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Radiofrequency Electromagnetic Field (RF-EMF) Exposure Assessment at a Nuclear Facility: Safety Monitoring and Public

(Penilaian Pendedahan Medan Elektromagnet Frekuensi Radio (RF-EMF) di Kemudahan Nuklear: Pemantauan Keselamatan dan Keselamatan Awam)

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ABSTRACT

The widespread adoption of 5G technology has brought numerous benefits; however, it has also raised public concerns regarding potential health risks associated with exposure to radiofrequency electromagnetic fields (RF-EMF). To address these concerns, this study evaluated RF-EMF levels at the Malaysian Nuclear Agency (Nuclear Malaysia) to ensure compliance with international safety standards. A key standard examined was the guidelines established by the International Commission on Non-Ionising Radiation Protection (ICNIRP 2020). To conduct the assessment, a NARDA broadband area monitor was used to measure the RF-EMF electric field strength (E) at eight primary locations within Nuclear Malaysia over 24 h. NARDA is a brand of Narda Safety Test Solutions (Narda STS), a global leader in developing and manufacturing measurement technology for RF-EMF. Data was gathered at six-minute intervals, resulting in 240 measurement points per site. These measurements were compared to the public exposure limit of 36.38 V/m at the 700 MHz frequency band. The results showed that all recorded RF-EMF levels were below the established safety thresholds. The study found a significant correlation between location and exposure levels; laboratory blocks (Block 11) recorded the lowest readings, while administrative offices, near the external telecommunication mast (Block 28), had the highest readings. The maximum exposure measured at Block 28 represented only 3.88% of the ICNIRP (2020) guidelines limit at 1.41 V/m. Additionally, these findings indicated that workers and the public faced minimal risk due to safe RF-EMF exposure levels at Nuclear Malaysia. Consequently, the transparent communication of these results can help improve public confidence in 5G technology within sensitive environments. This study also effectively presented the inaugural empirical mapping of RF-EMF exposure in a Malaysian nuclear research facility through real-time monitoring and public safety assessments. The overall process offers several benefits, including safeguarding public health, promoting responsible growth of digital infrastructure, and providing a scalable model for environmental safety.

Keywords: Electromagnetic field; public health; radiation safety; RF-EMF; 5G

ABSTRAK

Penggunaan teknologi 5G secara meluas telah membawa banyak manfaat; walau bagaimanapun, ia juga telah menimbulkan kebimbangan orang ramai mengenai potensi risiko kesihatan yang berkaitan dengan pendedahan kepada medan elektromagnet frekuensi radio (RF-EMF). Bagi menangani kebimbangan ini, kajian ini menilai tahap RF-EMF di Agensi Nuklear Malaysia (Nuklear Malaysia) untuk memastikan pematuhan dengan piawaian keselamatan antarabangsa. Piawaian utama yang disemak ialah garis panduan yang ditetapkan oleh Suruhanjaya Antarabangsa mengenai Perlindungan Sinaran Tanpa Pengion (ICNIRP 2020). Bagi menjalankan penilaian, monitor kawasan jalur lebar NARDA telah digunakan untuk mengukur kekuatan medan elektrik RF-EMF (E) di lapan lokasi utama di Nuklear Malaysia dalam tempoh 24 jam. NARDA ialah jenama Narda Safety Test Solutions (Narda STS), peneraju global dalam membangun dan mengeluarkan teknologi pengukuran untuk RF-EMF. Data dikumpulkan pada selang enam minit, menghasilkan 240 titik pengukuran setiap tapak. Pengukuran ini dibandingkan dengan had pendedahan awam iaitu 36.38 V/m pada jalur frekuensi 700 MHz. Keputusan menunjukkan bahawa semua tahap RF-EMF yang direkodkan adalah di bawah ambang keselamatan yang ditetapkan. Kajian ini mendapati korelasi yang ketara antara lokasi dan tahap pendedahan; blok makmal (Blok 11) mencatatkan bacaan terendah, manakala pejabat pentadbiran, berhampiran tiang telekomunikasi luaran (Blok 28), mempunyai bacaan tertinggi. Pendedahan maksimum yang diukur di Blok 28 hanya mewakili 3.88% daripada had garis panduan ICNIRP (2020) pada 1.41 V/m. Di samping itu, penemuan ini menunjukkan bahawa pekerja dan orang awam menghadapi risiko minimum disebabkan oleh tahap pendedahan RF-EMF yang selamat di Nuklear Malaysia. Oleh itu, komunikasi yang telus tentang keputusan ini dapat membantu meningkatkan keyakinan orang ramai terhadap teknologi 5G dalam persekitaran yang sensitif. Kajian ini juga secara berkesan membentangkan pemetaan empirik sulung pendedahan RF-EMF di kemudahan penyelidikan Nuklear Malaysia melalui pemantauan masa nyata dan penilaian keselamatan awam. Proses keseluruhan menawarkan beberapa faedah, termasuk melindungi kesihatan awam, menggalakkan pertumbuhan infrastruktur digital yang bertanggungjawab dan menyediakan model yang boleh diskala untuk keselamatan alam sekitar.

Kata kunci: Keselamatan radiasi; kesihatan awam; medan elektromagnet; RF-EMF; 5G

INTRODUCTION

The rollout of fifth-generation (5G) mobile networks has revolutionised global connectivity, offered faster data transmission and enabled a wide range of advanced, innovative applications. This technological expansion, however, has intensified public and institutional exposure to radiofrequency electromagnetic fields (RF-EMF), particularly in urban and high-density environments (Fernandez, Vecchia & Strauss 2021; Modenese & Gobba 2023). These exposures have prompted international agencies and regulators to ensure that health and safety standards are rigorously maintained.

To address these concerns, the International Commission on Non-Ionising Radiation Protection (ICNIRP 2020) established frequency-dependent guidelines that define safe exposure thresholds. Malaysia has adopted these standards into its national regulatory framework through the Malaysian Communications and Multimedia Commission (MCMC 2021), which is also aligned with the International Atomic Energy Agency's Basic Safety Standards (IAEA 2018). Compliance requires site-specific monitoring because RF-EMF levels are influenced by factors such as infrastructure density, device usage, and local environmental conditions (Bhatt et al. 2020; Foster et al. 2022).

