# Development of an Updated Societal-Risk Goal for Nuclear Power Safety

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**Abstract:** The safety-goal policy of the U.S. Nuclear Regulatory Commission (NRC) has never included a true societal-risk goal. In particular, safety goals have focused primarily on radiation-related fatalities, while experience with actual nuclear accidents has shown that societal disruption can be significant even in accidents that yield only small numbers of fatalities. We have evaluated the social disruption from severe reactor accidents as a basis to develop a societal-risk goal for nuclear plants, focusing on population relocation. Our analysis considers several different accident scenarios at five nuclear-plant sites in the U.S. The corresponding source terms were used as input to calculate offsite consequences using actual weather data for each of the five plant sites over a two-year period. The resulting plumes were then compared to population data to determine the population that would need to be relocated to meet current protective-action guidelines. Our results suggest that the number of people relocated is a good proxy for societal disruption, and relatively straightforward to calculate. Safety goals taking into account societal disruption could in principle be applied to the current generation of nuclear plants, but could also be useful in evaluating and siting new technologies.

**Keywords:** Consequence Modelling, Nuclear Power, Societal Risk, Safety Goal, RASCAL.

## 1. BACKGROUND

This paper describes analysis performed in the course of exploring possible revisions to the existing NRC nuclear plant safety goals. At present, there are two qualitative safety goals:

- Individual members of the public should be provided protection from the consequences of nuclear power plant operation such that individual bear no significant additional risk to life or health
- Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks

and two quantitative safety goals:

- The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed 0.1 percent of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed
- The risk to the population in the area of a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed 0.1 percent of the sum of cancer fatality risks resulting from all other causes

Note that these goals are not regulatory requirements, but rather high-level guidance to the formulation and implementation of regulatory requirements. In other words, they constitute a statement of what regulatory requirements are expected to accomplish.

There are multiple reasons to consider revising the current safety-goal structure. First, it has long been understood that the goals, as currently formulated, do not have a truly societal component; instead, they constrain only risks to individuals [1]. In particular, since the goal for latent-cancer fatalities is normalized by overall cancer risk to the neighboring population, it does not impose any constraints on the maximum number of cancer fatalities that could result from an accident. Moreover, as pointed out by the Advisory Commission on Reactor Safeguards (ACRS), "Larger societal risks are permitted for the nuclear power plant which has the larger surrounding population… This provides no incentive for more remote siting" [2]; see also [3].

Additionally, the existing focus on radiological risks to life or health leaves a gap in the types of issues addressed by the goals. Experience at both Fukushima and Chernobyl illustrates this point. For example, the Fukushima Daiichi accident resulted in an initial evacuation of about 134,000 people living between two and 12 miles from the plant [4], followed by an additional 354,000 people living between 12 and 18 miles from the plant four days later, for a total of nearly 500,000 people. The number of people who died as a result of the evacuation itself (for reasons unrelated to radiation) has been estimated to exceed the eventual cancer mortality [5], and about 150,000 of those evacuated had not been able to return home as of two years after the accident [6]. Additional concerns have included: the costs of the clean-up, decontamination, and relocation; the loss of ancestral homes and modern communities; the loss of land for crops and industrial activities; inability to sell contaminated foods; loss of freshwater resources; loss of fisheries and fishing income; and need for replacement electric power [7]. Thus, the extent of societal disruption incurred to avoid possible radiological consequences has been significant, more so than the actual radiological consequences to the general public. Similarly, after Chernobyl, roughly 350,000 people were evacuated and resettled from areas of Belarus, Russia, and Ukraine [8]. Moreover, Morris [9] has argued that those relocated from the rural area surrounding Chernobyl to other regions often did not fare well in the ensuing decades since 1986, due to "relocation trauma."

The tradeoff between interdiction costs and radiological consequences has been understood in principle for a long time [10], but the events at Fukushima have provided a recent and highly salient real-life example of this tradeoff. At Fukushima, the radiological consequences to the general public (which are addressed by the current safety goals, at least at the level of individual risk) have been dwarfed by the disruption-related consequences (which the goals do not address even implicitly). Thus, it could even be argued that the performance of the Fukushima plants was "satisfactory" from a radiological-safety point of view, although few would argue that it was satisfactory from a societal point of view. The current goals therefore provide only a partial basis for development and implementation of regulatory requirements.

