DEVELOPMENT OF A 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, and instead only constrain on risks to individuals. Experience with actual nuclear accidents at Chernobyl and Fukishima has shown that even in accidents that yield only small numbers of fatalities, the extent of the societal disruption incurred to avoid possible radiological consequences can been significant, more so than the actual radiological consequences to the general public. 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 based on accident scenarios considered in the State of the Art Reactor Consequence Analysis (SOARCA) study. The corresponding source terms were used as input into the Radiological Assessment System for Consequence Analysis (RASCAL) software to calculate offsite consequences using actual weather data for each of the five plant sites over a two-year period. The resulting radiological plumes were then compared to population data to determine the population that would need to be relocated over a period of one year to meet current protective-action guidelines. Our results suggest that the number of people relocated is a good proxy for societal disruption, is an objective measure, and is relatively straightforward to calculate given current dispersion models and geographic information systems. 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
Severe Accident Modeling, RASCAL, Societal Risk, Safety Goal

1. INTRODUCTION

WASH-1400 [9], NUREG-1150 [2] and later the State of the Art Reactor Consequence Analysis (SOARCA) [12, 13] showed that the incremental risk of accidental death or cancer from nuclear power accidents is typically much less than the risk from other causes. Nevertheless, a major concern to the public is the perceived potential for nuclear power accidents leading to an increase in the risk of cancer to the general population, or even immediate radiation sickness and death to people living in the vicinity of the plant. Following the release of radioactive material that occurred at the Fukushima-Daiichi reactors and subsequent measures taken by the Japanese government in relocating nearly 200,000 people [1], there is some reason to rethink the current dose-centric NRC nuclear plant safety philosophy.

Following the accident at Three Mile Island, the NRC released a safety goal policy statement [3] that established two qualitative 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 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 a 10 mile radius surrounding 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 cause

Note that these goals are not regulatory requirements, but rather high level guidance.

The first qualitative safety goal is typically referred as the individual health risk objective and is formulated in the first quantitative goal in terms of early fatalities; the second qualitative goal is referred to as the societal risk objective and is associated with the second quantitative goal dealing with the risk of latent cancer fatalities (LCFs). However, the second quantitative goal takes the expected number of LCFs within a ten mile region around the plant and normalizes by the population in the area, giving an estimate for the risk of cancer to an average individual. Thus, this goal is really just a different individual health risk objective, and doesn't address overall societal risk (e.g. the maximum number of cancer fatalities resulting from an accident). Thus, as expressed by the Advisory Commission on Reactor Safeguards, "Larger societal risks are permitted for the nuclear power plant which has the larger surrounding population… This provides no incentive for more remote siting" [4].

As noted earlier, recent experience at Fukushima has shown that these goals, focusing solely on radiological risks to life and health, do not capture the full consequences of severe accidents. Given relocation of roughly 200,000 people, it has been estimated that there will be more non-radiological deaths associated with the accident (~600) than the eventual cancer mortality (~130) [5]. Furthermore, an estimated 80,000 people were still unable to return home more than three years after the accident [6].

Thus, at Fukushima (and potentially after future similar accidents), the radiological health consequences to the general public may be less significant than the societal disruption associated with evacuation and relocation, which is not addressed by the safety goals. As indicated by Lindell and Prater [7], one of the most significant impacts of any disaster is often the loss of homes. According to Lundberg [8], "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." Based on these observations, we believe that the number of people relocated for a long period of time is a reasonable surrogate for societal disruption.

We choose to focus on the number of people that would be relocated for a period of at least one year as our proxy for societal disruption due to an accident at a nuclear power site. Of course a short term evacuation could also be disruptive (especially for at-risk populations such as the elderly), but we judged that the effects would be minimal compared to relocation for a year, in which complete communities would be uprooted and resettled elsewhere. Conversely, significantly longer relocations would eventually allow relocated individuals to settle into a 'new normal'.