Despite widespread adoption of ICNIRP (2020) guidelines, there remains limited empirical evidence on RF-EMF exposure within sensitive environments such as hospitals, schools, and research facilities. These settings require careful monitoring due to their societal importance and the need to maintain public confidence in radiation safety standards. International reviews also emphasise that continuous and transparent monitoring facilitates addressing public concerns while supporting technological progress (Bosch-Capblanch et al. 2024; Meyer, Cardis & Vrijheid 2024).

In Malaysia, studies on RF-EMF exposure have primarily focused on urban populations and telecommunication hotspots, with little attention given to critical national institutions (Hasan et al. 2024; Mohammad et al. 2022). As shown in Figure 1, the Nuclear Malaysia research facility comprises multiple blocks where scientific research and public services are conducted. However, no systematic mapping of RF-EMF exposure has been reported in such facilities, leaving a knowledge gap regarding compliance in high-sensitivity environments.

This study addresses that gap by conducting a 24-h RF-EMF monitoring campaign across eight blocks of Nuclear Malaysia. Measurements were recorded using the NARDA AMB-8059 broadband system and compared against the ICNIRP (2020) guidelines for public exposure limits of 36.38 V/m at 700 MHz, which is the lowest operational 5G band in the country. Beyond confirming compliance, the findings aim to establish a transparent safety baseline, thereby strengthening public trust in regulatory standards and providing a framework for future monitoring in other high-impact facilities (Ahmed, Khan & Hussain 2023; James & Lin 2023).

MATERIALS AND METHODS

EXPERIMENTAL MATERIALS

This study contained two primary objectives: (i) assessing the RF-EMF exposure levels in Nuclear Malaysia and (ii) examining compliance with the ICNIRP (2020) guidelines. Two phase methodology was employed to target both objectives: (i) Phase 1 (RF-EMF level measurement at specified locations) and (ii) Phase 2 (data analysis and comparison with international exposure standards). Phase 1 was conducted in designated blocks of the Nuclear Malaysia facility (Bangi, Selangor), involving systematic field measurements of the RF-EMF electric field strength (E). This process encompassed a total of eight blocks: (i) Block 11, (ii) Block 13T, (iii) Block 15, (iv) Block 28, (v) Block 32, (vi) Block 42, (vii) Block 57, and (viii) Block 60. The blocks delineated various operational zones within Nuclear Malaysia. Examples of these zones were administrative offices, technical units, research laboratories, server rooms, and utility areas (Figure 1). Figure 1 shows the map of the Nuclear Malaysia complex in Bangi, Selangor, with the eight monitored blocks indicated across the facility.

The eight blocks were selected to represent a variety of factors related to human occupancy, infrastructure density, and exposure to radiofrequency electromagnetic fields (RF-EMF). This selection process aimed to ensure that each block reflected different exposure conditions from sources like Wi-Fi routers, mobile communication equipment, and telecommunications masts. By doing so, the monitoring approach could capture the full range of RF-EMF exposure across the facility.

This strategy is consistent with findings from earlier studies on radiofrequency electromagnetic

FIGURE 1. Map of Nuclear Malaysia facility (Bangi, Selangor), showing the eight monitored blocks selected for RF-EMF exposure assessment

fields (RF-EMF), which emphasise the importance of selecting monitoring locations that are representative of the surrounding area. By doing so, it ensures that the measurements capture the diverse range of RF-EMF exposure levels and patterns, thereby providing a thorough and comprehensive spatial coverage of the environment under assessment (Ahmed, Khan & Hussain 2023; Roha 2024). The detailed characteristics of each chosen block, including their functions and the communication infrastructure present, can typically be found in Table 1.

EXPERIMENTAL METHODS

A high-precision RF-EMF monitoring device capable of detecting electric field strength (*E*) across a frequency range of 10 Hz to 60 GHz was used for the measurements, specifically the NARDA broadband area monitoring system (Model AMB-8059-03, Serial No. 490ZY30554), as shown in Figure 2(a). Nevertheless, the device underwent calibration by an accredited metrology laboratory on September 12, 2023, as per Narda Safety Test Solutions certificate number 30554 (detailed certificate records are provided in the supplementary file), prior to deployment. This process was critical to ensure accuracy, traceability, and compliance with the International Organisation for Standardisation (ISO) standards, specifically ISO 9001. This procedure was conducted prior to field deployment to guarantee accuracy and adherence to international standards via multiple stages. The calibration was performed according to internal procedure PTP 09-62 and confirmed that the equipment met all specified accuracy requirements, with an expanded measurement uncertainty estimated at ±3%. Tests included probe functionality, communication ports, global system for mobile communications (GSM), interlock, internal supply voltage, current consumption, file transfer protocol (FTP) data transfer, Wi-Fi, and GPS performance, all of which passed inspection. Calibration was performed at an ambient temperature of 23 ± 3 °C and relative humidity of 50 ± 30%, ensuring traceability to national and international standards, in accordance with the IAEA Safety Standards (IAEA 2018). Detailed certificate records are provided in the supplementary file.

The selection of NARDA broadband was also based on two of its primary features: (i) high ability to log timestamped data using internal GPS tracking and (ii) excellent effectiveness in continuous monitoring across indoor and outdoor settings. Figure 2(a) illustrates the instrument setup within a monitored block, while Figure 2(b) outlines the workflow, from calibration through deployment, real-time logging, and 24-h data collection.

This study simulated average human exposure scenarios by securely mounting the device on a tripod at a standard height of 1.5 m above the ground at each measurement site. Appropriate distances were maintained between the device and metallic objects to standardise environmental conditions across the sites. Additionally, uniform environmental conditions were maintained across all blocks to improve the comparability and reliability of the collected data. Environmental factors were controlled to minimise any confounding effects unrelated to telecommunication infrastructure or network activity. Measurements were conducted only during stable meteorological conditions, excluding periods of rainfall and limiting wind speeds to below 10 meters per second, as weather conditions have been shown to attenuate and scatter RF signals (Odesanya, Olukanni & Risi 2025).