Interestingly, although the safety goals themselves do not constrain societal risk, certain regulatory decision processes have been informed by societal-risk considerations essentially from the beginning of nuclear-plant deployment [11]. In fact, long before much was understood about severe-accident phenomenology, the potentially large magnitude of hypothetical accident consequences was of concern, and correspondingly, siting decisions were strongly influenced by consideration of the distance between proposed sites and large population centers. This does not mean that such considerations were necessarily explicit drivers in the formulation of regulatory requirements, but rather that they were part of the background of *siting decisions*. It is beyond the scope of this paper to recapitulate the history described in [11], but the following quote regarding ACRS thinking about the so-called "maximum credible accident" (MCA) is revealing:

> The ACRS and the staff, in general, opposed the metropolitan or the near-metropolitan siting of power reactors, even if Part 100 [of Title 10 in the Code of Federal Regulations] could be met. The staff took the position in the 1960s that more experience was needed before metropolitan siting could be approved. The ACRS generally favored improvements in safety design in order for metropolitan siting to be considered. For those reactors it approved, the regulatory staff stayed rather stringently within the prescriptions of Part 100 and its maximum credible accident (later designated the design basis accident), and declined to publicly discuss or examine safety aspects related to accidents which went beyond the MCA (e.g., in which containment integrity was lost).

Moreover, sensitivity to societal risk survives to some extent in Part 100 even now, in the stipulation that "Where very large cities are involved, a greater distance [from the city to the reactor] may be necessary because of total integrated population dose consideration." Regulatory analysis of certain issues also considers the person-rem averted by candidate plant modifications. Thus, consideration of societal risk takes place early in the licensing process, and later on in certain decision-making arenas.

Despite this, once a reactor has been sited, we would argue that decision making should still be informed by considerations of the potential consequences of severe accidents—and not only the radiological consequences. In particular, it is in principle possible to meet almost any cancer-fatality goal, simply by evacuating and relocating a sufficiently large number of people. However, if quantification of radiological consequences takes credit for evacuation and relocation without full consideration of the societal costs associated with such measures, the radiological consequences by themselves do not provide a full picture of the impact of an accident.

The societal disruption resulting from a nuclear-power accident could be at least as important as the health risks. Lindell and Prater [12] indicate that one of the most significant impacts of disasters is often the loss of dwellings. According to [13], "Displacement from one's home is not only a measurable loss in itself but can also contribute to…losing one's job and support network and…to drug use, violence, or other social ills." Relocation will of course also cause loss of productivity, since people who are relocated may not become productive again for a period of time. Based on these observations, number of people relocated appears to be a reasonable proxy for societal disruption. However, current safety-goal policy does not adequately constrain such disruption.

The remainder of this paper provides an initial assessment of the extent of societal disruption that could result from accidents at selected reactor sites in the U.S., as a basis for the possible development of a societal-risk goal. There are of course numerous ways to define societal disruption, some of which might be quite difficult to measure or quantify in a simple and objective manner suitable for use in safety goals. For purposes of this paper, therefore, we used the number of people that would need to be relocated for a period of at least one year as a proxy for the total societal disruption associated with relocation and land interdiction. Of course, even a short-term evacuation would be disruptive, and would create a risk of evacuation-induced injuries and fatalities (especially for vulnerable populations, such as the elderly)—but we judged that the overall disruption resulting from an evacuation of a few days would be minimal, if the vast majority of evacuees could soon go back to their previous lives. By contrast, relocation for a year or more would disrupt communities—shuttering businesses, requiring people to find new jobs, homes, and schools.

Section 2 of this paper describes the methods used in our analysis. Section 3 presents results. Section 4 gives our conclusions.

## 2. METHODS

In this paper, we evaluate the numbers of people that would need to be relocated after accidents at several different reactor sites in the U.S. The reactors considered included three pressurized water reactors (PWRs) and two boiling water reactors (BWRs). These plants were chosen to reflect a variety of sites (seashore, river, lakeshore, and inland) and regions (Eastern, Southern, and Midwestern), and a variety of population densities (from fewer than 25,000 people within 20 miles, to more than 400,000 people within 20 miles). Thus, we believe that the results of our analyses are representative of the range of societal impacts that could result from reactor accidents in the U.S.—but they do not represent a worst case.