2. METHODS

In quantifying a societal disruption proxy, we chose a subset of actual U.S. nuclear plants and investigated the off-site effects at these locations for several severe reactor accident source terms. Five reactor sites were chosen to represent different regions of the country (eastern seashore, eastern river, southern inland, midwestern plain and lakeshore), both pressurized water reactor (PWR) and boiling water reactor (BWR) types, and a range of population densities (for reference RASCAL projects plumes out to 25 miles). The selected reactors and their population statistics are summarized below.

Table 1: Information on selected reactors

Geographic Region	Reactor Type	10 Mile Population	20 Mile Population
Eastern Seashore (A)	PWR	130,424	440,608
Midwest Plains (B)	PWR	35,690	191,614
Midwest Lakeshore (C)	PWR	9,917	78,940
Eastern River (D)	BWR	44,595	480,856
Southern Inland (E)	BWR	5,569	23,287

Population numbers obtained from 2010 US Census data

The specific accident scenarios we analyzed were similar to those scenarios considered in the SOARCA study. An initial screening was done by SOARCA to eliminate accident scenarios with low frequencies (less than $1x10^{-8}$ per reactor year), since accident scenarios below this threshold contribute only about 4% to overall plant risk. For BWRs, the SOARCA team considered three accident scenarios: a long term station blackout (LTSBO, defined as the loss of offsite and onsite alternating current (AC) power); a short term station blackout (STSBO, defined as the total loss of AC and direct current (DC) power); and an STSBO with blackstart (starting the system without the use of AC or DC power) of reactor core isolation cooling (RCIC). For PWRs, the team again selected LTSBO and STSBO scenarios as well as an STSBO with thermally induced steam generator tube rupture (TI-SGTR), which is the most severe accident scenario considered in our study. An interfacing systems loss of coolant accident (IS-LOCA) was not considered in our study, since during an IS-LOCA, the amount of radiation released is significant enough that the concern shifts from evaluating future cancer risks to preventing immediate health effects.

SOARCA considers both mitigated and un-mitigated cases for all accidents considered, but for the purposes of our study, we will only be considering the un-mitigated scenarios leading to the largest evacuations. The Fukushima accident scenario is similar to the LTSBO scenario considered in this study, though it is unclear how much mitigation occurred between the multiple units compared to the SOARCA source term. At PWRs, SOARCA assumes that in an unmitigated accident, operators are not able to connect portable diesel driven pumps for refilling the vessel as well as the water supply for the turbine driven auxiliary feed water, and also cannot connect portable power supplies for essential instrumentation required to monitor conditions in containment and the core (in a mitigated accident, not studied here, these essential safety measures are assumed to be completed, resulting in lower offsite doses). Similarly, during unmitigated BWR accidents, SOARCA assumes operators complete only actions that are explicitly defined in the emergency operating procedures, such as opening a safety relief valve to vent containment (in mitigated accidents, SOARCA assumes additional actions, such as use of two portable AC power supplies to restore essential instrumentation as well as using portable pumps to fill the condensate storage tank). The following table shows the core damage frequency per reactor year for each scenario considered in this study based on SOARCA generic estimates.

Table 2: Unmitigated scenario core damage frequency (per reactor year)

Plant Type	**STSBO**	**LTSBO**	**STSBO with SGTR**	**STSBO with RCIC**
BWR	$1x10^{-7}$ to $5x10^{-7}$	$1x10^{-6}$ to $5x10^{-6}$	-	$1x10^{-7}$ to $5x10^{-7}$
PWR	$1x10^{-6}$ to $2x10^{-6}$	$1x10^{-5}$ to $2x10^{-5}$	$1x10^{-7}$ to $8x10^{-7}$	-

