based on a realistic assessment of future use of the subject property is sufficiently protective that the other less likely but plausible use scenarios will not cause potential doses to exceed 1 mSv/year. The choice of the exposure parameters should be done in such a way that it gives the highest predicted lifetime dose. Exposure pathways and the scenarios as well as the associated assumptions are depicted in fig 1 (Yu et al., 2001).  In doing radiological assessments, the worst case scenario (the resident farmer considered as the critical population group) should be used even if it is not realistic because it is the most restrictive and will therefore indicate that the potential uses for all acceptable scenarios will not exceed the limit of 1 mSv/year. This ensures that the biodiversity is conserved and future generations are protected.



Fig 1: Exposure pathways to be considered under different scenarios

**V. Pathway analysis for deriving soil concentration guides**

In calculating how big a dose an individual will receive from the radionuclides inhaled or ingested, we must first understand how the material will interact with his/her body, including where  if any it may concentrate, how   long it will remain in the  body, and what kind of damage it  will do before being excreted or exhaled. Currently all this information is contained in a single constant called dose conversion factors (DCFs). The DCFs relates the total lifetime dose received by   the individual to the amount of radionuclide that is ingested or inhaled. DCFs for adults are different from that for children. Dose/exposure analysis deals with the derivation of dose conversion factors (DCFs) often from Federal guidance reports (FGR 11 or 13 morbidity or mortality) for the radiation dose that will be incurred by the exposure to ionizing radiation (EPA 1999, Buffalo, 2002). The default dose conversion factors in RESRAD original version is for adults, and thus require significant adaptation in order to calculate doses to children. DCFs in FGR 11 - the default used by  RESRAD as published by USEPA in its 1988 FGR  No.11 were developed for a model individual called “Reference man” defined originally in ICRP, 1974 as “ a Man between 20-30 years of age, 70 kg weight, 170 cm height, and lives in a climate of from 10 – 20 degree Celsius.  He is a Caucasian and is a western European or North American in habit and custom”. Doses to   infants and children can be calculated using DCFs from ICRP that were published 1989 to 1996 (ICRP, 1989, 1993, 1995 and 1996). To simplify the problem of dealing with different ages, ICRP five specific age ranges, which are comparable to those of EPA in the 2002 update to the EPA’s FGR No.13 should be used. The parameters that control the rate of radionuclides release into the environment and the severity and duration of human exposure at a given location are determined by patterns of human activity referred to as exposure scenarios especially those that will likely result in the largest exposure to individuals (Yu et al., 2001). The major exposure pathways used to derive site specific guidelines are depicted in fig 1. Other minor exposure pathways are not taken into account in deriving soil guidelines because the dose distribution from these pathways is expected to be insignificant. The details about assumptions of the pathways is in Yu et al., 2001.

Fig 2: Major exposure routes and pathways

The basic criterion for releasing a site for use without affecting the biodiversity, present and future generation is that the radiological release criteria be satisfied. One of the key considerations is that there are over hundred parameters and most of the parameters have to be kept as default. However, if there is sound justification for changing some parameters then that should be done and the justification clearly provided. For reliable results, some specific parameters that should be modified as much as possible, despite the paucity of data are; area of contaminated zone, thickness of contaminated zone, length parallel to aquifer flow, density of contaminated zone, contaminated zone erosion rate, total porosity, field capacity, hydraulic conductivity, evapotranspiration coefficient, wind speed, well pump intake depth, well pumping rate, inhalation rate and occupancy factor.