The accident scenarios considered were similar to those considered in the State-of-the-Art Reactor Consequence Analysis (SOARCA) [14]. In particular, for all plants, we considered short-term station blackout (STSBO), defined as loss of onsite AC power for more than 15 minutes), and long-term station blackout (LTSBO), defined as loss of offsite power. (Note that STSBO is actually a more severe accident scenario than LTSBO, since in an LTSBO, DC batteries are assumed to be operational for several hours, while an STSBO assumes total loss of offsite, onsite AC, and onsite DC power.) In addition, we also considered an STSBO with a thermally induced steam-generator tube rupture (SGTR) for PWRs, and LTSBO with failure of reactor-core isolation cooling (RCIC) for BWRs. Note that we intentionally did not consider an interfacing-system loss-of-coolant accident (LOCA). The reason for this is because we wanted to focus exclusively on the long-term societal disruption associated with relocation to avoid latent cancer fatalities, while in interfacing-systems LOCA the amount of radiation released could be high enough that acute radiation effects would become a significant issue. It is important to note, however, that impacts of interfacing-systems LOCA could be much more severe than the results in this paper.

To ensure consideration of a wide range of weather conditions, each accident scenario was evaluated for the weather that was in effect on each of 24 different dates, chosen to be near the middle of each month in 2011 and 2012. (Specific dates were chosen in part based on availability of weather data, since data is missing for some dates.) For each date, the exact assumed start time of the accident was chosen randomly, to ensure a variety of atmospheric conditions. Plant-specific weather logs are not publicly available, so data from the nearest weather station of the National Weather Service (NWS) was used; there are weather stations within 10-40 miles of each of the plants analyzed in this paper.

Where possible, surface weather conditions (i.e., wind direction and wind speed, temperature, and precipitation) were obtained based on hourly quality-controlled local climate data (QCLCD) from the National Oceanic and Atmospheric Administration (NOAA). However, in some cases, wind directions changed significantly within a single hour. In those cases, one-minute data from the NWS Automated Surface-Observing System were used (averaged over four fifteen-minute intervals) in place of the missing QCLCD data. In addition, stability data from the NOAA Air Resources Laboratory was used to identify the stability class and mixing-layer depth in effect at any given time.

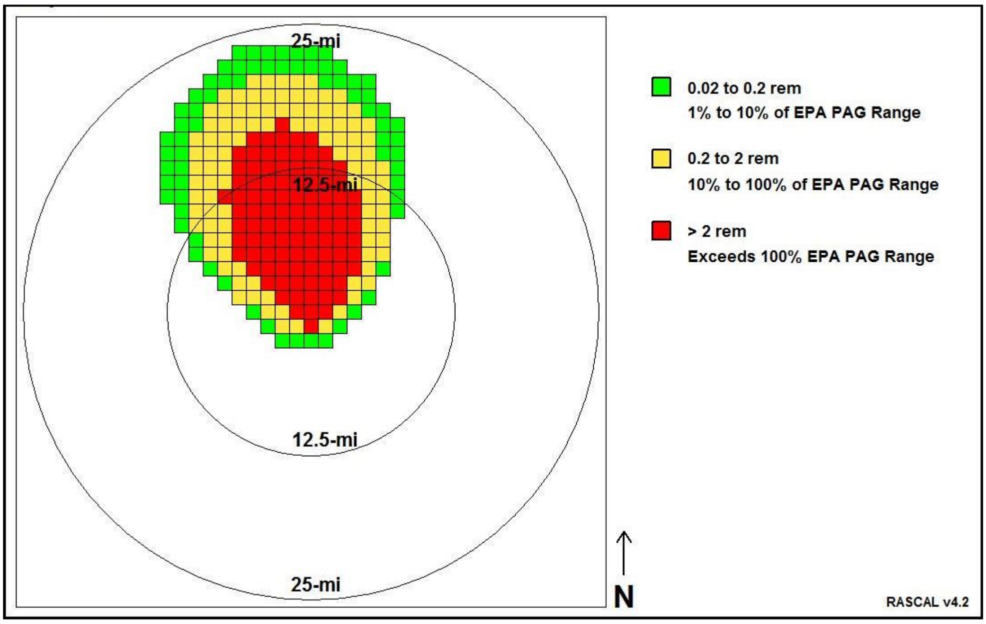
For simplicity, and because it is intended for use in emergency response, our dispersion analysis was conducted using the Radiological Assessment System for Consequence Analysis (RASCAL) [15]. We attempted to construct a RASCAL source term for each accident scenario that would be a reasonable match to the corresponding SOARCA source term. In general, the RASCAL and SOARCA source terms compare favorably, being within an order of magnitude of each other for all scenarios in terms of total radioactivity released. However, it was not possible to match the timing of the SOARCA source terms for BWRs, because of limits of the RASCAL model (which assumes earlier release times than in the SOARCA study). In addition, Hammond [16] compared the two-dimensional plume model used in RASCAL (using only surface-weather data) against the three-dimensional dispersion model used in the NOAA Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT), using surface and upper-air weather data, and found good comparability.