To model the off-site effects of the above scenarios, we used the Radiological Assessment System for Consequence Analysis (RASCAL) developed by the NRC for emergency response purposes. A description of RASCAL models and methods can be found in NUREG-1940 [10]. Because RASCAL is intended for use in emergency response (i.e. within a short time after an accident), RASCAL uses a two-dimensional rather than three-dimensional plume model, favoring speed over accuracy. This requires only surface weather data, as opposed to three-dimensional models which require data from upper-air observations. We used RASCAL partly because it is well known in the nuclear power industry, but also because it runs quickly, has a standard treatment of nuclear source terms in emergency response and was also used by the NRC to guide protective action decisions for Americans living in Japan after the Fukushima disaster [11]. Further work from Hammond [11, 12] has shown that the dispersion model used in RASCAL yields similar emergency response decisions to the more accurate, three-dimensional Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by the National Oceanic and Atmospheric Administration.

The NRC and many within the nuclear industry use MACCS2 for consequence analysis; by contrast, the program uses only a one-dimensional Eulerian Gaussian dispersion model [19], as opposed to the two-dimensional model used in RASCAL. Therefore, MACCS2 does not use as much meteorological data as RASCAL, accounting only for surface wind conditions at the time of release. RASCAL also allows us to use multiple specific weather scenarios to find the variability in different weather conditions as opposed to an averaged estimate within MACCS2. Moreover, MACCS2 source term calculations (done with MELCOR) and off-site release specifications are much more laborious, as unique physical plant processes are simulated for each scenario and model run [19]. With six different scenarios to quantify at five plants over 2 years, this would have been a limiting factor. Thus, RASCAL was judged to represent the best combination of speed, accuracy, and ease of use, though further work is being done to compare RASCAL results with MACCS2 calculations.

To examine the effect of a diversity of weather conditions, 24 weather observations were sampled at each reactor site in calendar years 2011 and 2012. Each observation was taken near the middle of the corresponding month (with specific dates chosen based on availability of weather data), with a random time on the chosen date specified as the time of reactor shutdown and general emergency declaration. Plant weather logs are not publicly available, so data from the nearest station of the National Weather Service (NWS) were used as a surrogate for true weather conditions at each plant. To obtain surface weather conditions (i.e. wind direction, wind speed, temperature and precipitation levels), hourly quality controlled local climate data (QCLCD) from the NWS was used. In addition, vertical stability data (i.e. cloud cover, ceiling height, and mixing layer depth) were obtained from the Air Resources Laboratory. With 24 scenarios at each plant chosen from all months of the year, a wide range of weather conditions was observed.

RASCAL inputs (such as how soon the core is uncovered in a given scenario, whether containment sprays are functioning, and containment pressure status and integrity) were taken from the SOARCA studies of Peach Bottom [12] for BWRs and Surry [13] for PWRS respectively. It should be noted that according to [10], RASCAL may slightly overestimate the speed and magnitude of releases, resulting in conservative projected doses. RASCAL and SOARCA comparisons are given in the following table. The RASCAL inputs were found by discretizing the SOARCA graphs that specify containment pressure vs. time and radionuclide quantities released vs. time. This discretization, together with the lack of physical modeling of accident progression in RASCAL, explains the discrepancies in total source terms. Note that the total source terms used in our RASCAL analysis are well within an order of magnitude of the SOARCA source terms and are also within the general source term uncertainty estimates of accidents [23] (although larger discrepancies were observed for some individual radionuclides). For comparison purposes, the Japan Nuclear Energy Safety Organization estimates that 3.7×10^6 Ci of I-131 and 1.6×10^6 Ci of Cs-137 was released to the environment between the multiple units during the Fukushima accident [10].

