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Alternative evacuation strategies for nuclear power accidents

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ABSTRACT

In the U.S., current protective-action strategies to safeguard the public following a nuclear power accident have remained largely unchanged since their implementation in the early 1980s. In the past thirty years, new technologies have been introduced, allowing faster computations, better modeling of predicted radiological consequences, and improved accident mapping using geographic information systems (GIS). Utilizing these new technologies, we evaluate the efficacy of alternative strategies, called *adaptive protective action zones (APAZs)*, that use site-specific and event-specific data to dynamically determine evacuation boundaries with simple heuristics in order to better inform protective action decisions (rather than relying on pre-event regulatory bright lines). Several candidate APAZs were developed and then compared to the Nuclear Regulatory Commission's keyhole evacuation strategy (and full evacuation of the emergency planning zone). Two of the APAZs were better on average than existing NRC strategies at reducing either the radiological exposure, the population evacuated, or both. These APAZs are especially effective for larger radioactive plumes and at high population sites; one of them is better at reducing radiation exposure, while the other is better at reducing the size of the population evacuated.

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1. Introduction

Current strategies used to determine who to evacuate following a nuclear-power plant accident have not changed significantly since the emergency planning guidelines were established in the early 1980s. While plans and studies have been modified and updated, this has been done under the constraint of a roughly constant evacuation area. Consequently, changes to protective actions have focused on issues such as in which order people should be evacuated, or in which direction they should evacuate [1,19]. Yet in the past thirty years, the task has radically changed; new technologies have been introduced, allowing faster computation, better modeling of predicted radiological consequences, improved accident mapping using geographic information systems (GIS), and new means to communicate. Additionally, the populations surrounding nuclear-power plants are denser; more people live closer to reactors than ever before. In the past 30 years, the average population living within 16 km of these plants has increased by 62%, from approximately 40,000 to almost 65,000 per site. Furthermore, at 12 of the 65 reactor sites in the U.S., populations have more than doubled [2]. In the wake of the Fukushima Daiichi nuclear accident – considering the range of new capabilities and the greater population at risk – this study sought to reexamine the U.S. nuclear-power plant evacuation strategy by removing the constraint of a constant evacuation area or predetermined evacuation zones.

This research is a proof of concept; its purpose was to develop alternative evacuation strategies for use during the early phase of nuclear-power plant accidents in order to take advantage of some of the recent technological advances. The early phase is defined by the U.S. Environmental Protection Agency (EPA) as "the period at the beginning of a nuclear incident when immediate decisions for effective use of protective actions are required and must therefore usually be based primarily on the status of the nuclear facility and the prognosis for worsening conditions" ([25], p. 5). Thus, the early phase is filled with uncertainty. The plant operators and emergency response officials know only that the situation at the reactor is a cause for concern and that an off-site radiological release is possible, so they can only guess at the extent of the problem. Despite this imperfect knowledge, officials must act and make decisions to protect the public from potential radiation exposure, generally in the form of evacuations (because distance is the best

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protection) and/or sheltering in place. In the earliest periods of this phase, decisions are made based on predictions of the radiological release [25].

Notwithstanding the likely discrepancies between early phase projected doses and actual off-site doses that will be observed later, protective action recommendations must be made in the early phase, because evacuation in advance of the plume (ideally at least 1 h before the plume's passage) is the best way to reduce dose [12,23]. This research explored alternative methods to determine who should be evacuated during the early phase. An ideal strategy would be able to perfectly evacuate the at-risk population before the radioactive plume passes. At present, of course, neither the APAZs developed in this research nor the NRC's method can achieve this standard; however, as will be shown, the APAZs demonstrate progress towards meeting that standard.

Because no method is perfect, the comparison between APAZs and the NRC's method was framed as a multi-attribute decision problem using the objectives of minimizing the population to be evacuated and maximizing the total radiological dose avoided. These objectives are based on the current regulatory position of the NRC, which focuses evacuation efforts on high-risk areas [27], as well as the EPA guideline that informs the NRC's policy, which states that evacuation risk should not exceed the risk from the avoided dose [11]. While there is general acceptance that avoiding radiological dose is beneficial, some might argue that instead of minimizing the population evacuated, the goal should be to maximize the size of evacuation. Because distance is a highly effective defense against radiation [12,23], some might argue that if the entire population surrounding a nuclear power plant could be evacuated prior to passage of the plume, that population could be guaranteed safety, suggesting that the objectives of high total dose avoided and high population evacuated would yield a desirable (if conservative) outcome. This logic is flawed, however, because maximizing the population evacuated can expose many people to risks greater than the risk of the radiological release, and ignores the risks and costs of evacuations.

