STUDY OF BORON NEUTRON CAPTURE THERAPY COMPONENTS AT THERMAL COLUMN FOR NUCLEAR REACTOR

SAFWAN BIN SHALBI

DOCTOR OF PHILOSOPHY

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

____

(Supervisor's Signature)

Full Name : Dr Norazlianie binti Sazali

Position : Senior Lecture

Date : 8/2/2023

____

(Co-supervisor's Signature)

Full Name : Dr. Januar Parlaungan Siregar

Position : Senior Lecture

Date :8/2/2023

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : SAFWAN BIN SHALBI

ID Number : PMD19002

Date : 8 FEBUARY 2023

STUDY OF BORON NEUTRON CAPTURE THERAPY COMPONENTS AT THERMAL COLUMN FOR NUCLEAR REACTOR

SAFWAN BIN SHALBI

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Doctor of Philosophy

Faculty of Mechanical & Automotive Engineering Technology

UNIVERSITI MALAYSIA PAHANG

FEBUARY 2023

ACKNOWLEDGEMENTS

"In the name of Allah, the most Gracious and the most Merciful"

Alhamdulillah, and thank you to Allah s.w.t., the Almighty, for providing me His showers of blessings. It also drives my effort, inspiration, and much forbearance throughout my research to finish it successfully. My most tremendous profound gratitude goes to my supervisor Dr. Norazlianie Binti Sazali, and my co-supervisor, Dr. Januar Parlaungan Siregar, for their sincere help, and full cooperative support and advice in completing this research. I am very honored to have been assisted by the experts at Hokkaido University, Prof. Emeritus Yoshiaki Kiyanagi. I am also grateful for the help extended by Nuclear Malaysia experts, namely Dr. Faridah Idris, Mr Hairi, Mr Aliff Ashraf. and other researchers, for their tremendous effort, encouragement, and critical propositions. Nobody has been more important to me in the pursuit of this research than the members of my family and friends. I want to thank my parents, Shalbi bin Md Shah and Salasilah bin Alias, who have supported me from the beginning of my journey. They are the ultimate role models. Most importantly, I am grateful to my loving and supportive wife, my one and only Fatin Nurwahdah Binti Ahmad, who provide continual inspiration. Finally, I appreciate all unnamed personals who helped and encouraged my journey to finish this research. May Allah s.w.t bless the good deed that has been done and bless us. Amin.

ABSTRAK

Kajian penyelidikan ini memberi tumpuan kepada penggunaan konkrit barit colemanite, pelindung pelbagai lapisan, dan kollimator untuk komponen terapi penangkapan neutron boron (BNCT). Kajian ini bertujuan untuk menggunakan konkrit barit colemanite sebagai perisai utama, mengaplikasikan dan menggunakan pelindung berbilang lapisan untuk pengatup rasuk dan penyumbat rasuk, dan mengoptimumkan pengeluaran fluks neutron terma dan separa terma sambil meminimumkan neutron laju dan fluks gamma dengan menggunakan kollimator dalaman dan luaran. Konkrit konvensional yang umumnya dijadikan sebagai perisai utama BNCT memerlukan lebih ketebalan dan kurang berkesan terhadap radiasi neutron dan gamma. Oleh demikian, konkrit komposit digunakan untuk meningkatkan sifat perisai dan mengurangkan ketebalan. Kajian ini menggunakan kaedah DOE untuk campuran konkrit dan mengkaji kesan colemanite sebagai agregat halus dan sebagai pengisi dalam campuran konkrit barit colemanite ke atas kesan ciri mekanikal dan ciri perisai konkrit. Konkrit barit colemanite diuji terhadap ciri mekanikal dan ciri sinaran. Pengujian kemerosotan, halaju ultra nadi, dan kekuatan mampatan digunakan untuk ciri mekanikal, manakala pengujian penghantaran neutron dan gamma adalah untuk ciri sinaran. Kajian ini menunjukkan bahawa colemanite sebagai pengisi dengan 1.85%, barit 46.95%, dan kandungan air yang lebih rendah sebanyak 4.65% berjaya mencapai kekuatan mekanikal Gred 40, perisai neutron dan perisai gamma yang lebih tinggi, dan keliangan yang tinggi berbanding perisai konkrit konvensional. Tambahan pula, berdasarkan simulasi Monte-Carlo N Particle, pelindung berbilang lapisan menggunakan konkrit barite colemanite, plumbum, dan polietilena boron 30% untuk penyumbat rasuk dan bidai rasuk didapati lebih cekap dalam melindungi radiasi berbanding dengan pelindung lapisan tunggal, dengan penyerapan radiasi lebih daripada 90%. Sementara itu, ketebalan perisai juga dapat dikurangkan dengan ketara hasil penggunaan pelindung berbilang lapisan yang hanya memerlukan kurang 60 cm berbanding perisai satu lapisan konvensional. Di samping itu, kajian yang menggunakan simulasi dan pengukuran Monte-Carlo N Particle menggunakan kadmium rod dan kerajang emas pada reaktor 250kw mencadangkan penggunaan kollimator dalaman dan luaran untuk memaksimumkan fluks neutron terma dan separa terma dengan 2 dan 1.2 kali lebih tinggi daripada pengukuran awal. Penyelidikan ini menyimpulkan bahawa konkrit barit colemanite adalah bahan pelindung utama yang sesuai untuk kemudahan penyelidikan nuklear dan penggunaan perisai berbilang lapisan dan kollimator dapat meningkatkan prestasi komponen BNCT di turus terma untuk reaktor nuklear.