Table 3: SOARCA and RASCAL source term comparison (Curies)

Accident Sequence	SOARCA Total	RASCAL Total	RASCAL I-131	RASCAL Cs-137
BWR STSBO	3.8×10^8 Ci	7.0×10^8 Ci	1.4×10^6 Ci	9.1×10^4 Ci
BWR LTSBO	6.6×10^8 Ci	2.5×10^8 Ci	4.6×10^4 Ci	4.6×10^3 Ci
BWR STSBO w/ RCIC	9.2×10^8 Ci	2.5×10^8 Ci	$4.8 \mathrm{X} 10^4$ Ci	4.7×10^3 Ci
PWR STSBO	4.4×10^8 Ci	1.0×10^8 Ci	2.5×10^5 Ci	3.4×10^4 Ci
PWR LTSBO	8.4×10^7 Ci	7.8×10^7 Ci	1.0×10^5 Ci	1.7×10^3 Ci

For each combination of accident scenario and weather scenario, RASCAL was used to compute the corresponding off-site plume dose profiles in the form of geographical ‘shapefiles’. The key result of interest for this project is the one year total effective dose equivalent (TEDE), but results for four days, two years, and 50 years were also produced. Note that the one year TEDE is based on ground contamination four days after the accident. A sample plume showing the level of computed one year offsite dose from an SGTR in May 2011 is shown in Figure 1. In this figure, the outer green squares represent areas where the dose would be between 0.02 and 0.2 REM and people would not be relocated. The yellow region is 0.2 – 2 REM, where again relocation would not be needed after the first few days following an accident. Finally, in the central red region, the dose would exceed 2 REM, requiring evacuation and relocation under the current protective action guidelines (PAG) of the Environmental Protection Agency (EPA).

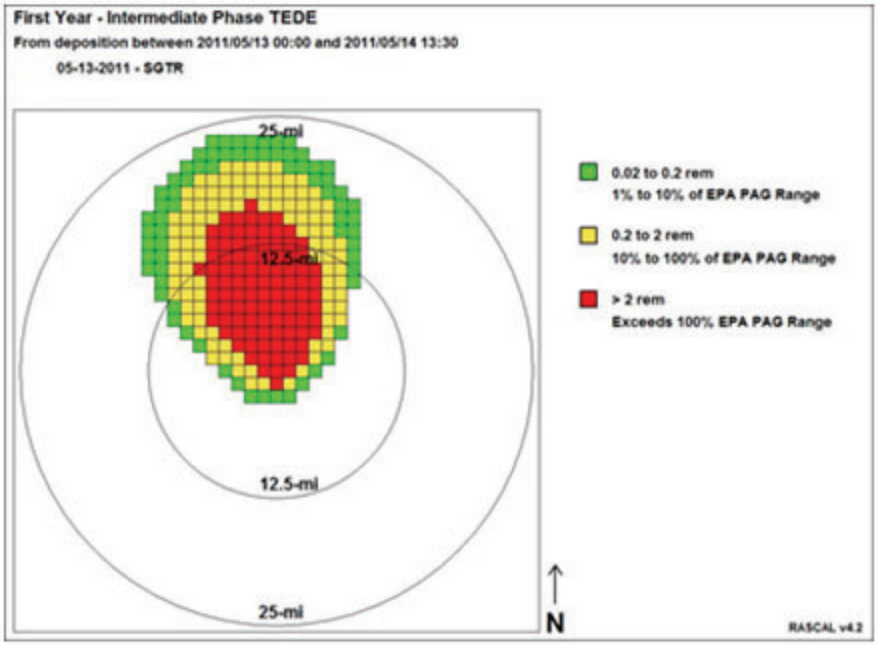

Figure 1: Offsite Dose Distribution

These shapefiles were then combined with population data using ArcGIS mapping and spatial analysis software. ArcGIS software uses map layers to organize information "to support geographical inquiry and, ultimately, spatial decision making" [14]. The level of analysis for our study is a census block (the finest level of detailed provided by ArcGIS), which is about the size of a city block or around 100,000 ft^2. Thus, the ArcGIS software was used to overlay RASCAL plume shapefiles over census population data obtained from the U.S. Census Bureau's TIGER/Line shapefiles [15]. We then compute, for each combination of accident scenario and weather conditions, the number of people that would be exposed to various dose thresholds, as well as the dose for each population cohort. This allowed us to determine how many people would need to be relocated using current EPA PAG thresholds, as well as alternative relocation thresholds.

