Assessment of Source Terms and Potential Doses Due to Steam Generator Tube Rupture of VVER-1200 at the El Dabaa Nuclear Power Plant in Egypt

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Background: As Egypt ventures into nuclear energy, ensuring the safety and security of its nuclear facilities is paramount. The ongoing construction of the El Dabaa Nuclear Power Plant (NPP) directs the necessity for Egypt to meticulously evaluate the potential outcomes of any conceivable accidents. A focused analysis on design-based accidents such as steam generator tube ruptures (SGTR) is imperative for assessing their impact on the local populace and the environment. Through comprehensive assessments, Egypt aims to enhance the safety protocols of its NPP. This preemptive strategy facilitates the identification and minimization of risk, along with the formulation of efficient emergency response frameworks. Such diligent preparations are essential for cultivating public confidence while ensuring compliance with international safety norms and securing the long-term sustainability of Egypt’s nuclear energy program.

Materials and Methods: The hypothetical scenario of a SGTR at the El Dabaa NPP was modeled using the Radiological Assessment System for Consequence Analysis (RASCAL) code. This model examined the potential consequences of such an accident by incorporating meteorological data from 2013 to 2023 across all seasons to compute the source term, total effective dose equivalent (TEDE), and thyroid dose. Then, these metrics were evaluated against established safety thresholds to determine compliance. The outcomes of this analysis provide critical insights and aid in formulating strategies for effective response to an accident, especially if the calculated doses exceed the permissible limits.

Results and Discussion: The analysis of the worst-case scenario for the SGTR accident at the El Dabaa NPP involves a U-tube breakage above the water level, exacerbated by a concurrent station blackout. This condition potentially leads to a considerable dispersal of radioactive materials, especially within a 0.4 km radius, with a TEDE reaching 4.80 × 10^3 mSv during autumn. However, the severity of this worst-case scenario fluctuates with seasonal weather conditions; notably in spring, the highest TEDE was 15 mSv at a 40 km distance. The source term distribution indicates that noble gases account for 31.6%, iodine group for 32.0%, and other sources constitute 36.4% of the total radioactive release. These findings confirmed that TEDE and thyroid dose exceeded the permissible thresholds, thereby highlighting the importance for protective measures to mitigate the potential risks of such accidents.

Conclusion: A comprehensive assessment of SGTR accidents at the El Dabaa NPP emphasizes the critical necessity for stringent safety protocols and protective interventions in worst-case scenarios. By preemptively addressing these risks, Egypt can fortify its nuclear safety framework, emergency response capabilities, and adherence to global safety standards. This proactive stance not only assures the long-term sustainability of Egypt’s nuclear energy program but also solidifies public confidence.

Keywords: El Dabaa, Radiological Assessment, Total Effective Dose Equivalent, Thyroid Dose, Source Term, Protective Action
**Introduction**

Under the stewardship of the Nuclear Power Plants Authority (NPPA), the El Dabaa Nuclear Power Plant (NPP) marks Egypt’s inaugural foray into nuclear energy. The project capacity is 4.8 GW through four Generation III+ Vodo-Vodyanoi Energetichesky Reactor (VVER; water-water energetic reactor)-1200 reactors [1]. Rosatom is tasked with the development and construction of this facility, which was designated for nuclear power generation in 1983. The NPPA was granted permission for the El Dabaa NPP in April 2019, and the construction license for the first reactor was issued in 2021. Situated approximately 320 km northwest of Cairo, the first reactor is projected to start commercial operations by 2028. To support the construction, more than 80 structures will be erected at the El Dabaa site through a collaborative effort between Rosatom’s subsidiary Atomstroy export and Korea Hydro & Nuclear Power (KHNP). In addition, Egypt will procure turbine island equipment from KHNP [2, 3].