ABSTRACT

This research study focuses on the use of barite colemanite concrete, multi-layer shielding, and collimators for boron neutron capture therapy (BNCT) components. The study aims to use barite colemanite concrete as primary shielding, implement the use of multi-layer shielding for beam shutters and beam stoppers, and optimize thermal and epithermal neutron flux while minimizing fast neutron and gamma flux using internal and external collimators. Conventional concrete as primary shielding for BNCT requires greater thickness and is less effective towards neutron and gamma radiation, thus composite concrete is used to improve shielding properties and reduce thickness. The study uses the DOE method for concrete mix and studies the effects of colemanite as fine aggregate and as filler in barite colemanite concrete mix to study effect on mechanical and shielding properties. The barite colemanite concrete testing with mechanical and shielding testing. The slump, ultra-pulse velocity, field-emission electron scanning, and compressive strength tests are used for the mechanical properties, while neutron and gamma transmission tests are used to determine shielding properties. The study found that barite colemanite concrete with 1.85% colemanite as filler, 46.95% barite, and a lower water content of 4.65% achieved mechanical strength of Grade 40, higher neutron and gamma shielding properties, and high porosity compared to conventional concrete shielding. Furthermore, based on Monte-Carlo N Particle simulation, the multi-layer shielding using barite colemanite concrete, lead, and 30% borated polyethylene for beam stoppers and beam shutters was found to be more efficient in shielding radiation compared to single-layer shielding, with more than 90% radiation absorption. The thickness of shielding was significantly reduced with the use of multi-layer shielding to less than 60 cm compared to conventional single-layer shielding. In addition, the study using Monte-Carlo N Particle simulation and measurement using rod cadmium and gold foil at 250kw reactor proposed the use of internal and external collimators to maximize thermal and epithermal neutron flux with 2 and 1.2 times higher from preliminary measurement. This research concludes that barite colemanite concrete is a suitable primary shielding material for nuclear research facilities and that the use of multi-layer shielding, and both internal and external collimators can improve the performance of BNCT components at the thermal column for nuclear reactors.

TABLE OF CONTENT

REFERENCES

Abdel-Rahman, M. A. E., Fouda, A. A., & El-Mongy, S. A. (2019). Study of γ-Fast Neutron Attenuation and Mechanical Characteristics of Modified Concretes for Shielding and Sheltering Purposes. Zeitschrift Für Anorganische Und Allgemeine Chemie, 645(8), 649–655. https://doi.org/10.1002/zaac.201900027

Agency, I. A. E. (2001). *Current status of neutron capture therapy*. Vienna: International Atomic Energy Agency. Retrieved from https://www.iaea.org/publications/6168/current-status-of-neutron-capture-therapy

Akan, Z., Türkmen, M., Çakır, T., Reyhancan, İ. A., Çolak, Ü., Okka, M., & Kızıltaş, S. (2015). Modification of the radial beam port of ITU TRIGA Mark II research reactor for BNCT applications. *Applied Radiation and Isotopes*, *99*, 110–116. https://doi.org/https://doi.org/10.1016/j.apradiso.2015.02.014

Akkurt, I., Basyigit, C., Kilincarslan, S., & Mavi, B. (2005). The shielding of γ-rays by concretes produced with barite. Progress in Nuclear Energy, 46(1), 1–11. https://doi.org/10.1016/j.pnucene.2004.09.015

Alves, M. F., Cremonini, R. A., & Dal Molin, D. C. C. (2004). A comparison of mix proportioning methods for high-strength concrete. Cement and Concrete Composites, 26(6), 613–621. https://doi.org/10.1016/s0958-9465(03)00036-2

Arno, M. (2009). Radiation Protection. In *Nuclear Engineering Handbook* (pp. 627–658). CRC Press.

Arif Sazali, M., Alang Md Rashid, N. K., & Hamzah, K. (2019). A review on multilayer radiation shielding. IOP Conference Series: Materials Science and Engineering, 555(1), 012008. https://doi.org/10.1088/1757-899x/555/1/012008

Ashraff Rosdi, M. A., Goh, P. S., Idris, F., Shalbi, S., Sarkawi, M. S., Mohd Ali, N. S., … Azman, A. (2018). Neutron and gamma ray fluences measurement at radial Beam Port 1 of TRIGA MARK II PUSPATI research reactor. IOP Conference Series: Materials Science and Engineering, 298, 012033. https://doi.org/10.1088/1757-899x/298/1/012033

ASTM International, ASTM C597 Standard Test Method for Pulse Velocity Through Concrete, ASTM Int. (2016) 4. doi:10.1520/C0597-16.2.

ASTM International, ASTM C109 Standard Test Method for Compressive Strength Hydraulic Cement Concrete, ASTM Int. (2021) 4. doi:10.1520/C109-21.2.

ASTM International, ASTM C143 Standard Test Method for Slump of Hydraulic Cement Concrete, ASTM Int. (2022) 4. doi:10.1520/C143-21.2.

Awoyera, P. O., Adesina, A., & Gobinath, R. (2019). Role of recycling fine materials as filler for improving performance of concrete - a review. Australian Journal of Civil Engineering, 17(2), 85–95.

https://doi.org/10.1080/14488353.2019.1626692

Azeez, M. O., Ahmad, S., Al-Dulaijan, S. U., Maslehuddin, M., & Naqvi, A. A. (2019). Radiation shielding performance of heavy-weight concrete mixtures. Construction and Building Materials, 224, 284-291.