3. RESULTS

The following table shows the 95% confidence intervals for the number of people needing to be relocated under the PAG for each type of accident scenario at each plant. The extremely wide confidence intervals are due to the wide range of weather conditions observed over the two year period sampled. They do not represent the absolute maximum and minimum numbers of people relocated. As can be seen, at the most highly populated reactor site (Eastern seashore) with the most severe accident scenario (STSBO with SGTR), the number of people needing to be relocated under current PAG thresholds can approach one million. The societal disruption associated with such a major relocation effort would clearly be massive. For comparison purposes, according to Goldman and Coussens [17], "The state of Louisiana evacuated approximately 1.5 million people before Hurricane Katrina made landfall".

Table 4: 95% Confidence intervals for number of people relocated based on 1-year, 2-rem EPA PAG (to one significant figure)

Plant	STSBO	LTSBO	STSBO w/ SGTR	STSBO w/ RCIC
A (Eastern Seashore)	30,000 - 400,000	0 - 20,000	300,000 - 1,000,000	-
B (Midwest 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

Figure 2 more explicitly shows the proportion of accident scenarios that relocate a number of people in the given range to demonstrate the variability possible within a given accident scenario (in this case, an STSBO with SGTR at Plant A). Although almost 50% of the weather scenarios considered would produce relocations of fewer than 700,000 people, nearly 25% of the weather scenarios would have required a relocation of over one million people (similarly, at Plant B, while the average number of people relocated for the same accident scenario is around 200,000, one quarter of weather conditions would result in a need to relocate more than 300,000 people).

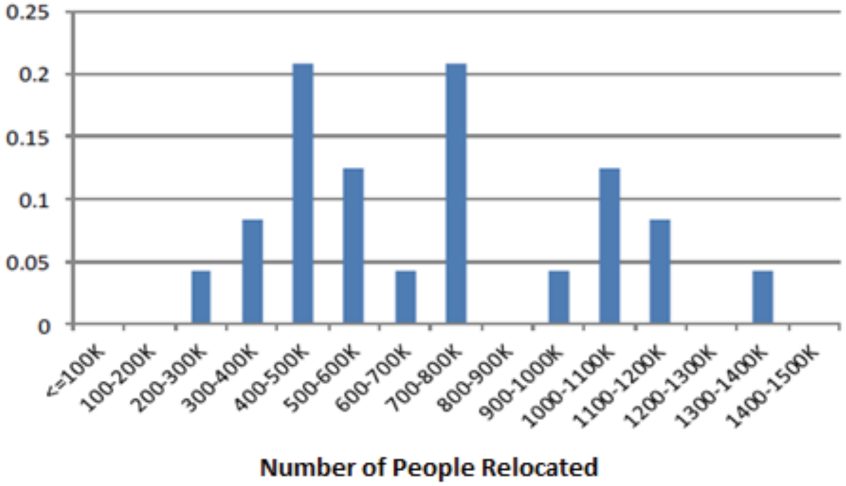

Figure 2: Histogram of Relocation Sizes for an SGTR at Plant A

Moreover, return to normalcy after a nuclear disaster may not be swift. The current EPA PAG for 50 years is 5 REM. Because that number is higher than the one year guideline of 2 REM, one might expect the number of people that would need to be relocated for many years would be smaller than the number of people relocated in the first year. However, the fact that the dose can be accumulated over the entire 50 years counteracts the effect of the higher dose threshold. Figure 3 shows the ratio of the number of people relocated using the 50 year PAG to the one year relocation numbers at Plant A. Although the 50 year numbers are usually smaller, they can sometimes be more than 50% greater than the one year relocation numbers.