Ambient temperature and relative humidity were continuously monitored using the internal sensors of the AMB-8059, ensuring that operation remained within the manufacturer's recommended range (0-50 °C; <95% RH). Additionally, to avoid interference from non-permanent sources, temporary transmitters such as mobile hotspots were prohibited within 5 meters of the monitoring device. Data collection took place on routine working days to accurately reflect typical occupancy and network usage, ensuring that the results accurately represented normal exposure conditions. A minimum separation from reflective surfaces was also maintained to achieve standardisation. The device gathered data over 24 h, collecting measurements at six-minute intervals (240 points per block). This process effectively captured both peak and average exposure levels concerning the day-night cycle. The primary parameter, electric field strengths (*E*), in this study adhered to ICNIRP (2020) guidelines, reinforcing its role as a standard exposure metric.

The raw temporal RF-EMF measurements were continuously logged at 6-min intervals over a 24-h period. Figure 3 illustrates a representative data extract from the raw data, including peak electric field strength (*E*, V/m), root mean square (RMS) status, ambient temperature (°C), and relative humidity (RH, %). Detailed data records are provided in the supplementary file. The supplementary file provides the complete 24-h temporal trend for all monitored blocks. This dataset illustrates how field strengths remained consistently low throughout the day, with minor fluctuations attributable to network activity rather than environmental variability, as ambient temperature and humidity were maintained within the instrument's operating range (27-29 °C; 65-70% RH). The peak values were used to calculate the percentage exposure limit, as shown in Equation (2).

Several values were obtained in Phase 2 through the examination of RF-EMF data from eight blocks using NARDA software. Examples of these variables were the maximum, minimum, and average *E* values. Specifically, worst-case exposure scenarios were represented by the maximum values. The benchmark, based on ICNIRP (2020) guidelines, then involved employing the 700 MHz frequency band. This selection was attributed to the stringent safety limit of the frequency band and its prevalent application in Malaysian 4G and 5G infrastructure (MCMC 2021). Therefore, the ICNIRP (2020) guidelines establish a limit for 700 MHz, which can be calculated using Equation (1).

$$E_{limit} = 1.375 \times \sqrt{f} \tag{1}$$

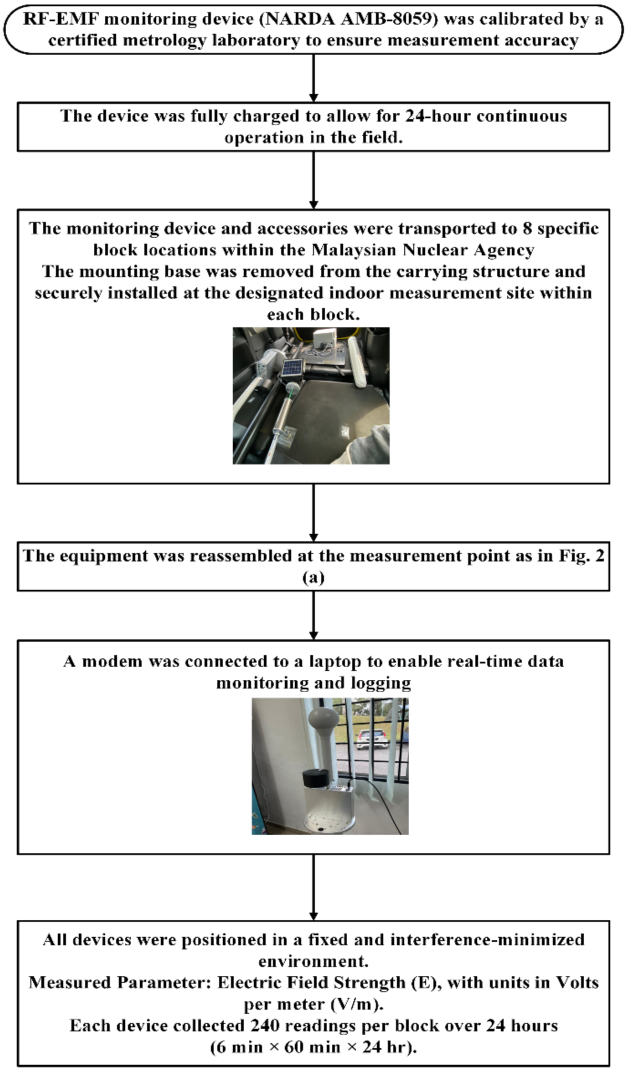
where f is the frequency. For a frequency of 700 MHz, a threshold of 36.38 V/m is used in this study.

The monitor's broad frequency range (10 Hz-60 GHz) ensures comprehensive coverage, but 700 MHz

TABLE 1. Summary of the measurement locations and site characteristics for RF-EMF monitoring at Nuclear Malaysia facility. Each block is identified by its location name, Global Positioning System (GPS) coordinates, antenna height (1.5 m), and a brief description of its operational functions, along with the expected RF exposure sources

Block	Location name	GPS coordinates	Antenna height (m)	Site description
11	Laboratory block A	2.92°N, 101.78°E	1.50	Office and laboratory area with minimal wireless equipment
13T	Technical block	2.92°N, 101.78°E	1.50	Mixed-use block with technical instrumentation
15	Reactor auxiliary area	2.92°N, 101.78°E	1.50	Adjacent to the leading research equipment, moderate RF traffic
28	Administration building	2.92°N, 101.78°E	1.50	Administrative offices, near the external telecommunication mast
32	ICT server block	2.92°N, 101.78°E	1.50	Close to internal servers, possible local RF sources
42	Safety and security unit	2.92°N, 101.78°E	1.50	Monitored area with surveillance devices
57	Central services block	2.92°N, 101.78°E	1.50	Includes utilities and centralised operations
60	Research block D	2.92°N, 101.78°E	1.50	Scientific laboratories and RF-based instrumentation

(a)



(b)

FIGURE 2. RF-EMF monitoring setup using the NARDA AMB-8059 broadband area monitor (a) On-site deployment of the NARDA AMB-8059 broadband area monitor for RF-EMF measurement at a designated block within the Malaysian Nuclear Agency, and (b) workflow for RF-EMF measurement using the NARDA AMB-8059