Dose profiles resulting from the RASCAL model were exported as geospatial "shape files." The key result of interest for this project is the total effective dose equivalent (TEDE) for the year immediately after an accident (although different time periods, such as two years, or 50 years, could also be considered). A sample shape file for an assumed SGTR is shown in Figure 1. In this figure, the red region of the plume indicates an area where doses would exceed the 2-rem protective action guideline; the yellow region indicates doses of 0.2-2 rem; and people in the green region would receive a dose of 0.02-0.2 rem in a year. (Note that we consider doses out to 25 miles in our analysis, whereas most analyses consider only doses within the 10-mile emergency-planning zone.)

These shape files are then input into the ArcGIS geographic-information system using a Python script, and then combined with population data obtained from the U.S. Census Bureau. The level of analysis used for our study is a census block—the finest level of detailed supported by the ArcGIS software, about the size of a city block. By overlaying the RASCAL shape files over the population shape files, one can compute, for a given accident scenario and a given weather condition, how many people in the surrounding area would be exposed to doses in a given range. From this, we can determine how many people would need to be evacuated or relocated using existing protective-action guidelines from the

U.S. Environmental Protection Agency, as well as how many people would need to be evacuated or relocated under various alternative protective-action guidelines.

**Figure 1: Sample Shape File for an STSBO with SGTR**




## 3. RESULTS

Table 1 gives 5th and 95th percentiles (i.e., 90% confidence intervals) for the number of people who would need to be relocated under current protective-action guidelines for each type of accident scenario, at each plant. (The ranges reflect variability due to weather conditions, but do NOT reflect absolute minima or maxima of the observed relocation numbers.) As can be seen, at the most highly populated site considered in this paper, and the most severe accident scenario, the number of people who would need to be relocated based on current protective-action guidelines could exceed 1,000,000. Clearly, the societal disruption associated with such a massive relocation would be enormous.

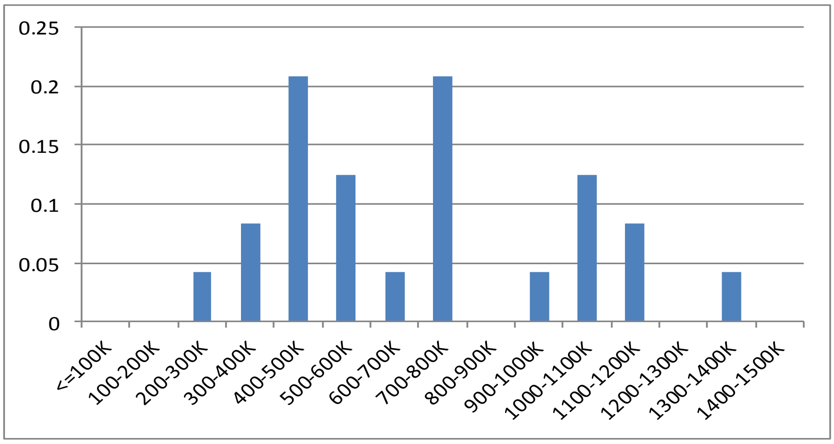
**Table 1: 90% Confidence Intervals for Number of People Relocated Based on 1-Year, 2-Rem Protective-Action Guideline (To One Significant Figure)**

| Plant | STSBO | LTSBO | STSBO w/ SGTR | LTSBO w/out RCIC |
|---|---|---|---|---|
| A (Eastern seashore) | 30,000-400,000 | 0-20,000 | 300,000-1,000,000 | |
| B (Midwestern inland) | 8,000-200,000 | 0-10,000 | 40,000-500,000 | |
| C (Midwest lakeshore) | 20-30,000 | 0-300 | 200-100,000 | |
| D (Eastern river) | 0-60,000 | 0-70,000 | | 0-80,000 |
| E (Southern inland) | 0-70 | 0-60 | | 0-80 |