**VI. Probabilistic analysis**

Calculations in which many different possible values of the parameters   are samples are called probabilistic calculations since each parameter may now take on a variety of different values and the model uses these values to predict the probability  that a given peak dose would result. Estimates for collective dose from current and future use of the site can be derived using RESRAD by applying the appropriate site specific parameters and integrating over the appropriate site occupancy. Alternative actions need to be evaluated to ensure that the action chosen is the most effective or cost beneficial one, since all regulations are based on the ALARA principle when socioeconomic factors and technical feasibility are taken into account. It is not possible to obtain sufficient data to fully or accurately characterize transport and exposure processes during risk assessment. Similarly it is not possible to predict future conditions with certainty. That is why the degree of uncertainty is always included in the assessment. The sensitivity and uncertainty analysis can be used to study the sensitivity of input parameters and the uncertainty of results. The sensitivity information can be used to set priorities for the collection of data for a particular site (Cheng et al., 1991). It is worth noting that even the models used are conservative (complex processes were broken to simple models to ease calculations) therefore the doses, cancer risks and guidelines are reasonable overestimates. The methodology used in the collection of RESRAD input data and typical values used in calculations are its data collection handbook Yu et  al., 1993a and b as well as the multi-agency radiation survey and site investigation manual (MARSSIM) (US EPA et al., 1997). A Monte Carlo pre-processor incorporated in the RESRAD allows the code to conduct uncertainty analysis and extends RESRAD from deterministic code to a stochastic code (Yu et al., 1993). The probabilistic interface of the code allows probabilistic analysis in a sequential fashion. Plots (histogram, cdf, and scatter plots) and statistics of the samples of the inputs can be viewed soon after sampling. This allows the user to check that the probabilistic inputs have been specified correctly before commencing the time consuming probabilistic runs of the code. When this is completed, multivariate linear regression can be performed between the inputs and selected outputs. The regression output lists the probabilistic variables in decreasing order of importance. (Yu et al., 2009). Risk assessors should also evaluate parameter sensitivity on a site specific and scenario specific basis. Parameters with high sensitivity based on NUREG/CR-6697 are - distribution coefficients, inhalation rates, mass loading for inhalation, exposure duration, fruits vegetables and grain consumption, leafy vegetable consumption, soil ingestion rate and drinking water intake. Analysis of exposure dose by RESRAD sensitivity analysis also indicated that cover depth during decommissioning commercial nuclear power plants is effective to reduce exposure dose (cover depth, density of cover material and cover erosion rate are all related to cover) (Sang et al., 2018). This sensitive parameters should therefore be obtained as much as possible. Because the parameters are so multidisciplinary, it is always better for risk assessors (usually health physicists) to collaborate with geologists and hydrologists. Though the code gives reasonable good results overall (provided the input data represent the environmental conditions specific to the site being modelled), risk assessors are advised to avoid putting too much significance on the precise values they derive. In large part this is due to the fact that they will have to retain many default values or make use of the generic recommendations for exposure factors which were derived from national averages and may not necessarily be the most appropriate values to use at your site or for your exposure scenarios.

**VII. Recommended minimum site specific parameters for use**

The parameters used in standard risk assessment guidance for superfund/ soil screening guidance for radionuclides calculations can be used when site specific values are not available (EPA 2020) RAGS/SSG (Buffalo, 2002). RESRAD allows the integrated consideration of multiple pathways, environmental factors, geometry factors,    and site characterisation data that do not fit into standard risk calculation. Most of the parameters are related to specific pathways and may be ignored or left as default values. If there is site specific information it could be substituted for the default values.  Most of the parameters are site specific but not receptor specific. In many cases recommended values are not available but are estimated based on site specific conditions. It is also assumed that when site-specific values are not provided or cannot be assigned from another source, the RESRAD default values are used. If the RESRAD default values are not acceptable, NUREG/CR-5512 volume 4 may be used to assign default   values for some exposure parameters. For receptor specific and scenario specific RESRAD parameter values and general receptor description see Buffalo, 2002.

The site specific parameters which should always be as much as possible obtained for better prediction include: concentration of the radionuclides, area of contaminated  zone, thickness of the contaminated zone, length parallel to aquifer flow, time since placement of materials, cover depth, density of cover material, cover depth erosion rate. Contaminated zone (erosion rate, total porosity, field capacity, hydraulic conductivity, b parameter), average annual wind speed, humidity in air, evapotranspiration coefficient, precipitation, irrigation and its mode, runoff coefficient.  Saturated and unsaturated zone (density,   total and effective porosity, field capacity, hydraulic conductivity, hydraulic gradient, b parameter. Water table drop rate, well pump intake depth, well pumping rate, inhalation rate, mass loading for inhalation, exposure duration, fraction of time   spent indoor/outdoors.

