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RE-EVALUATING THE CURRENT SAFETY GOALS

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The Safety Goals adopted by the United States Nuclear Regulatory Commission (NRC) consist of two qualitative safety goals (QSGs) backed up by two quantitative health objectives (QHOs). The QHOs establish risk limits for severe accidents in terms of their radiological consequences to affected individuals: in particular, the average individual health risks of early fatality and latent cancer fatalities from radiation exposure of members of the public living in the vicinity of a nuclear power plant. This paper is devoted to a re-examination of the coverage of the current safety goals in evaluating the total (radiological and non-radiological) risk posed by nuclear power plant operation. Specifically, we suggest the need to address societal consequences. By "societal consequences," we mean measures of consequences that reflect the number of people affected, and not just the individual risks. Recent Level 3 Probabilistic Risk Assessments (PRAs) suggest that given a high likelihood of evacuation of the close-in population before any release occurs, the current QHOs are satisfied by large margins, and the experience of an actual severe accident at Fukushima showed that actual human health effects from released radiation were not the dominant consequences: there were no early fatalities and no measurable increases expected in cancer rates above the baseline rates in the Japanese population. Hence, regardless of accident probability, Fukushima-type accidents with evacuation would satisfy the NRC's health-related safety goals. However, there were very significant societal costs, in that large numbers of people were relocated for long periods. We argue that, in addition to the risks addressed in current safety goals, societal risk should also be considered. The paper discusses specific possibilities for a goal and an associated quantitative objective.

I. BACKGROUND

In 1986, the Nuclear Regulatory Commission (NRC) issued a Safety Goal Policy Statement (SGPS) [1] that established two qualitative safety goals (QSGs) and two quantitative health objectives (QHOs). The adoption of these goals was meant to indicate to the public the NRC's expectation that nuclear power plants should be designed and operated in a safe manner so that members of the public should bear no significant risk of adverse health consequences resulting from living near a nuclear plant. The QSGs are: (1) Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant risk to life and health; and (2) 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.

The QHOs provided a quantitative guideline for what the NRC considered as no significant risk to members of the public from plant operation. They were developed in terms of the risk of radiation exposure to members of the public from accidental releases of radioactivity that could lead to either a prompt fatality or an induced cancer fatality. The QHOs are: (1) 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 one-tenth of one percent of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed; and (2) The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent of the sum of cancer fatality risks resulting from all other causes. The first QHO is calculated as an average individual risk over the population residing within one mile of the plant. The second QHO in practice is calculated as an average individual risk over people living within 10 miles of the plant. Although the second QHO is referred to in the SGPS as a societal health objective, it is actually estimated in Level 3 PRAs as an individual latent cancer fatality risk.

Both QHOs are focused on individual risk alone. QSG 2 mentions societal risk and states that societal risk to life and health from nuclear power plant operation should not be a significant addition to other societal risks. However, until recently, societal risk has not been examined in the context of safety goal evaluation, and it remains unaddressed in quantitative Level 3 probabilistic risk assessments (PRAs) of nuclear power plants, since there is no QHO for it that has been proposed or adopted by the NRC. This paper is devoted to a re-evaluation of the way safety goals have affected probabilistic risk assessments of the safety of operating nuclear power plants. In particular, it attempts to shift attention from individual health risk to societal risk that we believe is the main consequence of the accidents involving substantial offsite releases that have occurred at nuclear power plants Fukushima and Chernobyl. We try to identify the determinants of societal risk and offer some preliminary ideas of how a safety goal focused on societal risk could be framed.

I.A. Large Release

The SGPS defined another risk metric called a "large release frequency" (LRF) as a general plant performance guideline and established a quantitative risk guideline for it: "Consistent with the traditional defense-in-depth approach and the accident mitigation philosophy requiring reliable performance of containment systems, the overall mean frequency of a large release of radioactive materials to the environment from a reactor accident should be less than 1 in 1,000,000 per year of reactor operation." However, what constituted a large release was not defined.

Subsequent work sponsored by the NRC [2-5] attempted to provide a quantitative notion of what could be a threshold for considering a release to be "large." But these attempts were ultimately focused on trying to examine the notion of "large" in the context of individual health risk, in particular trying to identify a source term (quantity and timing of released radionuclides following core damage) that could lead to at least one early offsite fatality. For example, in Ref. 2, it was recommended by staff that the definition of large release should remain "reasonably consistent" with the QHOs. In particular, it was recommended that large release should be defined as a release that has the potential for causing an offsite fatality as a surrogate for the prompt fatality QHO. Ref. 3 recommended that large release should be defined as a release of radioactivity from the containment to the environment of a magnitude equal to or greater than… {an amount, to be determined by the staff, expressed in curies or fractions of the core inventory, based on representative site characteristics, for causing one or more prompt fatalities}. This recommendation started out as one that was reasonably congruent with the Commission[†] statement in the SGPS, but the clause at the end relating it to prompt fatality showed that staff had not thought beyond individual health consequences, and by implication the prompt fatality QHO, as a surrogate for defining large release.