Time	Peak W.	RMS W.	Temp	Current	RH
	V/m	V/m	C~	mA	%
0:00:00	1.11	LOW	28	32	66
12:06:00	1.15	LOW	28	28	66
12:12:00	1.05	LOW	29	28	65
12:18:00	1.03	LOW	29	28	65
12:24:00	1.11	LOW	29	32	65
12:30:00	1.19	LOW	29	32	65
12:36:00	1.14	LOW	29	32	65
12:42:00	1.12	LOW	29	32	65
12:48:00	1.09	LOW	29	28	65
12:54:00	1.09	LOW	28	28	65
1:00:00	1.01	LOW	28	28	65
1:06:00	1.17	LOW	28	28	66
1:12:00	1.01	LOW	28	28	66
1:18:00	1.06	LOW	28	28	66
1:24:00	1.04	LOW	28	28	66
1:30:00	1.35	LOW	28	28	66
1:36:00	1.05	LOW	28	24	66
1:42:00	1.32	0.51	28	24	66
1:48:00	1.25	LOW	28	24	66
1:54:00	1.3	LOW	28	24	66
2:00:00	1.13	LOW	28	24	66
2:06:00	1.01	LOW	28	24	66
2:12:00	1.14	LOW	28	24	66
2:18:00	0.97	LOW	28	24	66
2:24:00	1.03	LOW	28	24	66
2:30:00	1.18	LOW	28	24	66
2:36:00	1.11	LOW	28	24	66
2:42:00	1.18	LOW	28	20	66
2:48:00	1.02	LOW	28	20	66
2:54:00	1.15	LOW	28	20	66
3:00:00	1	LOW	28	20	66
3:06:00	1.06	LOW	28	20	67
3:12:00	0.87	LOW	28	20	67
3:18:00	1.13	LOW	28	20	67
3:24:00	1.02	LOW	28	20	67
3:30:00	1	LOW	28	20	67
3:36:00	1.02	LOW	28	20	67
3:42:00	1.11	LOW	28	20	67
3:48:00	1.14	LOW	28	20	67
3:54:00	1.12	LOW	28	16	67
4:00:00	1.13	LOW	28	16	67
4:06:00	0.98	LOW	28	16	67
4:12:00	0.84	LOW	28	16	66
4:18:00	1.1	LOW	29	12	66
4:24:00	1.15	LOW	29	16	65
4:30:00	1.05	LOW	29	16	66
4:36:00	1.12	LOW	28	16	66
4:42:00	1.12	LOW	28	16	66
4:48:00	0.99	LOW	28	16	66
4:54:00	0.95	LOW	28	16	66
5:00:00	1.06	LOW	28	16	66
5:06:00	1.11	LOW	28	16	66
5:12:00	0.98	LOW	28	16	66
5:18:00	1.14	LOW	28	12	66
5:24:00	1.06	LOW	28	12	67
5:30:00	1.2	LOW	28	12	67
5:36:00	1.04	0.5	28	12	67
5:42:00	1.29	LOW	28	12	67
5:48:00	1.13	0.52	28	12	67
5:54:00	1.21	LOW	28	12	67
6:00:00	1.29	0.51	28	12	67
6:06:00	1.19	LOW	28	12	67
6:12:00	1.2	LOW	28	12	67
6:18:00	1.2	LOW	28	12	67
6:24:00	1.12	LOW	28	12	67
6:30:00	1.16	LOW	28	12	67
6:36:00	1.24	LOW	28	12	67
6:42:00	1.4	LOW	28	12	67
6:48:00	1.24	LOW	28	12	67
6:54:00	1.12	LOW	28	12	67
7:00:00	1.08	LOW	28	8	67
7:06:00	1.23	LOW	28	8	67
7:12:00	1.31	LOW	28	12	67
7:18:00	1.17	LOW	28	8	67
7:24:00	1.26	0.53	28	8	67
7:30:00	1.02	LOW	28	8	67
7:36:00	1.17	0.5	28	8	67
7:42:00	1.2	0.52	28	8	67
7:48:00	1.17	LOW	28	8	67
7:54:00	1.22	LOW	28	8	67
8:00:00	1.09	LOW	28	8	67
8:06:00	1.12	LOW	28	4	67
8:12:00	1.11	LOW	28	4	67
8:18:00	1.29	LOW	29	4	66
8:24:00	1.18	0.54	29	8	66
8:30:00	1.1	0.5	28	8	66
8:36:00	1.08	LOW	28	8	67
8:42:00	1.27	0.51	28	8	67
8:48:00	1	LOW	28	8	67
8:54:00	1.03	LOW	28	4	66
9:00:00	1.18	LOW	28	4	66
9:06:00	1.26	LOW	27	4	66
9:12:00	1.23	0.51	27	4	65
9:18:00	1.24	LOW	27	4	65
9:24:00	1.22	0.52	26	4	65
9:30:00	1.16	LOW	26	4	65
9:36:00	1.14	LOW	26	4	65
9:42:00	1.19	0.52	25	4	65
9:48:00	1.26	0.59	25	4	65
9:54:00	1.23	0.57	25	4	65
10:00:00	1.22	0.67	24	4	65
10:06:00	1.3	0.64	24	4	65
10:12:00	1.21	0.65	24	4	65
10:18:00	1.29	0.62	24	4	66
10:24:00	1.17	0.65	24	4	66
10:30:00	1.01	0.64	24	4	66
10:36:00	1.02	0.62	24	4	66
10:42:00	1.11	0.62	23	4	66
10:48:00	1.04	0.58	23	4	66
10:54:00	1.07	0.63	24	4	67
11:00:00	1.12	0.63	24	4	67
11:06:00	1.22	0.63	24	4	67
11:12:00	1.11	0.59	24	4	67
11:18:00	1.2	0.64	24	4	67
11:24:00	1.16	0.61	24	4	67
11:30:00	1.22	0.64	24	4	67
11:36:00	1.26	0.61	24	4	67
11:42:00	1.2	0.66	24	4	67
11:48:00	1.15	0.63	24	4	67