The U.S. Nuclear Regulatory Commission (NRC) identifies steam generator tube ruptures (SGTR) as a prevalent cause of significant incidents in operational pressurized water reactors (PWRs). Unlike other loss of coolant accidents (LOCA), SGTR requires immediate operator intervention. To curb these failures, the nuclear sector has adopted various strategies including secondary side inspections, advancements in steam generator (SG) design, water chemistry management, and the refinement of eddy current tube inspection techniques. Despite these preventative measures, the risk of SGTR poses a threat of releasing contaminated coolant into the environment via secondary side safety and relief valves. Notably, accumulation of water in the secondary side of the SG can lead to overfill scenarios, thereby exacerbating the radiological impacts and increasing the probability of further failures [4].

The SGs in Russian VVER-1200 are horizontal-shell and tube-heat exchangers that transfer heat from the primary reactor coolant to generate steam for the turbine generators on the secondary side. Factors such as tube degradation, vibrations, stress corrosion, or water hammer can lead to SGTR. In the event of a rupture, the high-pressure coolant and radioactive-steam escapes through the relief valves or condenser off-gas [5]. Over two decades of NPP operations have witnessed SGTR incidents at facilities including Point Beach 1, Surry 2, Prairie Island 1, Ginna, Fort Calhoun, North Anna 1, McGuire 1, Palo Verde 2, Indian Point 2, and Oconee 2 [4, 6], thereby underscoring the importance of diligent oversight and continuous improvement in safety protocols.

The International Atomic Energy Agency mandates that NPP operators undertake a comprehensive assessment of potential risks employing a graded approach, considering even the most unlikely events. This assessment must prioritize the implementation of precautionary and urgent protective measures to prevent or mitigate severe deterministic effects before the release of any considerable amount of radioactive material. To reduce the deterministic impacts and the possibility of stochastic effects, protective actions, and responses should be implemented both preemptively and in the aftermath of radioactive material discharge through ongoing monitoring and assessment of the radiological conditions [7, 8].

This study aims to examine the radiological consequences of a SGTR event with and without offsite power to identify the protective measures for safeguarding the public and the environment from radiological hazards. This analysis utilizes the Radiological Assessment System for Consequence Analysis (RASCAL) computer code [9] to focus on the radiological impact in the vicinity of the NPP unit at the El Dabaa site. The findings can inform the development of an evacuation policy and preparedness plan, facilitating the enactment of effective safeguards against internal and external environmental risks.

**Materials and Methods**

### 1. Study Area

Weather data across all four seasons for 10 years (2013 to 2023) at the El Dabaa site were analyzed using the Wind and Rain Rose Plots software (WRPLOT) [10]. Simulations of SGTR events coinciding with station blackout (SBO) and SGTR scenarios with available offsite power were conducted using the RASCAL 4.3.3 code and the study methodology is shown in Fig. 1. In addition, we used Minitab software (Minitab Inc.) [11] to represent the findings of our statistical investigation.

#### 1) Wind rose models

Wind rose diagrams illustrate the average wind patterns and velocities within a specific area over time, which is crucial for predicting the dispersion of radioactive materials following nuclear disasters. These models represent each of the four seasons and provide essential insights into prevalent wind directions (WDs) and frequencies. Figs. 2–5 display the
dominant WDs and speeds for each season, offering a foundational understanding of the environmental factors affecting radiological dispersion.

2) Weather information

The analysis of weather data over a decade (2013 to 2023) included variables such as temperature (T), wind speed (WS), precipitation (R), stability classification (SC), and WD, with statistical evaluations performed using Minitab software. The objective was to identify the representative values for each meteorological parameter. Table 1 presents the representative meteorological data.

Statistical analysis indicated a $p < 0.005$ from the Anderson-Darling test across all weather conditions, leading to the

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Fig. 1. Study methodology. RASCAL, Radiological Assessment System for Consequence Analysis; TEDE, total effective dose equivalent; SGTR, steam generator tube rupture.

Fig. 2. Wind speed and direction for the El Dabaa site in spring.

Fig. 3. Wind speed and direction for the El Dabaa site in autumn.

Fig. 4. Wind speed and direction for the El Dabaa site in summer.