**VIII. Conclusion**

One of the cardinal radiation protection principles is the protection of people and the environment, now and in future. This underscores the need to ensure that the introduction of nuclear power does not alter the biodiversity and has had an insignificant health impact on the people and the environment.  Residual radioactivity codes are reliable family of codes that can be used for radiological protection during nuclear emergency. The codes are highly flexible as they accommodate different customized exposure situations and release scenarios. However, the quality of the output (dose and cancer risk) depends on the quality of over hundred input parameters specified during data entry. The total effective dose equivalent and cancer risk is insensitive to the majority of the parameters but it is also significantly sensitive to some few ones. Though most of the parameters are not receptor specific but site specific, the quality of the output also depends on the sensitive data entered which is lacking in Africa for most of the parameters. It is therefore strongly recommended that African researchers should try all that is possible to obtain the recommended values for the significantly sensitive parameters so that reasonable outputs can be obtained. Also it is highly recommended that while using the codes, probabilistic analysis including sensitivity and uncertainty analysis should always accompany deterministic analysis for a comprehensive assessment. The information in this paper will serve as a guide for safeguarding biodiversity and future generation in the event of a nuclear emergency or any other radiological release case, this will go a long way in restoring public confidence regarding the safety of people and the environment during nuclear energy projects in Africa.

**References**

(FGR 11) Keith F. Eckerman, Anthony B. Wolbarst, and Allan C.B. Richardson. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. Federal Guidance Report No. 11. EPA- 520/1-88-020. Oak Ridge, TN: Oak Ridge National Laboratory; Washington, DC: Office of Radiation Programs, U.S. Environmental Protection Agency, September 1988. On the Web at http://www.epa.gov/radiation/docs/federal/520-1-88-020.pdf.

(FGR 13) Keith F. Eckerman, Richard W. Leggett, Christopher B. Nelson, Jerome S. Puskin,

439–47, (2013).

Aghaie M, Minuchehr A, Alahyarizadeh G (2019) Evaluation of atmospheric dispersion of radioactive materials in a severe accident of the BNPP based on Gaussian model. Prog Nucl Energy 113:114–127

Al-Kloub MM, Mahura A, Baklanov A, et al (2020) Model Simulations of Local Meteorological Conditions in the Vicinity of a Hypothetical Nuclear Power Plant in Jordan. JJEES 26

Aly AIM, Hussien RA, Nassar N (2020) Radioactive dispersion in groundwater resulting from postulated accident at a proposed nuclear power plant, northwestern coast of Egypt. Groundw Sustain Dev 10:100326

and Allan C.B. Richardson. *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*. EPA 402-R-99-001. Federal Guidance Report No. 13, CD Supplement. Rev. 1. Oak Ridge, TN: Oak Ridge National Laboratory; Washington, DC: Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, April 2002. Includes original 1999 FGR no. 13, which is also on the Web at <http://www.epa.gov/radiation/docs/federal/402-r-99-001.pdf>.

and its consequences “, Progress in Nuclear Energy **74,** pp. 61-70, (2014).

Andrade ER, Stenders R, Castro MSC, et al (2020) Evaluation of cancer risk after a release from a hypothetical nuclear reactor steam generator tube rupture accident (SGTR). Ann Nucl Energy 136:107023

Bolshov LA, Dolganov KS, Kiselev AE, Strizhov VF (2019) Results of SOCRAT code development, validation and applications for NPP safety assessment under severe accidents. Nucl Eng Des 341:326–345

Buffalo Newyork (2002). White paper: using RESRAD in a CERCLA radiological risk assessment. Prepared by science applications International Corporation for U.S army corps of engineers. RAS 14151

Cheng, J.J., et al., 1991, *RESRAD Parameter Sensitivity Analysis*, ANL/EAIS-3, Argonne National Laboratory, Argonne, Ill.doses in residents living around the Fukushima nuclear power plant”, *Radiat. Res.* 180, pp.