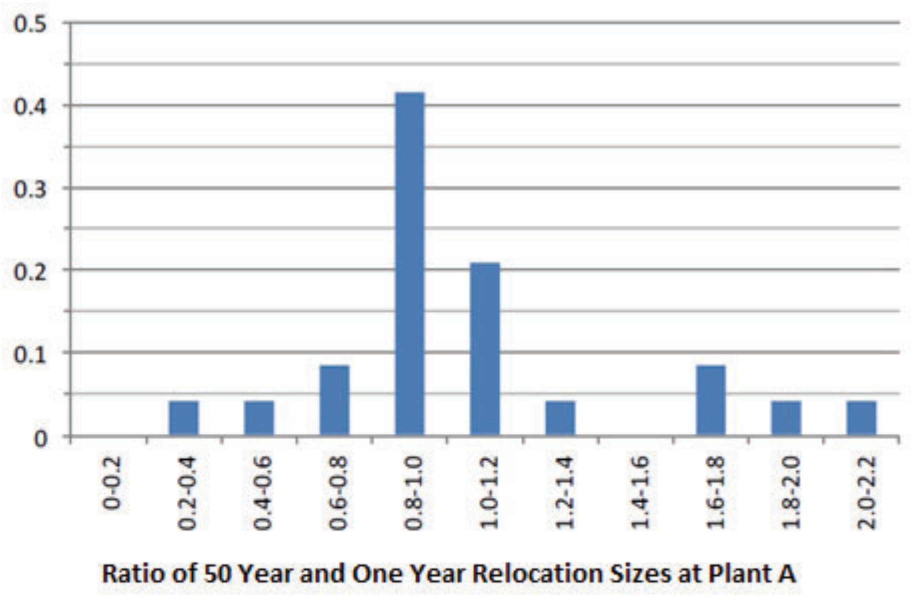

Figure 3: Histogram of 50 year to 1 year ratio

(Note that the 50 year relocation numbers do not necessarily imply that people would still need to be relocated 50 years after an accident. Depending on the weather conditions present at the time of the accident and the radioactive species present, at some point within the 50 years the amount of radiation present could fall back to an acceptable level and the relocated population could be allowed to return to their homes. However, the large relocated population numbers computed in the 50 year analysis do indicate that people may need to remain relocated for well over a year)

Based on the magnitude of relocations that might be necessary at highly populated sites, it seems sensible to reexamine whether higher relocation thresholds could still provide adequate protection from radiation, while keeping societal disruption to a minimum. Figure 4 shows the effects of changing the one year relocation PAG threshold from the current 2 REM to a range from .5 REM to 4 REM for several weather scenarios. In the most severe of the weather conditions shown in Figure 4 (the highest curve, for a hypothetical STSBO with SGTR occurring in February 2011), increasing the PAG from 2 REM to 3 REM would reduce the number of people needing to be relocated by 500,000, while causing roughly 650 additional LCF, for a ratio of about 800 people relocated to prevent one cancer fatality (based on a conversion factor of $5x10^{-4}$ LCF per person-rem, per the International Commission on Radiological Protection [20]). (Note also that the LCF numbers were computed using a linear no-threshold assumption, which can be controversial at low doses, since many people with low doses may face little to no risk. Therefore, the number of people that would need to be relocated to prevent one cancer fatality could in fact be even higher than the estimate of 800 indicated here).