Fig. 5. Wind speed and direction for the El Dabaa site in winter.
Table 1. El Dabaa Meteorological Data for RASCAL Simulation

<table>
<thead>
<tr>
<th>Season</th>
<th>Time</th>
<th>WS (m/s)</th>
<th>WD (º)</th>
<th>R (mm)</th>
<th>T (°C)</th>
<th>SC</th>
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<td>C</td>
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<tr>
<td>11/18 3:00 AM</td>
<td>3.0</td>
<td>270</td>
<td>26</td>
<td>D</td>
<td></td>
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</tr>
<tr>
<td>11/19 3:00 AM</td>
<td>2.0</td>
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<td>25</td>
<td>E</td>
<td></td>
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</tr>
<tr>
<td>11/19 3:15 AM</td>
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<td>270</td>
<td>25</td>
<td>E</td>
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<tr>
<td>11/20 3:30 AM</td>
<td>3.0</td>
<td>248</td>
<td>26</td>
<td>D</td>
<td></td>
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<tr>
<td>11/20 3:45 AM</td>
<td>3.0</td>
<td>270</td>
<td>26</td>
<td>D</td>
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<td>11/20 4:00 AM</td>
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<td>26</td>
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<td>11/20 6:00 AM</td>
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<td>D</td>
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<td>18</td>
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<tr>
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<td>270</td>
<td>18</td>
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</tr>
<tr>
<td>2/19 3:00 AM</td>
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<td>18</td>
<td>C</td>
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<tr>
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<td>17</td>
<td>C</td>
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<td>2/20 6:00 AM</td>
<td>2.0</td>
<td>270</td>
<td>17</td>
<td>C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RASCAL, Radiological Assessment System for Consequence Analysis; WS, wind speed; WD, wind direction; R, precipitation; T, temperature; SC, atmospheric stability classes.

3) RASCAL simulation model

The RASCAL software was developed by the Protective Measures Team of the U.S. NRC Operations Center. It serves as an independent tool for predicting the radiation doses and effects in case of radiological incidents, aiding in decision-making and emergency response. RASCAL uses the source term to dose model to estimate the radiation exposure caused by radioactive material to individuals in affected areas.

The latest version, RASCAL 4.3.4, incorporates dose pathways including inhalation of the plume, ground shine from deposited radionuclides, and cloud shine from the airborne plume. Utilizing Gaussian plume modeling, RASCAL simulates the spread of radioactive materials. The fundamental Gaussian puff model in RASCAL, expressed as Equation (1), employs the superposition principle to expand the one-dimensional diffusion equation solution to three dimensions [9, 13].

$$\frac{Q(x_0, y_0, z_0)}{q} = \frac{1}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} e^{-\frac{1}{2} \left(\frac{x-x_0}{\sigma_x}\right)^2} \times e^{-\frac{1}{2} \left(\frac{y-y_0}{\sigma_y}\right)^2} \times e^{-\frac{1}{2} \left(\frac{z-z_0}{\sigma_z}\right)^2}$$

(1)

where $Q$ denotes the amount of unconfined material (in Bq or g), and $\sigma$ indicates the dispersion parameter (in m), which depends on the distance from the release point when combined with a transport device to pass through the center of the puff ($x_0, y_0, z_0$), and $\chi$ denotes the concentration (in Bq/m$^3$ or g/m$^3$).

Radiological assessment studies across various NPPs and accident scenarios have enhanced our understanding of the potential impacts of nuclear incidents. At the Ninh Thuan 1 NPP, the research focused on determining radiation doses from radioactive releases during an International Nuclear Event Scale (INES) level 7 catastrophe, triggered by SBO and LOCA events [14]. Similarly, an assessment for the Advanced Power Reactor (APR)-1400 reactor at Shin Kori Unit 3 estimated radionuclide concentrations and radiation doses in the early phases of serious nuclear incidents, including LOCA and a long-term station blackout (LTSBO) [15]. The Rooppur NPP study assessed the outcomes of a total grid power failure on the Unit-1 VVER-1200 reactor, considering the impact of passive safety emergency core cooling systems (ECCS) during both dry and wet seasons [16]. For El Dabaa, previous research delineated offsite emergency-planning zones for the Egyptian NPP, employing a probabilistic safety assessment to evaluate a major accident scenario (LOCA) in a 1,200 MWt PWR, considering varying atmospheric conditions and their probabilities [7].
for the El Dabaa site are listed in Table 2 [13, 14, 17, 18].