Baalamurugan, J., Kumar, V. G., Chandrasekaran, S., Balasundar, S., Venkatraman, B., Padmapriya, R., & Raja, V. K. B. (2021). Recycling of steel slag aggregates for the development of high density concrete: Alternative & environment-friendly radiation shielding composite. Composites Part B: Engineering, 216, 108885. https://doi.org/10.1016/j.compositesb.2021.108885

Bai, G., Zhu, C., Liu, C., & Liu, B. (2020). An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties. Construction and Building Materials, 240, 117978. https://doi.org/10.1016/j.conbuildmat.2019.117978

Balog, J., Lucas, D., DeSouza, C., & Crilly, R. (2005). Helical tomotherapy radiation leakage and shielding considerations. Medical Physics, 32(3), 710–719. https://doi.org/10.1118/1.1861521

Bel, T., Arslan, C., & Baydogan, N. (2019). Radiation shielding properties of poly (methyl methacrylate) / colemanite composite for the use in mixed irradiation fields of neutrons and gamma rays. Materials Chemistry and Physics, 221, 58–67. https://doi.org/10.1016/j.matchemphys.2018.09.014

Belousov, S., Mitev, M., Ilieva, K., Riley, K., & Harling, O. (2011). IRT-Sofia BNCT beam tube optimization study. Applied Radiation and Isotopes, 69(12), 1936–1939. https://doi.org/10.1016/j.apradiso.2011.03.001

Bilici, İ., Aygün, B., Deniz, C. U., Öz, B., Sayyed, M. I., & Karabulut, A. (2021). Fabrication of novel neutron shielding materials: Polypropylene composites containing colemanite, tincal and ulexite. Progress in Nuclear Energy, 141, 103954. https://doi.org/10.1016/j.pnucene.2021.103954

Biswas, R., Rai, B., & Samui, P. (2021). Compressive strength prediction model of high-strength concrete with silica fume by destructive and non-destructive technique. Innovative Infrastructure Solutions, 6(2). https://doi.org/10.1007/s41062-020-00447-z

Brodusch, N., Demers, H., & Gauvin, R. (2017). Introduction. Field Emission Scanning Electron Microscopy, 1–4. https://doi.org/10.1007/978-981-10-4433-5_1

Briesmeister, J. F. (2000). MCNPTM-A general Monte Carlo N-particle transport code. *Version 4C, LA-13709-M, Los Alamos National Laboratory, 2*.

Cai, B., Laugeman, E., Hsu, H., Green, O., Knutson, N., Goddu, S. M., … Hugo, G. D. (2021). Technical Note: Self-shielding evaluation and radiation leakage measurement of a jawless ring gantry linac with a beam stopper. Medical Physics, 48(6), 3143–3150. https://doi.org/10.1002/mp.14858

Cacuci, D. G. (2010). *Handbook of Nuclear Engineering: Vol. 1: Nuclear Engineering*

Fundamentals; Vol. 2: Reactor Design; Vol. 3: Reactor Analysis; Vol. 4: Reactors of Generations III and IV; Vol. 5: Fuel Cycles, Decommissioning, Waste Disposal and Safeguards (Vol. 1). Springer Science & Business Media.

Cardoso, C., Camões, A., Eires, R., Mota, A., Araújo, J., Castro, F., & Carvalho, J. (2018). Using foundry slag of ferrous metals as fine aggregate for concrete. Resources, Conservation and Recycling, 138, 130–141. https://doi.org/10.1016/j.resconrec.2018.05.020

Cik, R. C. H., Foo, C. T., & Nor, A. F. O. (2015). Field Emission Scanning Electron Microscope (FESEM) Facility in BTI.

Chidiac, S. E., El-Samrah, M. G., Reda, M. A., & Abdel-Rahman, M. A. E. (2021). Mechanical and radiation shielding properties of concrete containing commercial boron carbide powder. Construction and Building Materials, 313, 125466. https://doi.org/10.1016/j.conbuildmat.2021.125466

D'Mellow, B., Thomas, D. J., Joyce, M. J., Kolkowski, P., Roberts, N. J., & Monk, S. D. (2007). The replacement of cadmium as a thermal neutron filter. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 577(3), 690–695. https://doi.org/10.1016/j.nima.2007.05.001

Da Silva, A. X., & Crispim, V. R. (2001). Moderator-collimator-shielding design for neutron radiography systems using 252Cf. *Applied Radiation and Isotopes*, *54*(2), 217–225. https://doi.org/10.1016/s0969-8043(00)00291-8

Darda, S. A., Soliman, A. Y., Aljohani, M. S., & Xoubi, N. (2020). Technical feasibility study of BAEC TRIGA reactor (BTRR) as a neutron source for BNCT using OpenMC Monte Carlo code. Progress in Nuclear Energy, 126, 103418. https://doi.org/10.1016/j.pnucene.2020.103418

Darwesh. (2018). Measurement of the Natural Radioactivity From Baghdad Soils Samples Using NaI(Tl) Detector. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.325199

Domanus, J. C. (1992). *Practical neutron radiography*. Springer Dordrecht.

Dommeti, V. S., & Cheruku, D. R. (2020). Multi-layer composites shielding for electromagnetic radiation protection. International Journal of Advanced Intelligence Paradigms, 17(1/2), 139. https://doi.org/10.1504/ijaip.2020.10028515

Dong, M., Xue, X., Yang, H., & Li, Z. (2017). Highly cost-effective shielding composite made from vanadium slag and boron-rich slag and its properties. Radiation Physics and Chemistry, 141, 239–244. https://doi.org/10.1016/j.radphyschem.2017.07.023

Durisi, E., Zanini, A., Manfredotti, C., Palamara, F., Sarotto, M., Visca, L., & Nastasi, U. (2007). Design of an epithermal column for BNCT based on D–D fusion neutron facility. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *574*(2), 363–369. https://doi.org/https://doi.org/10.1016/j.nima.2007.02.080

Ejiogu, I. K., Mamza, P. A., Nkeonye, P. O., & Yaro, S. A. (2020). Comparison of ACI, IS and DOE methods of concrete mix design. Nigerian Journal Of Engineering, 27(1), 68-68.