However, it was observed that if a large release was one that could lead to at least one early fatality, then its limiting frequency of 1E-06 per year identified in the SGPS came into conflict with the frequency identified with the early fatality QHO.[††] It was shown that an LRF of 1.0E-06 per year would be one or more orders of magnitude more stringent (i.e. conservative) than the prompt fatality QHO and even more so than the latent cancer QHO. Based on these results, as indicated in Ref. 4, the Commission approved termination of efforts to define large release. As discussed below, the main reason for this was trying to develop a definition of large release in the context of individual risk of prompt fatality alone, and attempting to shoehorn it into congruence with the QHO.

Accordingly, as related in Ref. 4, LRF was eventually replaced by another risk metric: the large *early* release frequency, or LERF, which is congruent with the prompt fatality QHO and whose numerical value was less stringent by one order of magnitude than the LRF. LERF is defined qualitatively as a large, unmitigated release from containment after occurrence of core damage but before effective evacuation of the close-in population that has the potential to lead to early offsite health effects [6]. Since Regulatory Guide 1.174 was adopted, acceptable surrogates for the QHOs have been identified: the large early release frequency (LERF) with a value of 1E-05 per year for the prompt or early fatality QHO, and the core damage frequency (CDF) with a value of 1E-04 per year for the latent cancer QHO.

I.B. QHOs and Plant Safety

In the context of PRAs performed after the TMI-2 accident, the QHOs performed a valuable function of indicating the level of risk considered significant by the Commission. The QHOs were not requirements, but they were meant to indicate to reactor designers and operators as well as the public what level of safety the regulations were trying to achieve. It is pertinent to ask what the important issues involved in plant safety are and how well "average individual risk" embodied in the QHOs addresses those issues. To assess this, one may consider the QHOs calculated in Level 3 PRAs and also examine the experience of a major accident in an LWR involving a substantial offsite release of radioactive materials, viz. Fukushima.

[†] In this paper, "Commission" refers to the five NRC Commissioners, and not to the agency as a whole.

[††] The prompt fatality QHO has been assumed for some time to have a frequency of 5E-07 per year based on data from the 1980s showing that the risk of a prompt fatality in the US (due to traffic accidents, etc.) was around 5E-04 at that time. The latent cancer fatality QHO is 2E-06 per year based on the cancer fatality rate of 2E-3 per year.

The most recent detailed Level 3 PRA was that carried out at the Surry and Peach Bottom nuclear power plants in the State-of-the-Art Reactor Consequence Assessment (SOARCA) program [7]. A major accident at the plant was hypothesized, a detailed evaluation of the failure of containment and the subsequent release, including timing and magnitude, of the core inventory of fission products was performed, and the atmospheric transport and dispersion of the releases taking into account hourly weather sequences (windspeed, stability class, etc.) was evaluated. But, like other Level 3 PRAs, it was assumed that protective action measures such as evacuation would be implemented prior to the calculation of doses and health effects. In fact, elaborate ETE (evacuation time estimate) models were developed to characterize the various cohorts (such as schoolchildren, other institutional inhabitants, general households, etc.) that would need to be evacuated. Given the time of release of various plume segments from the failed containment and the efficacy of the evacuation meant that there were essentially no recipients of radiation exposure and the QHOs were satisfied by large margins. Better and more modern understanding of accident progression suggests that unlike some of the rapid releases that were analyzed in early risk assessments like WASH-1400 [8], there is much more likely to be a considerable elapsed time between the onset of core damage and the start of release from a failed or bypassed containment for many severe accident sequences. This makes it all the more likely that the close-in population would have successfully evacuated,[†††] rendering the estimation of an early fatality QHO essentially infructuous.

For an actual accident, Fukushima provides a useful benchmark. There were zero fatalities attributed to the release of radioactive material from the Fukushima plant. Although there is a slight increase in the risk of acquiring some cancers for the people in the most contaminated areas around the plant, no measurable increases in cancer rates above baseline rates are expected in the Japanese population. Thus, regardless of the probability of the event occurring, the accident at the Fukushima site would have satisfied the NRC's health-related safety goals.