(2) RASCAL accident assumptions and scenarios
RASCAL simulations consider the location of the tube rupture in relation to the water level of the SG. A rupture below the water level, termed “partitioned,” results in mixing of SG water with primary system water, thereby diluting the radionuclide concentrations in the steam because of a “partitioning factor.” Conversely, a rupture above the water level, described as “not partitioned,” causes most of the primary
coolant to vaporize, thereby considerably increasing the radionuclide emissions.

The simulations consider the release of noble gases relatively unaffected by partitioning, given their stable presence in primary coolant leaks. The assumption for these simulations posits the SGTR above the water line, which represents a worst-case scenario [9, 19].

A prior research [20] developed a database of fission product retention in SGTR sequences and models to assess the effectiveness of different accident control measures for such events. Another study [21] focused on simulating an SGTR accident in the Personal Computer Transient Analyzer (PCTRAN) VVER-1200 nuclear reactor, considering the complete rupture of a single tube. This analysis examined the safety protocols and system responses to assess the potential repercussions of the accident and the capacity of the facility to lessen its impacts. Furthermore, a radiological scenario evaluation for the APR-1400 [22, 23] considered LOCA, SBO, and SGTR incidents. Utilizing PCTRAN APR-1400 for source term derivation and HOTSPOT for dose calculations [24], the study aimed to devise an emergency response strategy to mitigate the radiological consequences under varied meteorological conditions.

Additionally, a study examined the specific characteristics of the corrosive-mechanical damage in the primary circuit header to SG vessel branch welds in VVER-1000 NPPs as shown in Fig. 10 [13]. This analysis also explored the preventive approaches for analogous concerns in VVER-1200 SGs, focusing on operational safety and economic viability. Another study explored the probability of radioactive dissemi-

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**Table 2. Technical Specifications of the VVER-1200 Reactor for RASCAL Simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Generic PWR with large, dry containment [9]</td>
</tr>
<tr>
<td>Latitude</td>
<td>31.0472°</td>
</tr>
<tr>
<td>Longitude</td>
<td>28.5009°</td>
</tr>
<tr>
<td>Time zone</td>
<td>World offset from GMT/UTC +2</td>
</tr>
<tr>
<td>Reactor power</td>
<td>3,200 MWth [17, 18]</td>
</tr>
<tr>
<td>Average burnup in the reactor</td>
<td>40,000 MWd/MTU [17, 18]</td>
</tr>
<tr>
<td>Discharge burnup in spent fuel storage</td>
<td>50,000 MWd/MTU [17, 18]</td>
</tr>
<tr>
<td>Number of assemblies in the core</td>
<td>163 [17, 18]</td>
</tr>
<tr>
<td>Containment volume</td>
<td>2.5 × 10^6 ft^3 [14]</td>
</tr>
<tr>
<td>Coolant mass</td>
<td>1.728 × 10^7 kg [17, 18]</td>
</tr>
<tr>
<td>U-tubes inside each SG</td>
<td>10,978 [17, 18]</td>
</tr>
<tr>
<td>Primary coolant flow rate per SG</td>
<td>4,479.166667 kg/s [17, 18]</td>
</tr>
<tr>
<td>Coolant flow rate per SG tube</td>
<td>0.408012996 kg/s [17, 18]</td>
</tr>
</tbody>
</table>

VVER, Vodo-Vodyanoi Energetichesky Reactor; RASCAL, Radiological Assessment System for Consequence Analysis; PWR, pressurized water reactor; GMT, Greenwich Mean Time; UTC, Coordinated Universal Time; MWth, megawatts thermal; MWd/MTU, megawatt-days per metric ton of uranium; SG, steam generator.