Eckerman, K.F., et al., 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion and Ingestion,* EPA-520/1-88-020, Federal Guidance Report No. 11, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C.

Energy Agency (2000). Generic Procedures for Assessment and Response During a Radiological Emergency. IAEA-TECDOC-1162, Vienna

EPA 1999. *Cancer Risk Coefficients for Environmental Exposure to Radionuclides, Federal Guidance Report No. 13,* Air and Radiation, EPA 402-R-99-00, September.

Evangeliou, N., Balkanski, Y., CoziC, A., et al, “Global and local cancer risks after the Fukushima Nuclear Power Plant accident as seen from Chernobyl: A modeling study for radiocaesium (Cs-134 & Cs-137)”, Environment International **64**, pp.17–27, (2014).

Fairuz A, Sahadath MH (2020) Assessment of the potential Total Effective Dose (TED) and ground deposition (GD) following a hypothetical accident at the proposed Rooppur Nuclear Power Plant. Appl Radiat Isot 109043

FGR 12 Keith F. Eckerman and Jeffrey C. Ryman. *External Exposure to Radionuclides in Air, Water, and Soil: Exposure-to-Dose Coefficients for General Application, Based on the 1987 Federal Radiation Protection Guidance*. EPA 402-R-93-081. Federal Guidance Report No. 12. Oak Ridge, TN: Oak Ridge National Laboratory; Washington, DC: Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, September 1993. On the Web at

Gonzalez A.J, *et al*, “Radiological protection issues arising during and after the Fukushima

http://www.epa.gov/radiation/docs/federal/402-r-93-081.pdf.

IAEA-TECDOC-1844 (2018). Analysis Supporting Conversion of Research Reactors from High Enriched Uranium Fuel to Low Enriched Uranium Fuel. The case of the Miniature Neutron Source Reactors (MNSR).

International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public From Intake of Radionuclides: Part 1*. Annals of the ICRP, v.20 no. 2. ICRP publication 56. Oxford: Pergamon, 1989.

International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public From Intake of Radionuclides: Part 2 Ingestion Dose Coefficients*. Annals of the ICRP, v. 23 no. 3/4. ICRP publication 67. Oxford: Pergamon, 1993.

International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public From Intake of Radionuclides: Part 3 Ingestion Dose Coefficients*. Annals of the ICRP, v. 25 no. 1. ICRP publication 69. Oxford: Pergamon, 1995.

International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public From Intake of Radionuclides: Part 4 Inhalation Dose Coefficients*. Annals of the ICRP, v. 25 no. 3-4. ICRP publication 71. Oxford: Pergamon, 1995.

International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public From Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*. Annals of the ICRP, v. 26 no. 1. ICRP publication 72. Oxford: Pergamon, 1996.

International Commission on Radiological Protection. *Report of the Task Group on Reference Man*. [ICRP Publication] No. 23. Oxford: Pergamon Press, 1975. Adopted October 1974.

J. Simon, Y.V. Ibrahim , D.J. Adeyemo, N.N. Garba, A. Asuku, S. Bello, I.K. Ibikunle (2022). Radiological consequence analysis for hypothetical accidental release from Nigerian Research Reactor-1. Applied Radiation and Isotopes 186 (2022) 110308

Kim S, Park K, Min B-I, et al (2019) Assessment of radiological doses for people living in Korea following accidental releases of radionuclides from nuclear power plants in Korea and China. Radiat Prot Dosimetry 184:54–65

Koo, Y.H., Yang, Y.S., Song, K.W., “Radioactivity release from the Fukushima accident

Lebel LS, Morreale AC, Korolevych V, et al (2017) Severe accident consequence mitigation by fi ltered containment venting at Canadian nuclear power plants. Ann Nucl Energy 102:297–308

Liland A, Lind OC, Bartnicki J, et al (2020) Using a chain of models to predict health and environmental impacts in Norway from a hypothetical nuclear accident at the Sellafi eld site. J Environ Radioact 214:106159

Mazur A (2019) Hypothetical accident in Polish nuclear power plant. Worst case scenario for main Polish cities. Ecol Chem Eng S 26:9–28