11:54:00	1.17	0.63	24	4	67
12:00:00	1.09	0.61	24	0	67
12:06:00	1.36	0.64	24	0	67
12:12:00	1.25	0.62	25	0	66
12:18:00	1.26	0.64	25	0	66
12:24:00	1.37	0.62	25	0	65
12:30:00	1.19	0.63	25	0	65
12:36:00	1.19	0.63	25	0	65
12:42:00	1.23	0.58	25	0	66
12:48:00	1.17	0.61	25	0	66
12:54:00	1.15	0.61	25	0	66
1:00:00	1.21	0.63	24	0	66
1:06:00	1.26	0.61	24	0	66
1:12:00	1.16	0.6	24	0	66
1:18:00	1.14	0.61	24	0	66
1:24:00	1.15	0.61	24	0	66
1:30:00	1.28	0.64	24	0	66
1:36:00	1.23	0.6	24	0	66
1:42:00	1.29	0.65	24	0	66
1:48:00	1.38	0.61	24	0	66
1:54:00	1.2	0.61	24	0	66
2:00:00	1.2	0.68	24	0	66
2:06:00	1.41	0.6	24	0	66
2:12:00	1.39	0.65	24	0	66
2:18:00	1.25	0.62	24	0	66
2:24:00	1.16	0.62	24	0	66
2:30:00	1.1	0.63	24	0	66
2:36:00	1.14	0.64	24	0	65
2:42:00	1.2	0.65	24	0	65
2:48:00	1.4	0.61	24	0	65
2:54:00	1.19	0.63	24	0	65
3:00:00	1.14	0.64	24	0	65
3:06:00	1.38	0.6	24	0	65
3:12:00	1.12	0.64	24	0	65
3:18:00	1.17	0.65	24	0	65
3:24:00	1.06	0.64	24	0	65
3:30:00	1.1	0.64	24	0	65
3:36:00	1.33	0.64	24	0	65
3:42:00	1.06	0.64	24	0	65
3:48:00	1.1	0.64	24	0	65
3:54:00	1.18	0.65	24	0	65
4:00:00	1.05	0.65	24	0	65
4:06:00	1.08	0.64	24	0	65
4:12:00	1.08	0.65	24	0	64
4:18:00	1.01	0.61	25	0	64
4:24:00	1.21	0.65	25	0	63
4:30:00	1.19	0.66	25	0	64
4:36:00	1.08	0.65	24	0	64
4:42:00	1.16	0.66	24	0	64
4:48:00	1.23	0.66	24	0	64
4:54:00	1.07	0.62	24	0	64
5:00:00	1.12	0.65	24	0	64
5:06:00	1.04	0.57	25	0	65
5:12:00	1.24	0.53	25	0	65
5:18:00	1.16	LOW	25	0	65
5:24:00	1.13	LOW	25	0	65
5:30:00	1.18	LOW	26	0	65
5:36:00	1.21	0.52	26	0	65
5:42:00	1.23	LOW	26	0	65
5:48:00	1.38	LOW	26	0	65
5:54:00	1.23	0.51	27	0	65
6:00:00	1.18	LOW	27	0	65
6:06:00	1.17	LOW	27	0	64
6:12:00	1.18	LOW	27	0	64
6:18:00	1.1	LOW	27	0	64
6:24:00	1.1	LOW	28	0	64
6:30:00	1.04	LOW	28	0	64
6:36:00	0.9	LOW	28	0	64
6:42:00	0.88	LOW	28	0	64
6:48:00	0.89	LOW	28	0	64
6:54:00	0.95	LOW	28	0	64
7:00:00	0.87	LOW	28	0	64
7:06:00	1.1	LOW	28	0	64
7:12:00	0.86	LOW	29	0	63
7:18:00	1.17	LOW	29	0	63
7:24:00	0.89	LOW	29	0	63
7:30:00	1.02	LOW	29	0	63
7:36:00	1.03	LOW	29	0	63
7:42:00	1	LOW	29	0	63
7:48:00	0.99	LOW	29	0	63
7:54:00	0.91	LOW	29	0	63
8:00:00	0.94	LOW	29	0	63
8:06:00	1.02	LOW	29	0	63
8:12:00	0.91	LOW	29	0	63
8:18:00	0.92	LOW	30	0	62
8:24:00	1.09	0.51	30	0	62
8:30:00	1	0.5	30	0	62
8:36:00	1.15	LOW	30	0	62
8:42:00	1.06	LOW	29	0	62
8:48:00	1.13	LOW	29	0	62
8:54:00	1.11	LOW	29	0	63
9:00:00	1.14	LOW	29	0	63
9:06:00	1.16	0.51	29	0	63
9:12:00	1.03	LOW	29	0	63
9:18:00	1.02	LOW	29	0	63
9:24:00	1.1	LOW	29	0	63
9:30:00	1.2	0.52	29	0	63
9:36:00	1.22	LOW	29	0	63
9:42:00	1.2	LOW	29	0	63
9:48:00	0.98	LOW	29	0	63
9:54:00	1.11	LOW	29	0	63
10:00:00	1.03	LOW	29	0	63
10:06:00	0.97	LOW	29	0	64
10:12:00	1.02	LOW	29	0	64
10:18:00	1.21	LOW	29	0	64
10:24:00	1	LOW	29	0	64
10:30:00	1.09	LOW	29	0	64
10:36:00	1.09	LOW	29	0	64
10:42:00	1.01	LOW	29	0	64
10:48:00	1.18	LOW	29	0	64
10:54:00	1.08	LOW	29	0	64
11:00:00	1.12	LOW	29	0	64
11:06:00	1.01	LOW	29	0	64
11:12:00	1.03	LOW	29	0	64
11:18:00	1.02	0.5	29	0	64
11:24:00	0.99	LOW	29	0	64
11:30:00	1.08	LOW	29	0	64
11:36:00	1.13	LOW	29	0	64
11:42:00	1.11	0.5	29	0	64
11:48:00	1.21	LOW	29	0	64
11:54:00	1.19	LOW	29	0	64
AVERAGE	1.13	0.60	26.94	6.93	65.31