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**Fig. 8.** Stability classification during the summer.

**Fig. 9.** Stability classification during the spring.

**Fig. 10.** Steam generator of the Vodo-Vodyanoi Energetichesky Reactor [13]. 1: Steam header, 2: Feedwater inlet, 3: Feedwater header, 4: Heat exchange tubes, 5: Main coolant inlet, 6: Main coolant outlet.
nation following a steam-line breach in a VVER-1200 nuclear power facility. Their findings suggested that effective safety mechanisms considerably reduce the likelihood of radioactive release into the environment, employing the PCTRAN for safety system evaluation [15].

This research further delved into a LOCA scenario to highlight the vitality of the containment system in confining the radioactive materials. Additionally, a computational analysis addressed a grave incident involving LOCA, SBO, and ECCS failure within the VVER-1200 reactor core [9]. This particular study contemplated two scenarios: SGTR concurrent with an SBO (S1) and SGTR with available offsite power (S2), which highlights the paramount importance of preparedness and response mechanisms in nuclear safety management.

① Scenario 1 (no offsite power)

During a LTSBO scenario, the El Dabaa NPP encountered a complete loss of both offsite and onsite alternating current (AC) power, which rendered the AC-powered safety systems nonfunctional. As time progressed, the direct current batteries were also exhausted. This led to the closure of the stop valve of the turbine generator, causing the water to evaporate from the SGs.

A worst-case scenario was assumed when a full double-ended rupture occurred in a U-tube within the SG above the water line that caused steam to be vented from the secondary circuit through the safety relief valve (steam dump valves to atmosphere BRU-A) into the atmosphere.

The subsequent reduction in the SG water levels uncovered the reactor core, causing temperatures to rise. The reactor was manually shut down at 0:00 AM, with radionuclide emissions from the core commencing after an 8-hour interval, according to the default LTSBO delay period outlined in the State-of-the-Art Reactor Consequence Analyses (SOARCA) study. The leakage rate into the SG was recorded at 2 m³/hr, employing the RASCAL default steaming rate starting from 8:00 AM. Overall, this scenario involved a cascade of events including power loss, the sealing of the turbine generator’s stop valve, steam discharge from the secondary circuit, and core exposure, culminating in the release of radionuclides.

② Scenario 2 (offsite power available)

At the onset of this scenario at the El Dabaa NPP, a precipitous decline in the primary system pressure coincided with simultaneous rise in the secondary pressure at 0:00 AM. The reactor was promptly shutdown in response to the drop in primary system pressure, which is speculated to result from a SGTR. Operator interventions estimated a compensatory makeup flow, inclusive of safety injections, at approximately 34,019 kg/hr. The surge in secondary pressure triggered the activation of the high-pressure safety relief valve (BRU-A). This scenario presupposes the rupture site to be above the water line, indicative of a worst-case scenario, with the discharge point located 42.2 m above the ground level.

(3) Input data for meteorological conditions

The transportation and dispersal of radionuclides in the atmosphere are significantly influenced by meteorological variables such as WS, WD, R, and atmospheric SC. RASCAL 4.3.4 mandates the incorporation of meteorological data from 2 hours prior to the release for accurate modeling [9]. To simulate the variances in seasonal weather conditions, specific dates across different months were carefully selected. February was selected to represent winter conditions, November for autumn, July for summer, and April for spring. This approach ensures an accurate representation of weather patterns related to each season during the simulation. To a comprehensive overview of the meteorological trends, Table 1 compiles 96-hour historical weather data for the El Dabaa site, covering the designated periods for the modeling assessment.