El-Faramawy, N., Chopra, V., Rawash, S., El-Hafez, A. A., & Dhoble, S. J. (2021). Response of TLD-600/TLD-700 and CR-39 to neutrons for medical dosimetry. Luminescence. https://doi.org/10.1002/bio.4051El-Khatib, A. M., Hamada, M. S., Alabsy, M. T., Youssef, Y. M., Elzaher, M. A., Badawi, M. S., … Abbas, M. I. (2021). Fast and thermal neutrons attenuation through micro-sized and nano-sized CdO reinforced HDPE composites. Radiation Physics and Chemistry, 180, 109245. https://doi.org/10.1016/j.radphyschem.2020.109245

El-Khayatt, A. M., & Akkurt, İ. (2013). Photon interaction, energy absorption and neutron removal cross section of concrete including marble. Annals of Nuclear Energy, 60, 8–14. https://doi.org/10.1016/j.anucene.2013.04.021

El-Sayed Abdo, A. (2002). Calculation of the cross-sections for fast neutrons and gamma-rays in concrete shields. Annals of Nuclear Energy, 29(16), 1977–1988. https://doi.org/10.1016/s0306-4549(02)00019-1

Erdem, M., Baykara, O., Doğru, M., & Kuluöztürk, F. (2010). A novel shielding material

Faião-Flores, F., Coelho, P. R. P., Muniz, R. O. R., Souza, G. S., Arruda-Neto, J., & Maria, D. A. (2011). Antitumor potential induction and free radicals production in melanoma cells by Boron Neutron Capture Therapy. *Applied Radiation and Isotopes*, *69*(12), 1748–1751. https://doi.org/https://doi.org/10.1016/j.apradiso.2011.05.017

Falliano, D., De Domenico, D., Ricciardi, G., & Gugliandolo, E. (2018). Key factors affecting the compressive strength of foamed concrete. IOP Conference Series: Materials Science and Engineering, 431, 062009. https://doi.org/10.1088/1757-899x/431/6/062009

Farhi, E., Mohamad Idris, F., Mohamed, A. A., Yazid, H. B., Jamro, R., Harun Al Rashid, M., & Mohamed Zin, M. R. B. (2016). Neutron scattering instrumentation at low power reactors for science, engineering and education. Journal of Neutron Research, 18(2-3), 61–77. https://doi.org/10.3233/jnr-160024

Fauziah, N., Harto, A. W., & Sardjono, Y. (2013). A conceptual design of neutron collimator in the thermal column of Kartini research reactor for in vitro and in vivo test of Boron neutron capture therapy. *Jurnal Teknologi Reaktor Nuklir*, *15*(2), 112–119. Retrieved from http://inis.iaea.org/search/search.aspx?orig_q=RN:48003965

Geng, C., Tang, X., Guan, F., Johns, J., Vasudevan, L., Gong, C., … Chen, D. (2016). GEANT4 calculations of neutron dose in radiation protection using a homogeneous phantom and a Chinese hybrid male phantom. *Radiation*

Protection Dosimetry, *168*(4), 433–440. https://doi.org/10.1093/rpd/ncv364

Gohil, C. J., & Noolvi, M. N. (2015). Selective cancer treatment by Boron Neutron Capture Therapy (BNCT)–a review. *Int. J. Pharm. Chem. Anal*, *2*(3), 136–138.

Granada, J. R., Santisteban, J. R., Dawidowski, J., & Mayer, R. E. (2012). Neutron transmission: A powerful technique for small accelerator-based neutron sources. Physics Procedia, 26, 108–116. https://doi.org/10.1016/j.phpro.2012.03.015

Grillo, R. (2018). Study of the Influence of Curing Processes on Mechanical Resistance Properties of Concretes. Trends in Civil Engineering and Its Architecture, 2(1). https://doi.org/10.32474/tceia.2018.02.000128

Hadad, K., Nematollahi, M., Sadeghpour, H., & Faghihi, R. (2016). Moderation and shielding optimization for a 252Cf based prompt gamma neutron activation analyzer system. International Journal of Hydrogen Energy, 41(17), 7221–7226. https://doi.org/10.1016/j.ijhydene.2015.12.208

Hadji, T., & Attia, A. (2022). Case study of high strength concrete mix proportioning optimization. Multidiscipline Modeling in Materials and Structures. https://doi.org/10.1108/mmms-07-2022-0132

Hamdan, H., Muhid, M. N. M., Endud, S., Listiorini, E., & Ramli, Z. (1997). 29Si MAS NMR, XRD and FESEM studies of rice husk silica for the synthesis of zeolites. Journal of Non-Crystalline Solids, 211(1-2), 126–131. https://doi.org/10.1016/s0022-3093(96)00611-4

Hamzah, N. S., Ariff, M. K., Ramli, N., Usang, M. D., Rabir, M. H., Khalil, M. A., ... & Salleh, M. A. S. (2011). Dose Distribution Mapping at Reactor TRIGA PUSPATI.

Hong, S.-B., Kang, M.-J., Lee, K.-W., & Chung, U.-S. (2009). Development of scaling factors for the activated concrete of the KRR-2. *Applied Radiation and Isotopes*, *67*(7), 1530–1533. https://doi.org/https://doi.org/10.1016/j.apradiso.2009.02.056

Hossain, M. S., Islam, S. M. A., Quasem, M. A., & Zaman, M. A. (2010). Study of shielding behaviour of some multilayer shields containing PB and BX. *Indian Journal of Pure and Applied Physics*, *48*(12), 860–868.

Hu, G., Shi, G., Hu, H., Yang, Q., Yu, B., & Sun, W. (2020). Development of gradient composite shielding material for shielding neutrons and gamma rays. Nuclear Engineering and Technology, 52(10), 2387–2393. https://doi.org/10.1016/j.net.2020.03.029

Hussein, A. A. (2020). Assessing the Quality of Concrete Using Process Capability Index (Slump Test Case Study). Journal of Advanced Research in Dynamical and Control Systems, 12(01-Special Issue), 671–676. https://doi.org/10.5373/jardcs/v12sp1/20201116

Ichikawa, G., Tsuchida, K., Kiyanagi, Y., Ishikawa, A., Hirata, Y., Yoshihashi, S., … Igawa, K. (2019). Development of thermal neutron moderator for testing boron agents for Boron Neutron Capture Therapy (BNCT). Journal of Instrumentation, 14(06), T06010–T06010. https://doi.org/10.1088/1748-0221/14/06/t06010