FIGURE 3. Raw temporal variation of electric field strength, *E,* measured over 24 h, showing hourly fluctuations across the monitoring site

represents the lowest commonly used telecommunication frequency at the study sites. Using this frequency provides a conservative baseline for exposure evaluation, aligning with best practices in environmental safety monitoring. To assess compliance, each measured value was converted to a percentage of the ICNIRP (2020) guidelines limit using Equation (2).

$$Exposure\ (\%) = \left(\frac{Measured\ Value}{ICNIRP\ Limit}\right) \times 100 \qquad (2)$$

Benchmarking at 700 MHz plays a critical role in the context of regulatory frameworks and practical applications, particularly in Malaysia. This frequency band is not only a cornerstone for the rollout of long-term evolution (LTE) services but also a key player in the early deployment of 5G technology, making it highly relevant both domestically and globally (MCMC 2021).

Empirical studies underscore the significance of this frequency range in real-world scenarios. For instance, Bhatt et al. (2020) found that RF-EMF exposures in the 700-900 MHz range are often the predominant contributors to overall electromagnetic field exposure in urban settings, primarily due to the superior propagation characteristics of this band. Furthermore, research by Esposito et al. (2020) highlighted that employing conservative benchmarking practices markedly enhances the precision of occupational dosimetry assessments.

In a significant study conducted by Roha (2024) in Malaysia, calibration studies demonstrated that utilising the 700 MHz frequency not only captures environmental variations more comprehensively but also enhances the reliability and robustness of long-term exposure monitoring. By anchoring assessments to the 700 MHz benchmark, this study adopts a precautionary approach that reflects the worst-case scenario, aligning closely with international safety recommendations while also considering Malaysia's unique national infrastructure. This strategy not only fortifies the credibility of the compliance evaluation conducted by Nuclear Malaysia but also contributes to a more informed understanding of electromagnetic exposure assessments.

One significant example involves measuring the maximum exposure value of 1.41 V/m, as shown in Equation (3).

$$\left(\frac{1.41}{36.38}\right) \times 100 = 3.88\% \quad (3)$$

If each value across the blocks was below the safety threshold, this study concluded that there was a minimal health risk and adherence to regulatory standards. This study also ensured accessibility for scientific and public audiences. The process involved presenting the outcomes in technical and simplified formats. Thus, two elements (occupational safety and public confidence) were reinforced during the continued development of 5G infrastructure. This conclusion was based on RF-EMF exposure at MNA, adhering to the safe limits outlined by the ICNIRP (2020) guidelines.

RESULTS AND DISCUSSION

The analysis of this research utilised a worst-case scenario approach to determine the maximum RF-EMF exposure values that individuals might encounter at each measurement location. This method was used to assess compliance with safety limits set by regulatory bodies such as the ICNIRP (2020) and the MCMC (2021). In this worst-case scenario, RF sources are assumed to operate at their highest output levels, particularly during times of intense data transmission. Additionally, signal reflections from buildings or metallic structures can potentially increase RF radiation levels. The presence of multiple frequency bands, including GSM, LTE, and Wi-Fi, can also lead to higher cumulative exposure (Gryz, Karpowicz & Zradziński 2025; Najera et al. 2025; Simkó et al. 2025).

The maximum recorded exposure values were compared to establish safe exposure limits set by the ICNIRP (2020) guidelines. These safe exposure limits were determined conservatively, using the lowest frequency allocated for mobile and broadband telecommunications services in Malaysia, which is 700 MHz, according to the spectrum allocation issued by the Malaysian MCMC in 2021, as illustrated in Table 2. Table 2 indicates that the latest generation of mobile cellular and broadband networks, specifically 5G New Radio (5G NR), operates at the lowest assigned frequency of 700 MHz. By utilising the lowest frequency, the safety evaluation is approached conservatively, as lower frequencies penetrate tissues more deeply and necessitate stricter exposure controls (ICNIRP 2020).

The frequency spectrum allocation in Malaysia encompasses various generations of mobile networks, including 2G (GSM-900/1800), 4G (LTE-2100/2600), and 5G New Radio (NR). It is distributed among key providers: Digi, Maxis, Celcom, UMobile, Unifi Mobile, and Yes (YTL). Digi, Maxis, Celcom, and UMobile operate across similar bands, including low-band 5G (700-800 MHz) for broad coverage and mid-band 5G (3400-3500 MHz, Fcent 3410.4 MHz) for higher capacity. In contrast, Unifi Mobile and Yes (YTL) adopt more modern, data-centric strategies, utilising only Time Division Duplex (TDD) and Frequency Division Duplex (FDD) bands without legacy GSM or LTE allocations.

TABLE 2. Frequency band allocations for major Malaysian telecommunication operators across 2G, 4G, and 5G networks, including low-band (700-800 MHz) and mid-band (3400-3500 MHz) 5G deployments

Telco	GSM-900-2G (MHz)	GSM-1800-2G (MHz)	LTE-2100-4G (MHz)	LTE-2600-4G (MHz)	5G/NR-Low Band (MHz)	5G/NR-Mid Band (MHz)
Digi	930-935	1860-1880	2155-2170	2670-2690	700-800	3400-3500
Maxis	950-960	1805-1825	2125-2140	2620-2640	700-800	3400-3500
Celcom	935-945	1840-1860	2140-2155	2650-2670	700-800	3400-3500
UMobile	945-950	1825-1840	2110-2155	2640-2650	700-800	3400-3500
Unifi Mobile	N/A	N/A	N/A	869-879 (FDD)*	2360-2390 (TDD)*	2575-2595 (TDD)
Yes (YTL)	N/A	N/A	N/A	2330-2360 (TDD)*	2595-2615 (TDD)*	N/A

*FDD- Frequency Division Duplex (upload /download different frequencies)

*TDD- Time Division Duplex (upload/download in the same band but alternating times)

The 700 MHz band, repurposed from analogue TV, offers wide-area and indoor coverage, especially in rural zones (El Falou & Alouini 2022). Meanwhile, the 3400-3500 MHz band (C-band) provides a balance between coverage and capacity for urban 5G deployment. These bands are deployed using FDD, which separates uplink and downlink frequencies, or TDD, which alternates them on a single frequency - An efficient mode for high-density networks. Supported by the MCMC and aligned with International Telecommunication Union (ITU) and 3GPP standards, this allocation enables optimised performance nationwide. In this study at Nuclear Malaysia, exposure levels were benchmarked against the 700 MHz ICNIRP (2020) threshold to assess safety conservatively. This approach ensures comprehensive risk evaluation and informs safe, future-proof infrastructure planning.