Results and Discussion

1. Distribution of the Source Term

Two accident scenarios involving SGTR were selected based on their probability and the potential impact on the surrounding area. The simulations were performed to assess the atmospheric dispersion of hazardous materials at a specific location. RASCAL calculates approximately 70 source terms for the VVER-1200 reactor, representing the release of radionuclides during an accident. These simulations provide insights into the potential radiological environmental effects and assist in establishing exposure limits for at-risk individuals.

The contribution of a radionuclide to the source term is influenced by several critical factors, including the yield of fission products, the physical state and chemical activity of the nuclide, reaction to reduction mechanisms, and the severity of the accident. Fig. 11 presents a comparison of actual activity levels for eight groups in the S1 and S2 SGTR scenarios upon conclusion of the RASCAL simulation. The data indicates that
for S1, Noble gases and halogens are predominant in the source term, with total activities of $6.29 \times 10^{16}$ Bq and $6.44 \times 10^{16}$ Bq, respectively. In scenario S2, alkali metals and noble gases exhibited stronger activities at $8.50 \times 10^{12}$ Bq and $5.41 \times 10^{12}$ Bq, respectively. The distribution of radionuclide types (noble gases, I, and others) into the atmosphere for both scenarios is illustrated in Figs. 12 and 13. In S1, approximately 31.6% of noble gases and 32% of I were released, while in S2, these percentages shifted to 34.4% for noble gases and decreased to 3.9% for I. Other groups remained significant contributors, accounting for 36.4% and 61.7% in each scenario, respectively. In condition S1, the ratio of noble gases to I-131 was 3:1, whereas in case S2, the ratio of noble gases to I-131 activity increased significantly to 27:1.

Fig. 14 details the source terms and their cumulative activities of total effective dose equivalent (TEDE) pathways during the transit of the plume for two distinct accident scenarios. Among the radionuclides included in the RASCAL source terms, 18 in S1 and 16 in S2 were identified as the most significant contributors to these pathways. Cs-137, Cs-134, Ru-
106⁹, I-131, I-133, La-140, and Ce-144⁹ consistently exhibited the highest activities in both scenarios, attributed to their lengthy half-lives relative to the interval from shutdown to release. Nonetheless, a pronounced variation in released activity levels was observed between the scenarios.

The particulars of each scenario, such as the specific accident conditions and operating parameters, were crucial in determining the production of H-3 and Co-58. In S2, accentuated by a coolant contamination factor of 30, notable releases of H-3 ($8.3 \times 10^{12}$ Bq), Co-60 ($3.4 \times 10^9$ Bq), and Co-59 ($1.4 \times 10^{11}$ Bq) were recorded. Conversely, scenario S1 exhibits significant contributions from radionuclides such as Pu-241 and Te-132, which are derivatives of Am-241 and I-132, respectively, and are generated in larger volumes during SGTR accidents lacking offsite power. The specific volume of activity released depends on a multitude of accident-specific factors including reactor design, scenario nuances, fuel composition, and operational conditions, whereas other radionuclides in the source term posed a minimal impact on the overall dose.

2. Radiological Doses

Table 3. Importance of Protective Action Guidelines and Related Preventative Measures in the Early Phases

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<th>Protective actions</th>
<th>PAGs [25]</th>
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<td>10–50 mSv (TEDE)</td>
</tr>
<tr>
<td>Sheltering</td>
<td></td>
</tr>
<tr>
<td>Iodine tablets thyroid blocking</td>
<td>250 mSv (thyroid dose)</td>
</tr>
</tbody>
</table>

PAG, protective action guideline; TEDE, total effective dose equivalent.

In the initial stages of a severe nuclear incident, several measures and strategies are undertaken to mitigate the aftermath and effectively manage the crisis. Protective action guidelines (PAGs) are instrumental in this phase, directing decision-making processes and safeguarding public health and safety. PAGs are established by regulatory authorities and are based on scientific and technical considerations. Certain key aspects of the PAGs during the early phase of a nuclear accident are listed in Table 3 [25].