It has long been recognized that the QHOs do not address some important aspects of plant safety; they do not, for example, constrain the total number of latent cancer fatalities or the siting of plants in high population density areas [9]. The latter factor was referred to in Commissioner Bernthal's additional comments in the SGPS that the QHOs would permit siting of a nuclear power plant in New York City's Central Park. The large release guideline could be viewed, in a sense, as an attempt to cover those aspects of plant safety not addressed by the QHOs.

II. SOCIETAL RISK

Something that is clearly missing in making decisions on nuclear power plant safety based on individual health risk (and, even more, average individual health risk) is that the major consequences of a Fukushima-like accident are substantial societal impacts, including the relocation and housing of large numbers of displaced people for extended periods, loss of land use and associated products, loss of community facilities and the cost of decontaminating large areas. In addition, there are also extended psychological impacts on the relocated population that are considered to be severe, and deaths from accidents during evacuation that have nothing to do with radiation exposure.

Several recent studies on nuclear power plant accidents have concluded that rather than individual health risk from radiation exposure, the major impact is societal risk such as described above that happened at Fukushima and a safety goal based on societal impact is needed [10-12]. Bier *et al.* [10] focused on various accidents at five nuclear plant sites in the US and evaluated the social disruption that would occur in terms of the number of people that would need to be relocated for an extended period to meet protective-action criteria for habitability. They concluded that the number of people relocated is a good proxy for societal impact. Denning and Mubayi [11] focused on comparing the monetized societal risk of nuclear power plant accidents to that of other major disruptive events to which the public is exposed by characterizing the monetized societal risk in the United States from major societally disruptive events, such as hurricanes, in the form of a complementary cumulative distribution function (CCDF). They applied the NRC's 0.1% goal to a comparison of the CCDFs of the nuclear plant risk to the overall background societal risk and concluded that societal risk remains the dominant risk of nuclear power plant accidents. Pascucci-Cahena [12] made similar points and suggested that "number of nuclear refugees" is a better indicator of accident severity than fatalities.

Relocation of substantial numbers of people and interdiction of large areas of land for extended periods of time remains the major consequence of a nuclear power plant severe accident that will occur regardless of how small the health impact on individual members of the public is from radiation risks. The trade-off between protective action measures and the health impacts of power plant accidents has been studied for some time using different risk measures whether extended relocation versus latent cancers prevented as in Ref. 10 or cost of preventive actions versus imputed cost of cancer fatalities as in some earlier studies [13]. Given this experience, we

[†††] The exception to this is if the accident is an external event such as a large seismic event that could disrupt the road and bridge network, making evacuation difficult.

believe that the large release risk criterion already in the SGPS seems to be an appropriate way to develop a societal safety goal for nuclear power plant operation. In fact, Commissioner Asselstine, in his additional comments appended to the SGPS [1], stated his belief that defining a large release was "an appropriate objective in ensuring that there is no undue risk to the public health and safety associated with nuclear power."

III. SOCIETAL SAFETY GOAL

The existing safety goals are stated in terms of qualitative safety goals and quantitative health objectives. Proceeding analogously, one could address the need for societal goals in something like the following way, first articulating a high-level goal and then operationalizing it in terms of a quantitative objective.

> Qualitative goal:
> There should be no significant likelihood of a large-scale, long-term evacuation needed as a result of a reactor accident.

In principle, the actual "need for an evacuation" depends on how protective action guidelines are formulated. The present consideration focuses on "need for evacuation," and leaves the actual dose considerations to be addressed under protective action guidelines.

The quantitative objective could be defined as follows:

> Quantitative objective:
> The overall mean frequency of the release of radioactive Cesium from the containment to the environment of a magnitude equal to greater than or equal to X % of the core inventory of Cesium, based on representative site characteristics, that could lead to the evacuation and extended relocation for more than one year of Y number of persons of the offsite population, should be less than 1 in 1,000,000 per reactor year.

The above statement leaves unspecified the environmental release magnitude X and the scale Y of the evacuation required. But it is clearly societal in nature. Its specifics derive from the discussion provided below.

The characterization of nuclear power plant societal risk in terms of a large release can be simplified considerably by focusing on the ground contamination caused by the release of the radioactive isotope of cesium, Cs-137, that has a relatively long half-life of about 30 years. The other fission product that could be used to characterize societal risk is iodine, but while it may contribute to radiation exposure of individuals, the short half-life of its main isotope I-131 is around 8 days, so it is not likely to be important in long-term land contamination and relocation. Hence the proposal to formulate the quantitative objective in terms of the large release frequency metric along the lines proposed in Ref. 3 consists of specifying a limiting value of Cs release as a fraction of the core inventory that could cause extended (more than a year, say) relocation of a substantial number of the offsite public.