Table 3 summarises the maximum electric field strengths (*E*) recorded at each block. Meanwhile, Figure 2 illustrates the maximum *E* measured across eight blocks at Nuclear Malaysia, comparing these values to the ICNIRP guidelines (2020) for the public exposure limit of 36.38 V/m.RF-EMF measurements were conducted at eight designated blocks within the Nuclear Malaysia facility, each with distinct spatial, operational, and electromagnetic characteristics. The measurement device was set at a consistent antenna height of 1.5 m, approximately the height of a human head. This configuration simulates realistic human exposure scenarios, as recommended by ICNIRP (2020).

The results of this study demonstrate that RF-EMF exposures at Nuclear Malaysia are substantially below the ICNIRP (2020) guidelines of 36.38 V/m at 700 MHz. As shown in Figure 4 and Table 4, maximum *E* across the eight monitored blocks ranged from 0.60 V/m to 1.41 V/m, corresponding to only 1.65-3.88% of the public exposure limit. The highest level was measured at Block 28 (Administration Building), located adjacent to a telecommunication mast, while the lowest was observed at Block 11 (Laboratory A), a zone with limited wireless equipment. This spatial variation highlights the influence of infrastructure density and proximity to communication sources, consistent with previous research indicating that environmental features and device usage patterns strongly affect RF-EMF background levels (Bhatt et al. 2020; Chiaramello et al. 2019; Foster et al. 2022).

Temporal patterns, illustrated in Figure 5, showed modest diurnal variation. Exposures were slightly higher during the afternoon, peaking at 1.41 V/m, compared to morning and night measurements. This trend corresponds to peak telecommunication activity and mirrors observations reported by Bhatt et al. (2020), Nitsch et al. (2022), and Roosli et al. (2023), which indicate that exposure levels increase during working hours and decrease overnight. Importantly, even at these daily maximum, the exposures at Nuclear Malaysia remained more than one order of magnitude below ICNIRP's reference levels, affirming compliance with international safety standards.

From a health standpoint, the observed exposure levels in this study support the exclusion of thermal effects, as values below 5% of ICNIRP thresholds correspond to negligible specific absorption rates (ICNIRP 2020). However, the ongoing debate regarding potential non-thermal effects is worth noting. Systematic reviews indicate possible associations between long-term low-level RF-EMF exposure and adverse outcomes, including oxidative stress, neurological impairment, and cancer (Belpomme et al. 2018; Cordelli et al. 2024; Hardell & Carlberg 2019; Meyer, Cardis & Vrijheid 2024; Pophof et al. 2024).

Furthermore, this study's findings align with animal studies reviewed by Mevissen et al. (2025), which reported moderate evidence of increased tumour incidence under chronic conditions. However, contrasting reviews from Bosch-Capblanch et al. (2024), Roosli et al. (2023), and Ramirez-Vazquez et al. (2023) emphasise the absence of consistent or causal relationships, particularly concerning self-reported symptoms and reproductive outcomes.

Considering this uncertainty, the International Agency for Research on Cancer (IARC 2019) has classified RF-EMF as a Group 2B possible carcinogen. This classification underscores the importance of long-term monitoring rather than suggesting immediate risk (El Falou & Alouini 2022; Gryz, Karpowicz & Zradziński 2025; IARC 2019; Odesanya, Olukanni & Risi 2025). The findings of this study further contribute to this ongoing conversation about RF-EMF exposure and its potential health implications.

When placed in an international context, the results from Nuclear Malaysia align closely with global findings. Bhatt et al. (2020) reported typical outdoor exposures in Australia ranging from 0.5 to 2.5 V/m. In contrast, Jalilian et al. (2019) observed that public RF-EMF exposures in Europe have not increased, despite a rise in wireless device use. Similarly, Abdullah et al. (2020) confirmed that adopting 700 MHz as a benchmark provides conservative and robust compliance assessments, a strategy also endorsed by Esposito et al. (2020) and James and Lin (2023). These studies support the approach used in this work, where benchmarking at 700 MHz serves as a precautionary measure by capturing the worst-case conditions of whole-body absorption.

The strengths of this study include its conservative frequency benchmarking, the block-based design that provided spatial granularity across laboratories, administrative zones, and service areas, and the use of continuous 24-h monitoring, which improves reliability compared to snapshot measurements. Nevertheless, limitations must be acknowledged. The study was confined to a single facility, which restricts generalisability, and monitoring was conducted over only one 24-h period, excluding seasonal or long-term traffic variability. Furthermore, the study measured only environmental field strengths, without including personal dosimetry or biological endpoints, which limits interpretation to compliance rather than health outcomes. These constraints align with the gaps identified by Karipidis et al. (2024) and

TABLE 3. Maximum electric field strength, E (V/m), measured at each block within Nuclear Malaysia and corresponding percentage relative to the ICNIRP guidelines general public E_{limit} of 36.38 V/m

Block	Electric field strength, E (V/m)	Percentage of ICNIRP limit (%)
28	1.41	3.88
42	1.20	3.30
32	1.15	3.16
57	1.10	3.03
60	1.00	2.75
15	0.90	2.48
13T	0.75	2.06
11	0.60	1.65