The immediate hours post-accident are critical for executing decisions aimed at protecting the populace and the environment, enabling an evaluation of the consequences and impact of the incident [26]. Figs. 15 and 16 present the maximum TEDE in mSv relative to downwind distance for two distinct accident scenarios (S1 and S2), under varying meteorological conditions delineated in Table 1. Fig. 15 reveals that the peak maximum TEDE is observed at approximately 0.4 km from the emission source, diminishing with the increased distance. In extreme scenarios such as during autumn and spring, doses at 0.4 km reach 4,800 and 4,200 mSv, respectively, with a reduction observed as distance extends. The spring season consistently exhibits increased dose levels, peaking at 15 mSv at 40 km.

These dose fluctuations are attributed to variations in atmospheric SC ranging from B (moderately unstable), C (slightly unstable), D (neutral), and E (slightly stable), among other meteorological parameters. Fig. 16 demonstrates the maximum TEDE under scenario S2 with offsite power avail-
ability, noting a peak dose of 0.44 mSv at 0.4 km, which gradually lessens to 0.02 mSv at 3.2 km during autumn. In spring, the plume extends to approximately 6.4 km, with a maximum dose of 0.01 mSv. These differences in dose levels are influenced by a combination of onsite elements such as source terms, operational conditions, safety system availability, and mitigation efforts, as well as offsite factors including atmospheric stability, WS and direction, temperature, and proximity to the source term.

The doses illustrated in Fig. 13 align closely with those reported for the VVER-1200 nuclear reactor in Bangladesh [16]. Specifically, under a LTSBO scenario both without and with the operation of ECCS over 24 hours during the monsoon season, doses of 4,400 mSv and 3,600 mSv were recorded, respectively, based on site-specific meteorological data. These figures present a contrast to simulations for the El Dabaa site, where a significant leak from the primary to secondary circuit leading to core damage was modeled using the RASCAL code, yielding maximum doses of 1,170 mSv and 2,950 mSv at 2 km distance under stability classes D and F, respectively [7].

Moreover, at the Rooppur NPP in Bangladesh, simulations of a large break LOCA with SBO for the VVER-1200 reactor utilizing Oak Ridge Isotope Generation and Depletion Code-Scale (ORIGEN-S) and HOTSPOT codes calculated doses of $1.01 \times 10^2$ Sv at 0.4 km during the summer. For winter, the maximum dose reached $1.28 \times 10^3$ Sv at 0.4 km, and during the rainy season, it escalated to $1.03 \times 10^4$ Sv at 0.01 km distance [27]. These discrepancies are attributable to differing assumptions across accident scenarios, meteorological data variations, and levels of conservatism in the analyses.

Figs. 17 and 18 depict the thyroid dose distribution across the fall, spring, summer, and winter seasons for two SGTR accident scenarios. Both scenarios exhibited a consistent pattern with elevated doses near the site during the fall, especially within 0.4 km. In scenario 1 (S1), the dose at this proximity is $4.6 \times 10^4$ mSv, whereas in scenario 2 (S2), it is $4.40 \times 10^1$ mSv. As the distance increases in the downwind direction, the doses sharply decline to 40 km, except during the spring.

In S1, the dose at 40 km is 160 mSv, whereas in S2, the plume extends up to 4.8 km with a dose of 0.012 mSv. The reduction in plume concentration is influenced by variations in weather conditions and the presence of the I group, comprising 32% in S1 and 3.9% in S2. Conversely, with varied weather typified by stability classes D and F under LOCA conditions at El Dabaa, thyroid doses at 2 km were reported as $8.00 \times 10^0$ Sv and $2.1 \times 10^1$ Sv, respectively [7].