Apart from the values of X and Y, a key feature of the above definition that addresses societal risk is the phrase "representative site characteristics" that incorporates factors such as population density that are missing from the current QHOs based on average individual risk, as pointed out by Commissioners Asselstine and Bernthal in their additional comments to the SGPS. What X and Y may be requires much more detailed study, and they are ultimately policy choices on the part of decision-makers akin to the 0.1% in the current safety goals. A very preliminary review of the literature on source terms and consequences suggests that X % may be in a range of 1 to 10% while the study carried out in Ref. 10 provides a possible range for Y from 1E+04 to 1E+05 persons at various reactor sites in the US. We offer these preliminary suggestions in a spirit of enquiry into developing a societal safety goal that could be more useful to the stakeholders in this area.

IV. CONCLUSIONS

For historical reasons, the existing safety goal structure has been focused on the Commission's expectation that nuclear power plants should be designed and operated in a safe manner so that members of the public should bear no significant risk of *adverse health consequences* resulting from living near a nuclear plant. Moreover, the safety goals focus, in effect, on average individual radiological risk: the overall magnitude of adverse consequences (e.g., the number of people affected) is not addressed. The releases at Fukushima had only slight radiological consequences, but very significant non-radiological societal consequences.

The present work suggests adding a safety goal and an associated quantitative objective. The goal is to minimize the likelihood of a large-scale, long-term evacuation as a result of a reactor accident. The form of the quantitative objective discussed is based on previous work that tried to define a "large release." In this discussion, it is recognized that the need for "long-term" relocation is driven by somewhat long-lived isotopes. Precise specification of the parameters of such an objective (release magnitude, number of people relocated) depends on policy and on protective action guides [14], and is left for further work.

Possibly depending on the details of the qualitative goal and the associated quantitative objective, it is likely that some nuclear power reactor technologies will find it easier than others to satisfy the goal and the objective.

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REFERENCES

1. “Safety Goals for the Operations of Nuclear Power Plants; Policy Statement; Republication,” 51 FR 30028, August 21, 1986 (USNRC).
2. SECY 89-102, “Implementation of Safety Goal Policy,” March 30, 1989 (USNRC).
3. SECY 90-405, “Formulation of a Large Release Definition and Supporting Rationale,” December 14, 1990 (USNRC).
4. SECY 13-0029, “History of the Use and Consideration of the Large Release Frequency Metric by the US NRC,” recounts in detail the attempts made by the Commission staff over the years to arrive at a definition of a large release that would be consistent with the QHOs (USNRC).
5. NUREG/CR-6094, “Calculations in Support of a Definition of Large Release, Brookhaven National Laboratory, 1995 (USNRC).
6. Regulatory Guide 1.174 (US NRC, 1998).
7. NUREG/CR-7110, “State-of-the-Art Reactor Consequence Analyses Project,” Sandia National Laboratories (USNRC, 2012).
8. "Reactor safety study. An assessment of accident risks in U. S. commercial nuclear power plants,” WASH-1400 (NUREG-75/014) (USNRC, 1975).
9. V.M. Bier, “The US Nuclear Regulatory Commission safety goal policy: A critical review,” Risk Analysis Vol. 8, pp. 563-568, (Society for Risk Analysis, 1988).
10. V.M. Bier, M. Corradini, R.W. Youngblood, Caleb Roh, and Shuji Liu, “Development of an Updated Societal-Risk Goal for Nuclear Power Safety, Proceedings of PSAM-12, 22-27 June 2014.
11. R. Denning and V. Mubayi, “Insights into the Societal Risk of Nuclear Power Plant Accidents,” Risk Analysis, Vol. 37, No. 1 (Society for Risk Analysis, 2016).
12. Ludivine Pascucci-Cahena, “Nuclear refugees after large early radioactive releases,” Proceedings of PSAM-12, 22-27 June 2014.
13. V. Mubayi, “Cost tradeoffs in consequence management at nuclear power plants: A risk based approach to setting optimal long-term interdiction limits for regulatory analyses,” Proc. ASME Pressure Vessels and Piping Conference, Hawaii, 1995.
14. “Protective Action Guides (PAGs),” EPA-400/R-16/001, November 2016, www.epa.gov/radiation/protective-action-guides-pags.