For comparison purposes, according to Goldman and Coussens [17], "The state of Louisiana evacuated approximately 1.5 million people before Hurricane Katrina made landfall." In New Orleans in particular, roughly 80-90% of the population evacuated prior to Hurricane Katrina in 2005 [18]. The population of New Orleans in the year immediately after Hurricane Katrina was reduced by more than half, but by the time of the 2010 census, it was back up to three quarters of what it had been [19].

Moreover, the variability in consequences for any given accident scenario can be significant, depending on accident conditions. See for example Figure 2, for an STSBO with SGTR at Plant A. Although half of all relocations are smaller than 700,000, a quarter of the weather conditions considered would have resulted in relocation of more than one million people. Similarly, although not shown here for reasons of space, while the average relocation after a similar accident at Plant B would be about 200,000 people, one quarter of all weather conditions considered would have resulted in relocations of between 300,000 and 600,000 people.

**Figure 2: Histogram of Relocation Sizes (STSBO with SGTR at Plant A)**

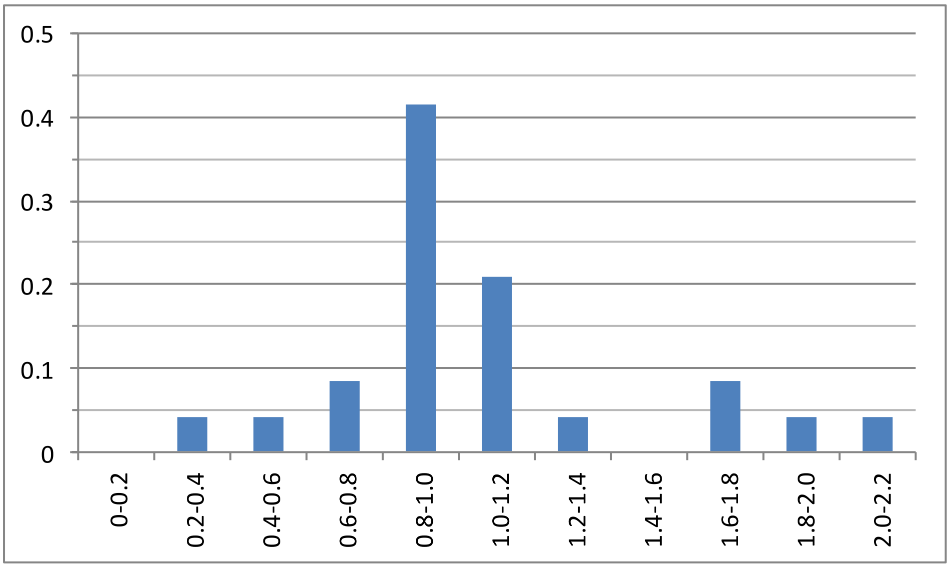



Unfortunately, both the experience in Japan and Chernobyl, and the current protective-action guidelines promulgated by the U.S. Environmental Protection Agency, also suggest that return to normal after a major nuclear disaster might not be rapid. In fact, under current protective-action guidelines, the number of people who would need to be relocated for up to 50 years is approximately the same as the number needing to be relocated for one year. The 50-year protective-action guideline suggested by the U.S. Environmental Protection Agency is 5 rem, which is enough larger than the one-year guideline of 2 rem that one might expect long-term relocation areas to be significantly smaller than the areas for a one-year relocation. However, the fact that the dose is accumulated over such a long period of time counteracts that benefit. For example, at Plant B, the average relocation after an SGTR based on the 50-year relocation guideline would be more than 95% the size of the one-year relocation (based on current population sizes). As shown in Figure 3, depending on the direction of the original plume, although the 50-year relocation is usually smaller than the one-year relocation, it could be more than 50% larger—as much as doubling the number of people needing to be relocated.