Mitrakos D, Potiriadis C, Housiadas C (2016) An approach for estimating the radiological signifi cance of a hypothetical major nuclear accident over long distance transboundary scales. Nucl Eng Des 300:422–432

Nagataki S, Takamura N., Kamiya K. and Akashi M., “Measurements of individual radiation

nuclear reactor accident”, *J. Radiol. Prot.*Vol. 33, pp. 497–571, (2013)

Park S-U, Lee I-H, Joo SJ, Ju J-W (2017) Emergency preparedness for the accidental release of radionuclides from the Uljin Nuclear Power Plant in Korea. J Environ Radioact 180:90–105

Parks, B., 1997, *CAP-88-PC*, *Version 2.0 User’s Guide*, ER-8/6TN, U.S. Department of energy, Germantown, Md.

Piguet F-P , Eckert P, Knüsli C, et al (2019) Modeling of a Major Accident in Five Nuclear Power Plants From 365 Meteorological Situations in Western Europe and Analysis of the Potential Impacts on Populations, Soils and Affected Countries

Sang, J.P., Ji, B.H., Suhee, L and Seokyoung, A (2018). Analysis of exposure dose by RESRAD sensitivity analysis. Proceedings of the Korean radioactive waste society conference. 2018.05a Pg 387-388.

Simonis, A., Poskas, P., Poskas, G., et al, “Modeling of the radiation doses during dismantling of RBMK-1500 reactor emergency core cooling system large diameter pipes”, Annals of Nuclear Energy 85, pp. 159–165 (2015).

Title 10, Part 834, *Code of Federal Regulations*.

U.S. Department of Energy, 1997, “Radiation Protection of the Public and the Environment,”

Yu, C. (2007a). Modeling radionuclide transport in the environment and assessing risks to humans, flora, and fauna: The RESRAD family of codes. In *ACS symposium series* (Vol. 945, pp. 58-70). Oxford University Press.

Yu, C. (2007b). Tools for Assessing Radiological Doses to Human and Biota. In *Radiological Assessment: Detection, Identification, and Evaluation, Health Physics Society Professional Development School Textbook*.

Yu, C., 1999, “RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities,” Chapter 11, pp. 207–231 in *Decommissioning and Restoration of Nuclear Facilities*, Health Physics Society 1999 summer school textbook, M.J. Slobodien (editor), Medical Physics Publishing, Madison, Wis.

Yu, C., E. Gnanapragasam, B. Biwer, J.-J. Cheng, S. Kamboj, T. Klett, A. Zielen, W.A. Williams, S. Domotor and A. Wallo (2009). RESRAD-OFFSITE – A new member of the RESRAD family of codes. *Radioprotection*, vol. 44, n◦ 5 (2009) 659–664

Yu, C., et al., 1993a, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil*, ANL/EAIS-8, Argonne National Laboratory, Argonne, Ill., Apr.

Yu, C., et al., 1993b, *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0*, ANL/EAD/LD-2, Argonne National Laboratory, Argonne, Ill.

Yu, C., LePoire, D., Gnanapragasam, E., Arnish, J., Kamboj, S., Biwer, B. M., ... & Mo, T. (2000). *Development of probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 computer codes*. US Nuclear Regulatory Commission.

Yu, C., Orlandini, K. A., Cheng, J. J., & Biwer, B. M. (2001a). *Assessing the impact of hazardous constituents on the mobilization, transport, and fate of radionuclides in RCRA waste disposal units* (No. ANL/EAD/TM-93). Argonne National Lab., IL (US).

Yu, C., Zielen, A. J., Cheng, J. J., LePoire, D. J., Gnanapragasam, E., Kamboj, S., ... & Peterson, H. (2001b). User’s manual for RESRAD version 6. *Oak Ridge, TN: US Department of Energy Office of Scientific and Technical Information*.

Zhu Y, Guo J, Nie C, Zhou Y (2014) Simulation and dose analysis of a hypothetical accident in Sanmen nuclear power plant. Ann Nucl Energy 65:207–213