Ing, H., Djeffal, S., Clifford, T., Machrafi, R., & Noulty, R. (2007). Portable spectroscopic neutron probe. *Radiation Protection Dosimetry*, *126*(1–4), 238–243. https://doi.org/10.1093/rpd/ncm049

Khalaf, M. A., Ban, C. C., & Ramli, M. (2019). The constituents, properties and application of heavyweight concrete: A review. Construction and Building Materials, 215, 73–89. https://doi.org/10.1016/j.conbuildmat.2019.04.146

Kankaanranta, L., Seppälä, T., Koivunoro, H., Saarilahti, K., Atula, T., Collan, J., … Joensuu, H. (2012). Boron neutron capture therapy in the treatment of locally recurred head-and-neck cancer: final analysis of a phase I/II trial. *International Journal of Radiation Oncology, Biology, Physics*, *82*(1), 67–75. https://doi.org/10.1016/j.ijrobp.2010.09.057

Kapusta, B., Sainte-Catherine, C., Averty, X., Decroix, G. M., Scibetta, M., & Rommens, M. (2003). *Present status on the mechanical characterization of aluminum alloys 5754-NET-O and 6061-T6 irradiated at high fluences*.

Kardjilov, N., Manke, I., Woracek, R., Hilger, A., & Banhart, J. (2018). Advances in neutron imaging. Materials Today, 21(6), 652–672. https://doi.org/10.1016/j.mattod.2018.03.001

Kasesaz, Y., Khalafi, H., Rahmani, F., Ezzati, A., Keyvani, M., Hossnirokh, A., … Amini, S. (2014). Design and construction of a thermal neutron beam for BNCT at Tehran Research Reactor. *Applied Radiation and Isotopes*, *94*, 149–151. https://doi.org/https://doi.org/10.1016/j.apradiso.2014.08.004

Kato, I., Fujita, Y., Maruhashi, A., Kumada, H., Ohmae, M., Kirihata, M., … Ono, K. (2009). Effectiveness of boron neutron capture therapy for recurrent head and neck malignancies. *Applied Radiation and Isotopes*, *67*(7, Supplement), S37–S42. https://doi.org/https://doi.org/10.1016/j.apradiso.2009.03.103

Keshavamurthy, R. S., Subramanian, D. V., Prasad, R. R., Haridas, A., Mohanakrishnan, P., & Chetal, S. C. (2011). Experimental Measurements of Neutron Attenuation in the Advanced Shield Material Ferro Boron in KAMINI Reactor. *Energy Procedia*, *7*, 273–278. https://doi.org/https://doi.org/10.1016/j.egypro.2011.06.035

Khan, M., & Ali, M. (2018). Effect of super plasticizer on the properties of medium strength concrete prepared with coconut fiber. Construction and Building Materials, 182, 703–715. https://doi.org/10.1016/j.conbuildmat.2018.06.150

Kharita, M. H., Yousef, S., & AlNassar, M. (2011). Review on the addition of boron compounds to radiation shielding concrete. Progress in Nuclear Energy, 53(2), 207–211. https://doi.org/10.1016/j.pnucene.2010.09.012

Khatib, J., & Mangat, P. (1995). Absorption characteristics of concrete as a function of location relative to casting position. Cement and Concrete Research, 25(5), 999–1010. https://doi.org/10.1016/0008-8846(95)00095-t

Kim, J. H. (2018). Three principles for radiation safety: time, distance, and shielding. The Korean Journal of Pain, 31(3), 145. https://doi.org/10.3344/kjp.2018.31.3.145

Kok, K. D. (2009). *Nuclear Engineering Handbook*. CRC Press.

Kolias, S. (1994). Investigation of the possibility of estimating concrete strength by porosity measurements. Materials and Structures, 27(5), 265–272. https://doi.org/10.1007/bf02473043

Korkut, T., Karabulut, A., Budak, G., Aygün, B., Gencel, O., & Hançerlioğulları, A. (2012). Investigation of neutron shielding properties depending on number of boron atoms for colemanite, ulexite and tincal ores by experiments and FLUKA Monte Carlo simulations. *Applied Radiation and Isotopes*, *70*(1), 341–345. https://doi.org/https://doi.org/10.1016/j.apradiso.2011.09.006

Kortov, V. S., Milman, I. I., Nikiforov, S. V., & Gorelova, E. A. (2000). The use of thermoluminescent detectors for radiation monitoring on territories of atomic power plants. *Journal of International Research Publication*, (1), 1311–8978.

Kumada, H. (2022). Current Status of the Development of Compact Accelerator-Based Neutron Source Devices for Boron Neutron Capture Therapy in the World (No. IAEA-CN--301).

Kraft, G. (2000). Tumor therapy with heavy charged particles. *Progress in Particle and Nuclear Physics*, *45*, S473–S544. https://doi.org/https://doi.org/10.1016/S0146-6410(00)00112-5

Lamarsh, J. R., & Baratta, A. J. (2001). *Introduction to nuclear engineering* (Vol. 3). Prentice hall Upper Saddle River, NJ.

Lee, G.-W., Hee Kwon, J., Jang, S.-C., Roh, C., Myung, K., & Suk Huh, Y. (2017). Surface Characterization of Porous Nanomaterials in Environmental Applications by Scanning Electron Microscopy. Microscopy and Microanalysis, 23(S1), 1384–1385. https://doi.org/10.1017/s1431927617007589

Liu, Z., Zhao, K., Hu, C., & Tang, Y. (2016). Effect of Water-Cement Ratio on Pore Structure and Strength of Foam Concrete. Advances in Materials Science and Engineering, 2016, 1–9. https://doi.org/10.1155/2016/9520294

Masni Majid, S., & Mat Basir, S. (2019). The Present and Future Prospects of Malaysia's Atomic Energy Licensing Act 1984 (Act 304) on Nuclear Liability. International Journal of Asian Social Science, 9(12), 691–701. https://doi.org/10.18488/journal.1.2019.912.691.701