According to this study, no protective actions are required for SGTR S2. In contrast, the protective effects recommended for SGTR S1 are summarized in Table 4.
3. Pathways’ Relative Importance

In the worst-case scenario S1 (spring season), the temporal effects on the three pathways to TEDE near the release point are analyzed. During the initial plume passage (0 day), inhalation is identified as the predominant pathway, accounting for 99% of the total dose potential. Cloudshine contributes 1.4%, while the ground shine is considered negligible. The dominance of inhalation doses is attributed to a substantial contribution of I-131 to TEDE (31% at 0 day). Conversely, a smaller fraction (2.4%) from the Xe group results in a lesser cloudshine dose. After plume passage, the groundshine dose emerges as the primary contributor to TEDE. The groundshine fraction of the total dose potential progressively increases to 0.95, 0.94, 0.99, 0.99, and 1.0 at 1, 7, 30, 183, and 365 days, respectively. During these intervals, inhalation shifts to a secondary pathway, whereas the impact of cloudshine remains minimal, as depicted in Fig. 19.

In scenario S2, also during the spring season, inhalation significantly outweighs other pathways, contributing 99.9% of the total dose potential at the time of plume passage (0 day). Ground shine poses a minimal effect, with cloudshine accounting for 0.3%. The larger percentage of I-131 in TEDE (25% at 0 day) signifies the predominance of inhalation doses. Furthermore, a reduced proportion (0.2%) from the Xe group yields a lesser cloudshine dose. After the plume disperses, the groundshine dose becomes the key source of TEDE contribution. The groundshine portion of the total dose potential rises to 0.76, 0.81, 0.96, 1.0, and 1.0 at 1, 7, 30, 183, and 365 days, respectively. In these periods, the cloudshine posed minimal influence, with the inhalation serving as the secondary path-

Fig. 19. Relative importance of pathways to total effective dose equivalent (TEDE) (steam generator tube ruptures concurrent with an station blackout [S1]).

Fig. 20. Relative importance of pathways to total effective dose equivalent (TEDE) (steam generator tube ruptures with available off-site power [S2]).

way, as illustrated in Fig. 20.

Monitoring and evaluating the deposition of radionuclides from the plume to the ground post-severe accidents is critical. The degree of ground deposition directly influences the permissible groundshine doses to the public, necessitating a thorough assessment owing to its potential impact on flora and fauna. In instances of significant deposition, stringent food consumption restrictions may be required to safeguard public health.

Conclusion

The comprehensive analysis of the potential outcomes from a SGTR incident at the El Dabaa NPP offers critical insights into the hazards such an event may pose. The worst-case scenario examined, featuring a U-tube rupture above the water line during a SBO, demonstrates the risk of substantial release of radioactive material near the facility. Using the RASCAL code along with a decade of meteorological data, the study highlights the significance of assessing potential impacts under various weather conditions. The analysis determined that the TEDE exceeded the acceptable thresholds, reaching $4.80 \times 10^3$ mSv within a 0.4 km radius of the plant during autumn. Nonetheless, the intensity of this worst-case scenario fluctuated with changing weather conditions, noting the highest TEDE at 15 mSv at 40 km away during spring.

The investigation into the source term distribution revealed that noble gases constituted 31.6% of the total activity, with the I group at 32.0% and other sources accounting for 36.4%. These results underline the necessity for effective
management and mitigation strategies for the dispersion of various radioactive materials in the event of an SGTR accident. The analysis clearly demonstrates the importance of enacting protective measures to mitigate risks associated with such incidents. Exceedances of TEDE and thyroid dose beyond established thresholds emphasize the critical need to safeguard the local community and the environment.

By preemptively addressing these risks and using the insights gained from this comprehensive analysis, Egypt can enhance the safety protocols and emergency preparedness at the El Dabaa NPP. These proactive measures affirm a dedication to adhering to international safety standards and play a crucial role in fostering public confidence in Egypt’s nuclear energy agenda.

This investigation lays a robust groundwork for the ongoing refinement of safety and emergency response strategies at the El Dabaa facility. Leveraging the insights from this comprehensive review, Egypt is poised to sustain and securely advance its nuclear energy program, ensuring its longevity and safety.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Ethical Statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Data Availability

All datasets used and/or analyzed in the current study are available from the corresponding author on reasonable request.

Author Contribution


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