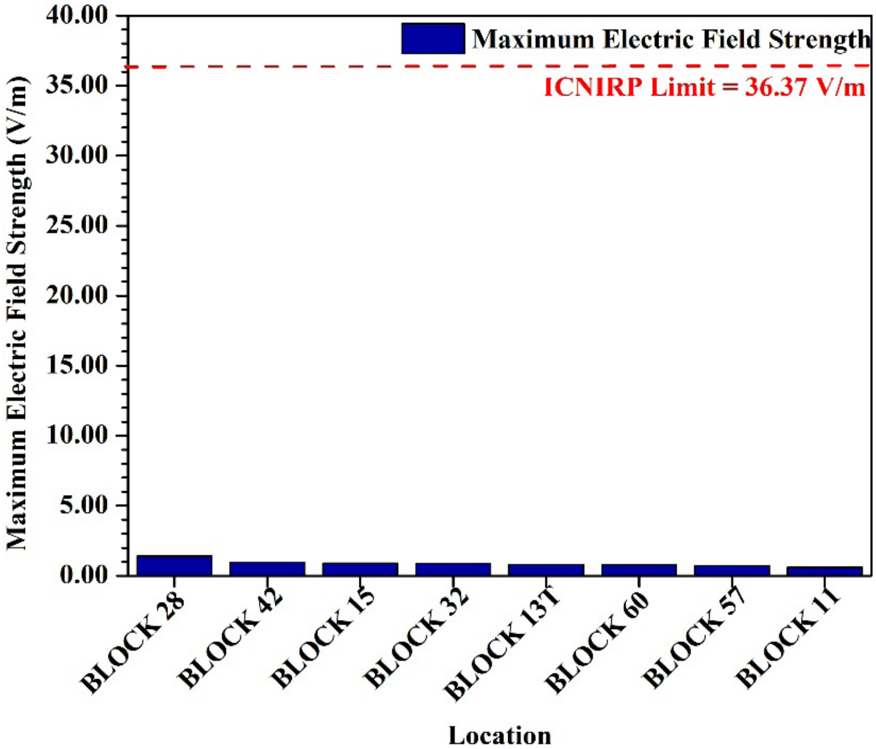


FIGURE 4. Maximum electric field strength (V/m) measured across eight blocks compared with the ICNIRP public exposure limit of 36.37 V/m

TABLE 4. Electric field strength (V/m) measured across different periods (morning, afternoon, and night) for each monitored block

Time	Electric field strength, E (V/m)							
	Block 13T	Block 15	Block 11	Block 57	Block 32	Block 42	Block 60	Block 28
Morning (00:00-11:59)	0.80	0.84	0.60	0.63	0.78	0.85	0.77	1.40
Afternoon (12:00-17:59)	0.58	0.90	0.59	0.72	0.88	0.96	0.79	1.41
Night (18:00-23:59)	0.58	0.84	0.59	0.64	0.64	0.89	0.56	1.22

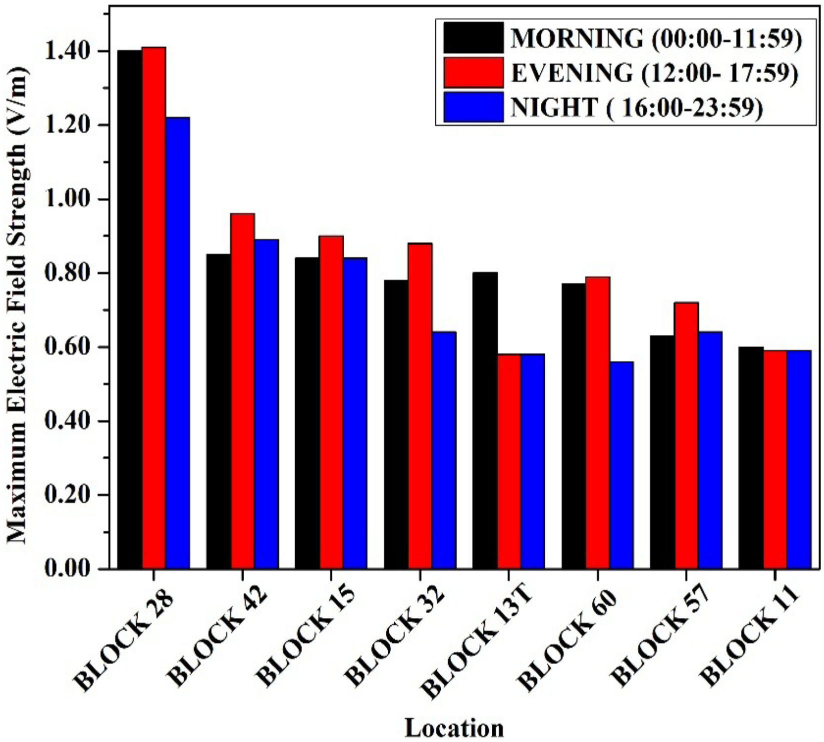


FIGURE 5. Maximum electric field strength (V/m) recorded across eight blocks at the Malaysian Nuclear Agency during morning, evening, and night monitoring periods

Razek (2023) who emphasise the importance of integrated approaches that combine epidemiology, engineering, and toxicology to enhance understanding of RF-EMF health effects.

In summary, the findings confirm that RF-EMF levels at Nuclear Malaysia are far below ICNIRP safety thresholds, thereby ruling out short-term thermal effects and ensuring consistency with the IAEA's radiation protection framework (IAEA 2018). While non-thermal effects remain uncertain, the results provide reassurance of compliance and contribute to public confidence in the safe operation of telecommunication infrastructure within sensitive environments. The limitations of this study suggest that future work should expand monitoring to include additional facilities, cover longer timeframes, and integrate personal dosimetry and biological markers to address ongoing uncertainties. Transparent communication of such data, as emphasised by Fernandez, Vecchia and Strauss (2021) and Ramirez-Vazquez et al. (2024), remains crucial for maintaining regulatory accountability and public trust.

CONCLUSION

This study provides the first comprehensive mapping of RF-EMF exposure levels within Nuclear Malaysia, employing 24-hour broadband monitoring across eight operational blocks. The results show that all measured RF-EMF levels were below the ICNIRP guidelines public E_{limit} of 36.38 V/m, with the highest recorded value constituting only 3.88% of the threshold. These findings confirm that the electromagnetic environment at Nuclear Malaysia remains within internationally accepted safety limits, reinforcing institutional and public confidence in RF-EMF safety amidst 5G infrastructure deployment. The data gathered not only supports compliance with Malaysian and international regulatory guidelines but also serves as a foundational reference for future environmental health assessments, longitudinal studies, and risk communication strategies in high-sensitivity research environments.

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