Matsubayashi, N., Tanaka, H., Takata, T., Okazaki, K., Sakurai, Y., & Suzuki, M. (2021). Development of real-time neutron detectors with different sensitivities to thermal, epithermal, and fast neutrons in BNCT. Radiation Measurements, 140, 106489. https://doi.org/10.1016/j.radmeas.2020.106489

Matsumoto, Y., Fukumitsu, N., Ishikawa, H., Nakai, K., & Sakurai, H. (2021). A Critical Review of Radiation Therapy: From Particle Beam Therapy (Proton, Carbon, and BNCT) to Beyond. Journal of Personalized Medicine, 11(8), 825. https://doi.org/10.3390/jpm11080825

Matsuo, H., & Saito, T. (1985). Irradiation Behaviors of Nuclear Grade Graphite in Commercial Reactor, (III) Mechanical Properties. Journal of Nuclear Science and Technology, 22(4), 313–319. https://doi.org/10.1080/18811248.1985.9735661

McCaffrey, J. P., Mainegra-Hing, E., & Shen, H. (2009). Optimizing non-Pb radiation shielding materials using bilayers. Medical Physics, 36(12), 5586–5594. https://doi.org/10.1118/1.3260839

Mesbahi, A., Alizadeh, G., Seyed-Oskoee, G., & Azarpeyvand, A.-A. (2013). A new barite–colemanite concrete with lower neutron production in radiation therapy bunkers. *Annals of Nuclear Energy*, *51*, 107–111. https://doi.org/https://doi.org/10.1016/j.anucene.2012.07.039

Microspec-6. (n.d.). Retrieved from Bubble Thechnology Industries website: https://bubbletech.ca/product/microspec-6/

Miller, M., Quintana, J., Ojeda, J., Langan, S., Thorp, S., Pozzi, E., … Graiño, F. (2009). New irradiation facility for biomedical applications at the RA-3 reactor thermal column. Applied Radiation and Isotopes, 67(7-8), S226–S229. https://doi.org/10.1016/j.apradiso.2009.03.10

Minsky, D. M., Valda, A. A., Kreiner, A. J., Green, S., Wojnecki, C., & Ghani, Z. (2011). First tomographic image of neutron capture rate in a BNCT facility. *Applied Radiation and Isotopes*, *69*(12), 1858–1861. https://doi.org/https://doi.org/10.1016/j.apradiso.2011.01.030

Mirzayev, M. N., Abdurakhimov, B. A., Demir, E., Donkov, A. A., Popov, E., Tashmetov, M. Yu., … Horodek, P. (2021). Investigation of the formation of defects under fast neutrons and gamma irradiation in 3C–SiC nano powder. Physica B: Condensed Matter, 611, 412842. https://doi.org/10.1016/j.physb.2021.412842

Miyashita, Y., Sanjeewani, D., & Kuwano, R. (2019). Effect of curing conditions on long term mechanical property of improved surplus soils. E3S Web of Conferences, 92, 11001. https://doi.org/10.1051/e3sconf/20199211001

Mohammad Abdul Kreem, O. (2012). Influence of Concrete Mix Proportions and Curing Regimes on Density, Absorption, and Voids in Hardened Concrete. AL-Rafdain Engineering Journal (AREJ), 20(4), 103–117. https://doi.org/10.33899/rengj.2012.54159

Mujiyono, M., Suharto, S., Mukhammad, A. F. H., Nurhadiyanto, D., & Sumowidagdo, A. L. (2018). Manufacture of Nickel Collimator for BNCT: Smelting of Nickel Using Electrical Arc Furnace and Centrifugal Casting Preparation. Indonesian Journal of Physics and Nuclear Applications, 3(1), 21–28. https://doi.org/10.24246/ijpna.v3i1.21-28

Munem, E. M. E. A. (2007). *Neutron flux measurements with Monte Carlo verification* *at the thermal column of a TRIGA MARK II reactor: Feasibility study for a BNCT facility*. Retrieved from http://inis.iaea.org/search/search.aspx?orig_q=RN:43128496

Nagrockiene, D., Pundienė, I., & Kicaite, A. (2013). The effect of cement type and plasticizer addition on concrete properties. Construction and Building Materials, 45, 324–331. https://doi.org/10.1016/j.conbuildmat.2013.03.076

Nakamura, S., Shibahara, Y., Endo, S., & Kimura, A. (2021). Thermal-neutron capture cross-section measurement of Tantalum-181 using graphite thermal column at KUR. Journal of Nuclear Science and Technology, 58(10), 1061–1070. https://doi.org/10.1080/00223131.2021.1908187

Naus, D. J., Oland, C. B., Ellingwood, B. R., Graves, H. L., & Norris, W. E. (1996). Aging management of containment structures in nuclear power plants. Nuclear Engineering and Design, 166(3), 367–379. https://doi.org/10.1016/s0029-5493(96)01254-x

Ndagi, A., Umar, A. A., Hejazi, F., & Jaafar, M. S. (2019). Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review. IOP Conference Series: Earth and Environmental Science, 357, 012015. https://doi.org/10.1088/1755-1315/357/1/012015

Obryk, B., Villari, R., Batistoni, P., Colangeli, A., De Felice, P., Fonnesu, N., … Quintieri, L. (2018). TLD calibration for neutron fluence measurements at JET fusion facility. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 904, 202–213. https://doi.org/10.1016/j.nima.2018.07.050

Ouda, A. S., & Abdelgader, H. S. (2018). Assessing the physical, mechanical properties, and γ-ray attenuation of heavy density concrete for radiation shielding purposes. Geosystem Engineering, 22(2), 72–80. https://doi.org/10.1080/12269328.2018.1469434

Oto, B., Madak, Z., Kavaz, E., & Yaltay, N. (2019). Nuclear radiation shielding and mechanical properties of colemanite mineral doped concretes. Radiation Effects and Defects in Solids, 174(9-10), 899–914. https://doi.org/10.1080/10420150.2019.1668390

Oto, B., Gür, A., Kavaz, E., Çakır, T., & Yaltay, N. (2016). Determination of gamma and fast neutron shielding parameters of magnetite concretes. *Progress in Nuclear Energy*, *92*, 71–80. https://doi.org/https://doi.org/10.1016/j.pnucene.2016.06.011

Paiva, F., Siqueira, P. T. D., & Cavalieri, T. A. (2015). *Comparing the responses of TLD 100, TLD 600, TLD 700 and TLD 400 in mixed neutron-gamma fields*.