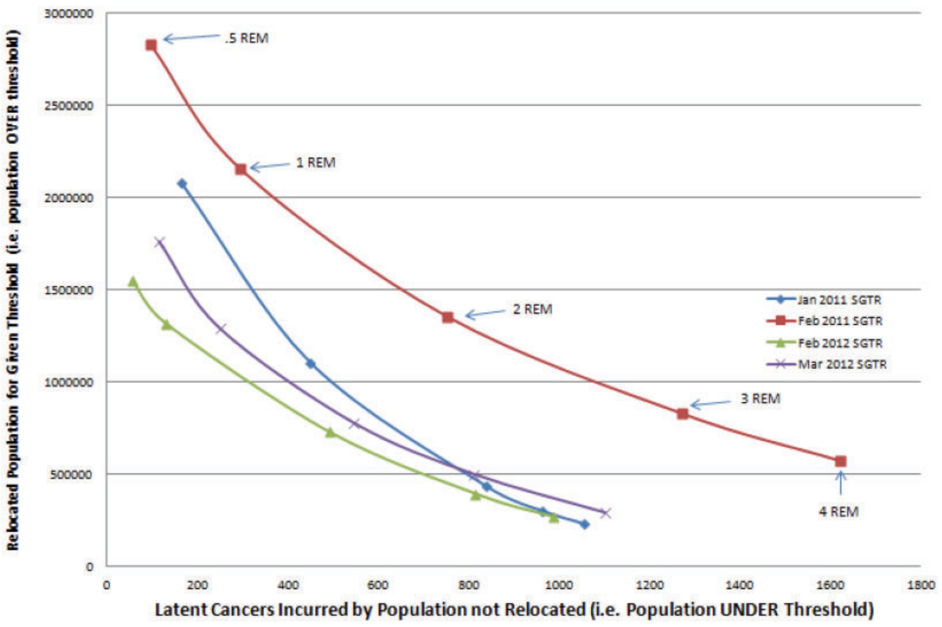

Figure 4: People Relocated and Number of Cancer Cases at Plant A, for various Relocation Thresholds (.5 REM to 4 REM)

The societal disruption resulting from massive relocations under the current PAG (including economic losses—e.g., houses and business facilities that would not be usable) could clearly be enormous, and would lead to significant political pressure from people and businesses wanting to return to the interdicted area. In fact, Morris [16] 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. Reducing the number of people relocated could thus lead to a non-trivial reduction in societal disruption—especially taking into account the fact that the disruption would be experienced immediately (and last for years), while most cancer fatalities would not be expected to occur until many years after the accident.

4. CONCLUSION

The results of this work and relocation experiences from both Japan and Chernobyl, support the idea that the NRC safety goals should consider the societal disruption that could result from severe reactor accidents, in addition to the fatality risk. Theoretically, it is possible to meet all current NRC fatality goals (both prompt and latent), simply through the evacuation and relocation of a sufficiently large group of people. However, this does not match our intuition about what constitutes an acceptable level of societal risk due to nuclear power.

The total number of people that would need to be relocated after the accident is a simple but potentially useful metric for overall societal disruption (that would need to be including health risks caused by evacuation and relocation, as well as economic losses associated with land interdiction). Focusing exclusively on relocation may of course underestimate the long term opportunity costs of interdicting land that is currently not populated, but might have become valuable in future if not for the contamination. However, the number of people needing to be relocated is a reasonably objective measure and relatively easy to calculate using current dispersion and population models, and in our view captures some of the most important aspects of disruption.

Future work using this approach may take into account the frequencies of the various accident scenarios. A simple threshold on the expected number of people that would need to be relocated to meet cancer-fatality goals would help to constrain total societal disruption, and could also provide insight into siting policies for new reactor types such as small modular reactors (with smaller source terms, and therefore less contaminated land). Also, recognizing the inherent tradeoff between cancer risk and relocation might lead one to consider limiting the weighted sum of expected cancer fatalities and expected people relocated (with weights of course chosen to reflect the much greater impact of a fatality). Using this approach a plant might be able to meet an overall societal risk goal through either large relocations and small cancer risk, or small relocations and larger cancer risk. This might encourage reconsideration on the PAG to achieve the best balance between relocation and cancer risk.
In the past 30 years, the population living within 10 miles of a nuclear power plant in the U.S. has increased by more than 50% and at 12 of the 65 reactor sites, populations have more than doubled [21]. Relocation of large populations comes with inherent health risks as well as large economic losses from land interdiction. Given these facts and the lessons learned from experiences at Japan and Chernobyl, we believe that current safety goals and PAG thresholds should be revised to account for societal disruption that would be associated with nuclear accidents requiring large relocations.

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