Note that 50-year relocation ratios greater than 1.0 in Figure 3 do not necessarily imply that large relocations would be needed for the entire 50 years. Limitations of RASCAL make it difficult to determine at what point during that time the dose would drop to an acceptable level. Depending on the radioactive species, it's possible that most of the 50-year dose could be accumulated early during that time period. In future work, this could be analyzed in more detail. However, the number of people who would experience a 5-rem dose over 50 years can in some cases exceed the number who would experience a 2-rem dose over one year, suggesting that relocations larger than those shown for one year might be needed, and might need to extend for a significant period of time.

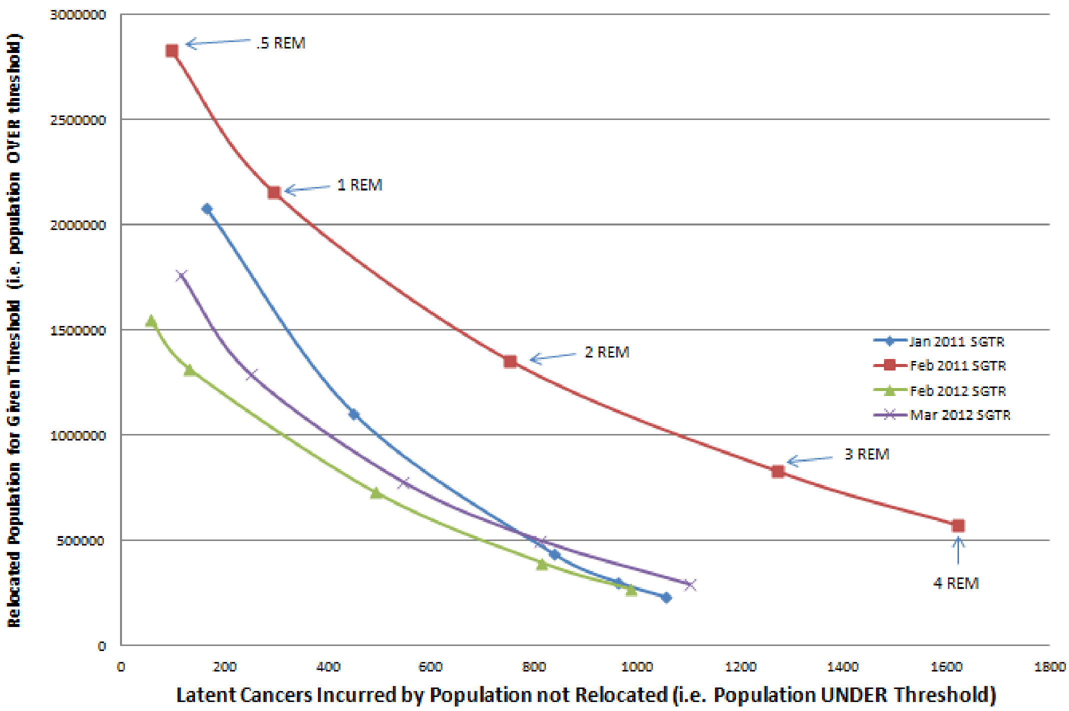
The magnitude of the relocations that might be needed at highly populated sites suggest that it would be prudent to explore whether smaller relocations might still provide adequate radiation protection, with substantially less societal disruption. For example, for several representative sets of weather conditions at Plant A, Figure 4 shows the effect of changing the one-year relocation threshold from the current 2 rem. In the most severe of the weather conditions shown in Figure 4 (the red curve, for a hypothetical STSBO with SGTR occurring in February 2011), increasing the protective-action threshold from 2 rem to 3 rem could reduce the number of people that would need to be relocated by 500,000, while causing roughly 650 additional latent cancer fatalities, for a ratio of about 800 people relocated to prevent one cancer fatality (based on a conversion factor of $5 \times 10^{-4}$ latent cancer fatalities per person-rem, per the International Commission on Radiological Protection).

**Figure 3: Histogram of the Ratio of 50-Year to 1-Year Relocation Numbers (STSBO with SGTR at Plant B)**




Note that the results shown in Figure 4 were computed using the linear no-threshold assumption, which is controversial at low doses. Thus, our results conflate substantial doses to people just outside of the protective-action area with extremely small doses to large numbers of people (who may in fact have zero risk of radiation-induced cancer due to an accident). So, in reality, the number of people who would need to be relocated to prevent one cancer fatality may be higher than would be indicated by our approach.