Pal, R. (2005). Porosity-dependence of Effective Mechanical Properties of Pore-solid Composite Materials. Journal of Composite Materials, 39(13), 1147–1158. https://doi.org/10.1177/0021998305048744

Pauzi, A. M., Sarif, M. A. M., Mohamed, A. A., & Idris, F. (2017). Study of moderator (collimator) materials for boron neutron capture therapy (BNCT) facilities using SANS. *Journal of Nuclear And Related Technologies*, *14*(1), 6–15.

Payudan, A., Haryadi, A., & Abdullatif, F. (2017). Optimization of collimator neutron design for Boron Neutron-Capture Cancer Therapy (BNCT) based cyclotron 30 MeV. *Indonesian Journal of Physics and Nuclear Applications*, *2*(3), 128–136. https://doi.org/https://doi.org/10.24246/ijjpna.v2i3.128-136

Piotrowski, T. (2021). Neutron shielding evaluation of concretes and mortars: A review. Construction and Building Materials, 277, 122238. https://doi.org/10.1016/j.conbuildmat.2020.122238

Pomaro, B. (2016). A Review on Radiation Damage in Concrete for Nuclear Facilities: From Experiments to Modeling. Modelling and Simulation in Engineering, 2016, 1–10. https://doi.org/10.1155/2016/4165746

Rabir, M. H., Karim, J. A., & Zin, M. R. M. (2017). Neutron flux characterisation of irradiation facilities in RTP. *Jurnal Sains Nuklear Malaysia*, *29*(2), 33–43.

Rajput, S. P. S. (2018). An Experimental study on Crushed Stone Dust as Fine Aggregate in Cement Concrete. Materials Today: Proceedings, 5(9), 17540–17547. https://doi.org/10.1016/j.matpr.2018.06.070

Rosca, B., & Serbanoiu, A. A. (2022). Study on influence of natural aggregate maximum size on compressive strength of polystyrene aggregate concrete of structural grade. Materials Today: Proceedings, 61, 433–439. https://doi.org/10.1016/j.matpr.2021.11.356

Roslan, M. K. A., Ismail, M., Kueh, A. B. H., & Zin, M. R. M. (2019). High-density concrete: Exploring Ferro boron effects in neutron and gamma radiation shielding. Construction and Building Materials, 215, 718–725. https://doi.org/10.1016/j.conbuildmat.2019.04.105

Saran, A. A., & Magudeswaran, P. (2017). SEM analysis on sustainable high performance concrete. Int J Innov Res Sci Eng Technol, 6(6), 10237-10246.

Sakamoto, S., Kiger, W. S. 3rd, & Harling, O. K. (1999). Sensitivity studies of beam directionality, beam size, and neutron spectrum for a fission converter-based epithermal neutron beam for boron neutron capture therapy. *Medical Physics*, *26*(9), 1979–1988. https://doi.org/10.1118/1.598784

Sariyer, D., & Küçer, R. (2018). Double-layer neutron shield design as neutron shielding application. In *AIP Conference Proceedings* (Vol. 1935). https://doi.org/10.1063/1.5026020

Sarkawi, M. S. B. (2020). Design, Construction And Facility Enhancement For Digital Neutron Radiography At Reactor Triga Puspati (Doctoral Dissertation, Universiti Teknologi Malaysia).

Savadkoohi, M. S., & Reisi, M. (2020). Environmental protection based sustainable development by utilization of granite waste in Reactive Powder Concrete. Journal of Cleaner Production, 266, 121973.

https://doi.org/10.1016/j.jclepro.2020.121973

Shirmardi, S. P., Shamsaei, M., & Naserpour, M. (2013). Comparison of photon attenuation coefficients of various barite concretes and lead by MCNP code, XCOM and experimental data. Annals of Nuclear Energy, 55, 288–291. https://doi.org/10.1016/j.anucene.2013.01.002

Shultis, J. K., & Faw, R. E. (2011). *An MCNP primer*. Retrieved from http://hdl.handle.net/2097/15754

Shultis, J. K., & Faw, R. E. (2005). RADIATION SHIELDING TECHNOLOGY. Health Physics, 88(4), 297–322. https://doi.org/10.1097/01.hp.0000148615.73825.b1

Singh, K., Singh, S., Dhaliwal, A. S., & Singh, G. (2015). Gamma radiation shielding analysis of lead-flyash concretes. *Applied Radiation and Isotopes*, *95*, 174–179. https://doi.org/10.1016/j.apradiso.2014.10.022

Sis, H., Bentli, I., Demirkiran, N., & Ekmekyapar, A. (2018). Investigating dissolution of colemanite in sulfuric acid solutions by particle size measurements. Separation Science and Technology, 54(8), 1353–1362. https://doi.org/10.1080/01496395.2018.1532961

Solleh, M. R. M. (2016). *Moderator, collimator and shielding studies for BNCT research at Malaysian Nuclear Agency*. Universiti Sains Malaysia.