Evacuation can have adverse health impacts. Evacuation risks include travel, events in which travel is the contributing cause, and activities other than travel (i.e., preparation or reception activities) [3,30]. Witzig and Weerakkody have estimated travel risk to be 6×10^{-8} fatalities per vehicle-km; this risk is considered to be an upper bound as the actual risk is expected to be lower than normal automobile travel due to conditions of heavier traffic and lower travel speeds [3,30]. Injuries or fatalities in which travel contributed to their occurrence is the second category of risk. An example is an individual who evacuates the wrong direction and drives into a radioactive plume; it is believed to be an order of magnitude greater than travel risk [30]. The last evacuation risk, estimated to be 5×10^{-6} per person, is due to evacuation preparations and the arrival at the reception center ([3,30]). These three risks collectively form evacuation risk. For a given emergency, the evacuation risk is a function of the number of individuals that leave. When larger numbers of people evacuate who are not required to evacuate (i.e., shadow evacuations), the collective risk to the population will significantly increase [3]. The EPA evacuation risk estimate (for fatalities) corresponds to Witzig and Weerakkody's upper bound estimate meaning that for radiation doses of less than 3 mSv, the evacuation risk is greater than the radiation risk [11]. Maximizing the evacuation area relocates many people who would receive doses less than 3 mSv, exposing them to needless risk. As noted by Aumonler and Morrey, "evacuation risks constitute a harm which should be considered in a decision as to whether to evacuate a population put at risk by a radiological incident" ([3], p. 290). For this reason, a safer course of action would evacuate those whose radiation risk is greater than their evacuation risk, but not those whose evacuation risk is greater than their radiation risk.

Minimizing the population evacuated and maximizing the total dose avoided embodies the EPA's position that the protective actions should not be "higher than justified on the basis of optimization of cost and the collective risk of effects on health" ([11], p. 135). Thus, for this research, a high dose avoided and low population evacuated are assumed to be preferred.

Using these two objectives, APAZs were compared to the NRC's strategy using a concept called the "efficient frontier," to allow decision makers to evaluate alternatives using their own value systems. Alternatives are plotted on the basis of the decision objectives (i.e., dose avoided and population evacuated). Dominated options can be excluded from consideration; the decision maker can then select a preferred option based on his or her preferences from among the non-dominated strategies on the efficient frontier.

Current U.S. response protocols have been previously well documented. The interested reader is encouraged to review these earlier articles for a more in-depth understanding [11,21,23,24,28]. While the regulations that dictate emergency response have been updated (such as the EPA's Protective Action Guides and Planning Guidance for Radiological Incidents [25] and the NRC's guidance for protective action strategies [27]), as noted earlier, the fundamental initial evacuation strategy has remained constant. In the event of a nuclear-power plant accident, plant operators would determine evacuation areas using the NRC's guidance for protective action strategies [27]. Based on the postulated source term and forecast meteorological conditions, a projected radiological plume is calculated and then fit to pre-established evacuation zones; this is the NRC's keyhole strategy. (This strategy has been criticized because the plume model provides a simplified view of a complex process that may not correlate with the observed plume causing the wrong people to evacuate [23]).

This research proposes an alternative method to determine the evacuation area. In this approach, instead of fitting the projected plume to pre-established zones, the evacuation area would be determined by applying a heuristic enlargement strategy directly to the forecast plume.

2. Calculations

2.1. Development and testing of APAZs

Candidate APAZs (described subsequently) were tested using weather data from five nuclear power plants: Limerick; Catawba; Turkey Point; Pilgrim; and Arkansas Nuclear One. These plants were selected based on their proximity to National Weather Service (NWS) data-collection sites. The forecast and hindcast weather data (i.e., predicted and observed weather conditions) used in this analysis was produced by the National Oceanic and Atmospheric Agency (NOAA) and the NWS.

The source term varied depending on the plant's output power and reactor type. The source term for each nuclear-power plant was calculated using the time that the core was assumed to be uncovered in an unmitigated short-term station blackout (STSBO) scenario, described in the State-of-the-Art Consequence Analysis (SOARCA) [9]. The total release ranged from 3.3×10^{18} Bq to 1.2×10^{19} Bq. These postulated releases are of the same order of magnitude as that from the Fukushima Daiichi accident [26].

Forecast and hindcast plumes used in this research were generated with NRC's Radiological Assessment System for Consequence AnaLysis (RASCAL) [6]. Nineteen candidate APAZ strategies were tested using 120 weather observations from summer 2012 and winter 2012–2103. Protective action zones, formed by enlarging a forecast plume in accordance with a given heuristic, were compared to the hindcast plumes.