**Figure 4: People Relocated and Number of Cancer Cases at Plant A, by Relocation Threshold**



While it is not immediately clear that a relaxation of protective-action guidelines would be desirable, the societal disruption resulting from massive relocations under current protective-action guidelines (including economic losses—e.g., houses and business facilities that would no longer be available) would be enormous, and would lead to extreme political pressure from people and businesses wanting to return to the interdicted area. (In fact, Morris [9] suggested that approximately 1% of the people evacuated from the zone immediately surrounding the Chernobyl plant—mainly middle aged or older people—returned shortly after the accident, and suffered little or no ill effects due to contamination.) Reducing the number of people relocated could thus lead to a non-trivial reduction in societal disruption—especially taking into account that the disruption would be experienced immediately (and last for years), while most cancer fatalities would not be expected to occur for many years.

## 4. CONCLUSION

The results of our work, and the experiences in Japan and Chernobyl, support the idea that quantitative safety goals should consider the societal disruption that could result from severe reactor accidents. In particular, it is in principle possible to meet almost any cancer-fatality goal, simply by evacuating and relocating a sufficiently large number of people—but this does not seem to match established intuitions about what constitutes an acceptable level of societal risk due to nuclear power (as evidenced by the emphasis on remote siting from the earliest days of the nuclear industry).

The present work shows that the total number of people relocated under a particular protective-action guideline is a simple but potentially useful metric for societal disruption (including health risks caused by evacuation or relocation, and economic losses associated with land interdiction). This is certainly not a perfect proxy; for example, it may underestimate long-term opportunity costs due to contamination of land that is currently sparsely populated, but might have become desirable if it had not been contaminated. Still, number of people relocated has the advantages of being objective and relatively easy to estimate, given current dispersion models and geographic-information systems.

However, we have only begun to explore the formulation of a probabilistic goal based on this metric, taking into account both the frequencies of various accident scenarios, and the uncertainty about consequences due to unpredictability of weather conditions (e.g., wind directions) at the time of an accident. At the simplest possible level, one might just propose a threshold on the expected number of people that would need to be relocated in order for a plant to meet its cancer-risk goal (taking into account accident frequencies as well as their consequences). Such a limit would constrain the total societal disruption from nuclear-power accidents, and might therefore be helpful in developing siting policies or recommendations for new types of reactors (e.g., small modular reactors, with much smaller source terms). However, such a threshold might actually be a binding constraint at plants in highly populated areas. This is especially significant given that populations in the vicinity of nuclear plants have been rising. For example, in the past 30 years, the population living within 10 miles of a nuclear plant in the U.S. has increased by more than 50%; at 12 of the 65 reactor sites, populations have more than doubled [20]. Thus, some plants that might have originally been suitably remote may no longer be considered distant from significant population centers, raising the question of whether such plants may justify safety improvements that might not be necessary at more remote locations.

At a more complicated level, recognizing the inherent tradeoff between cancer risk and the number of people relocated, one might propose limiting the weighted sum of expected cancer fatalities and expected number of people relocated (with the weights chosen to reflect the much greater societal impact of a fatality than a relocation). Such a goal might encourage conscious deliberation on the most appropriate protective-action guidelines for relocation, since for example it might be possible for a given plant to meet such a goal with a small number of cancer fatalities and a large relocation, or a smaller relocation and a larger number of cancer fatalities.

Moreover, taking into account the societal risk aversion to large multiple-fatality accidents (and also to large relocations), one might envision a decision-theoretic goal that constrained not just the expected numbers of fatalities and relocations, but perhaps the numbers of fatalities and relocations raised to some power slightly greater than one, as suggested by the ACRS [21]. For plants with the same mean relocation size, this approach would be more constraining at the location with the greater variability of relocation size. Finally, it seems reasonable to assume that a large number of fatalities would be particularly undesirable if accompanied by a large number of relocations, and vice versa. In that case, small numbers of fatalities and small numbers of relocations could be considered in some sense “substitutes,” so one might propose to use a multi-linear utility function [22] as a safety goal.

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