Soltani, Z., Beigzadeh, A., Ziaie, F., & Asadi, E. (2016). Effect of particle size and percentages of Boron carbide on the thermal neutron radiation shielding properties of HDPE/B4C composite: Experimental and simulation studies. *Radiation Physics and Chemistry*, *127*, 182–187. https://doi.org/10.1016/j.radphyschem.2016.06.027

Strobl, M., Manke, I., Kardjilov, N., Hilger, A., Dawson, M., & Banhart, J. (2009). Advances in neutron radiography and tomography. *Journal of Physics D: Applied Physics*, *42*(24), 243001. https://doi.org/10.1088/0022-3727/42/24/243001

Suzuki, M. (2019). Boron neutron capture therapy (BNCT): a unique role in radiotherapy with a view to entering the accelerator-based BNCT era. International Journal of Clinical Oncology, 25(1), 43–50. https://doi.org/10.1007/s10147-019-01480-4

TheConstructor. (2018, September 3). Concrete Slump Test for Workability -Procedure and Results. Retrieved from The Constructor website: https://theconstructor.org/concrete/concrete-slump-test/1558/

Tzika, F., & Stamatelatos, I. E. (2004). Thermal neutron self-shielding correction factors for large sample instrumental neutron activation analysis using the MCNP code. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 213, 177–181. https://doi.org/10.1016/s0168-583x(03)01601-x

Tyagi, G., Singhal, A., Routroy, S., Bhunia, D., & Lahoti, M. (2021). Radiation Shielding Concrete with alternate constituents: An approach to address multiple hazards. Journal of Hazardous Materials, 404, 124201. https://doi.org/10.1016/j.jhazmat.2020.124201

Uchikawa, H., & Tsukiyama, K. (1973). The hydration of jet cement at 20°C. Cement and Concrete Research, 3(3), 263–277. https://doi.org/10.1016/0008-8846(73)90030-6

Vasanelli, E., Colangiuli, D., Calia, A., Sileo, M., & Aiello, M. A. (2015). Ultrasonic pulse velocity for the evaluation of physical and mechanical properties of a highly porous building limestone. Ultrasonics, 60, 33–40. https://doi.org/10.1016/j.ultras.2015.02.010

Victor L. Hauser. (1984). Neutron Meter Calibration and Error Control. Transactions of the ASAE, 27(3), 722–728. https://doi.org/10.13031/2013.32860

Vega-Carrillo, H. R., Villagrana-Muñoz, L. E., Rivera-Perez, E., de Leon-Martinez, H. A., Soto-Bernal, T. G., & Hernández-Davila, V. M. (2013). Concrete enclosure for shielding a neutron source. *Applied Radiation and Isotopes*, *79*, 37–41. https://doi.org/https://doi.org/10.1016/j.apradiso.2013.04.030

Wang, J., Yung, J., Kadbi, M., Hwang, K., Ding, Y., & Ibbott, G. S. (2018). Assessment of image quality and scatter and leakage radiation of an integrated MR-LINAC system. Medical Physics, 45(3), 1204–1209. https://doi.org/10.1002/mp.12767

Wagiran, H. (1997). *Prinsip asas sinaran dan reaktor nuklear*. Penerbit UTM.

Walker, S. J. (1998). Boron neutron capture therapy: principles and prospects. *Radiography*, *4*(3), 211–219. https://doi.org/https://doi.org/10.1016/S1078-8174(98)80048-5

Waly, E.-S. A., & Bourham, M. A. (2015). Comparative study of different concrete composition as gamma-ray shielding materials. *Annals of Nuclear Energy*, *85*, 306–310. https://doi.org/DOI:101016/janucene201505011

Wonglee, S., Liamsuwan, T., Pornroongruengchok, W., Channuie, J., Picha, R., & Khaweerat, S. (2018). Collimator design for neutron radiography station using Monte Carlo simulation. Journal of Physics: Conference Series, 1144, 012095. https://doi.org/10.1088/1742-6596/1144/1/012095

Xu, D., Guo, Z., Li, S., Zheng, J., Li, T., Zhang, L., … Zhang, J. (2013, July 29). *The Research of Shielding Material for Mixed Field*. https://doi.org/10.1115/ICONE21-16188

Yang, X.-P., Yu, B.-X., Li, Y.-G., Peng, D., Lu, J., Zhang, G.-L., … Lü, J.-G. (2014). Neutron collimator design of neutron radiography based on the BNCT facility. Chinese Physics C, 38(2), 028201. https://doi.org/10.1088/1674-1137/38/2/028201

Yao, Y., Zhang, X., Li, M., Yang, R., Jiang, T., & Lv, J. (2016). Investigation of gamma ray shielding efficiency and mechanical performances of concrete shields containing bismuth oxide as an environmentally friendly additive. *Radiation Physics and Chemistry*, *127*, 188–193. https://doi.org/https://doi.org/10.1016/j.radphyschem.2016.06.028

Yılmaz, E., Baltas, H., Kırıs, E., Ustabas, İ., Cevik, U., & El-Khayatt, A. M. (2011). Gamma ray and neutron shielding properties of some concrete materials. *Annals of Nuclear Energy*, *38*(10), 2204–2212. https://doi.org/https://doi.org/10.1016/j.anucene.2011.06.011

Zayed, A. M., Masoud, M. A., Shahien, M. G., Gökçe, H. S., Sakr, K., Kansouh, W. A., & El-Khayatt, A. M. (2021). Physical, mechanical, and radiation attenuation properties of serpentine concrete containing boric acid. Construction and Building Materials, 272, 121641. https://doi.org/10.1016/j.conbuildmat.2020.121641

Zafiropoulos, D., & Scarabottolo, G. (2001). Neutron spectra using a portable neutron spectrometer. *Radiation Protection Group. Sl: Legnaro National Laboratories (INFN)*.

Zailani, R., Priambodo, G., & Sardjono, Y. (2018). Neutron and Gamma Spectrum Analysis of Kartini Research Reactor for Boron Neutron Capture Therapy (BNCT). *Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega*, *20*(2), 59–68.

Zolghadri, S., Yousefnia, H., Afarideh, H., Bahrami-Samani, A., Jalilian, A. R., & Ghannadi-Maragheh, M. (2013). Measurement of thermal neutron capture cross-section and resonance integral for the 165Ho(n,γ)166gHo reaction by the activation method. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *295*, 94–98. https://doi.org/https://doi.org/10.1016/j.nimb.2012.11.013