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ABSTRACT

Since they were adopted in 1986, the US NRC's Safety Goals have played a valuable role as a de facto risk acceptance criterion against which the predicted performance of a commercial nuclear power reactor can be evaluated and assessed. The current safety goals are cast in terms of risk metrics called quantitative health objectives (QHOs), limiting numerical values of the risks of the early and latent health effects of accidental releases of radioactivity to the offsite population. However, while demonstrating compliance with current safety goals has been an important step in assessing the acceptance of the risk posed by LWRs, new or somewhat different goals may be needed that go beyond the current early fatality and latent cancer fatality QHOs in assessing reactor risk. Natural phenomena such as hurricanes seem to be suitable candidates for establishing a background rate to derive a risk goal as their order of magnitude cost of damages is similar to those estimated in severe accident Level 3 PRAs done for nuclear power plants. This paper obtains a risk goal that could have a wider applicability, compared to the current QHOs, as a technology-neutral goal applicable to future reactors and multi-unit sites.

Key words: Safety Goals, Offsite Damage Costs, Hurricane Costs

1 INTRODUCTION

Since they were adopted in 1986, the US NRC's Safety Goals have played a valuable role as a de facto risk acceptance criterion against which the predicted performance of a commercial nuclear power reactor can be evaluated and assessed. In the Safety Goal Policy Statement, the Commission stated that it "has established two qualitative safety goals which are supported by two quantitative objectives. These two supporting objectives are based on the principle that nuclear risks should not be a significant addition to other societal risks." [1] The current safety goals are cast in terms of risk metrics called quantitative health objectives (QHOs), limiting numerical values of the risks of the early and latent health effects of accidental releases of radioactivity to the offsite population. The numerical values of the limiting risks of prompt and latent cancer fatalities were established by the Commission as a very small fraction (0.1%) of the background societal rates in the U.S. of prompt fatalities and latent cancers. In the Commission's view, it believed "that this ratio of 0.1 percent appropriately reflects both of the qualitative goals – to provide that individuals and society bear no significant additional risk…The 0.1 percent ratio to other risks is low enough to support an expectation that people living or working near nuclear power plants would have no special concern due to the plant's proximity." [2]

For currently operating light water reactors in the US, the latent cancer fatality risk QHO can be shown to be basically met if the plant's core damage frequency (CDF) ≤ 1E-04 per year, and the prompt fatality risk QHO can be met if the plant's large early release frequency (LERF) ≤ 1E-05 per year, respectively [3]. The CDF can be estimated in a Level 1 PRA and the LERF is often obtained from an extended Level 1 or a simplified Level 2 PRA. This has been the practice for most PRAs performed to date for various regulatory or related purposes, making a Level 3 PRA unnecessary for demonstrating compliance with the safety goals.

However, while demonstrating compliance with current safety goals has been an important step in assessing the acceptance of the risk posed by LWRs, there are several reasons why a new or somewhat different approach to formulating the safety goals may be explored that goes beyond the current early fatality and latent cancer fatality QHOs in assessing reactor risk. After the Fukushima accident, then NRC Chairman Jaczko remarked: "There were no prompt fatalities, [and] the latent cancers…will likely not be significantly different from whatever background cancer incidents would likely have occurred in those areas without Fukushima…the real human consequences we are dealing with are evacuations of large populations, perhaps extended relocation of populations; significant efforts to clean up, decommission and decontaminate perhaps significant areas of land and the societal consequences that entails." [4]

The likelihood of the prompt and latent health effects of reactor accidents has been reduced due to two reasons: First, the implementation of protective measures, such as evacuation, mandated at all reactor sites, and second, an improved understanding of the evolution of severe accidents that has significantly decreased the possibility of rapid releases, due to phenomena such as steam explosions, that were modeled in early PRAs like WASH-1400. [5] Based on the improved understanding of severe accidents as well as on the Fukushima experience, societal disruption for extended periods of time, involving significant cost, is likely to be the main consequence of reactor accidents, rather than extensive offsite public health impacts in the form of prompt fatalities or even significant numbers of latent cancers that could be demonstrably attributed to accidental radiation exposure. Jaczko commented "we have dramatically reduced the likelihood that there will be accidents in which we see any type of prompt fatality and any type of significant impact from a latent health exposure from direct or indirect radiation exposure...as we look to the future, for a risk analysis framework, if we are going to be honest about talking about the consequences, we have to figure out a way to encapsulate these ideas into our risk models." [6]

2 CONSEQUENCES OF NUCLEAR POWER PLANT ACCIDENTS

The consequences of a severe accident at a nuclear power plant are estimated from the potential radiation exposure of the offsite population due to the release of fission products from the core inventory following core damage and containment failure. The resultant health effects arise from several exposure pathways whose relative importance is a function of the time period following the release.

In the short-term, i.e., within a few days after the release, the important pathways are: inhalation exposure from breathing of contaminated air and external cloudshine exposure, during the passage of the plume, as well as groundshine exposure from standing on ground contaminated by the deposition of radioactive material. [7] Depending on the magnitude and rate of the release, the consequent dose and the resultant acute (early) health effects, which may include fatal impairment of vital organs, may be effectively reduced by emergency protective actions. These include evacuation or sheltering and temporary relocation of potentially affected populations downwind of the release and administration of potassium iodide as a protective measure to block uptake of radioactive iodine by the thyroid.

The long-term dose is due primarily to three pathways: groundshine from living on contaminated land or inhabiting contaminated buildings, inhalation from resuspended radioactive particles deposited on the ground, and ingestion of contaminated food and water. The long-term dose, and hence the number of latent cancers, can be reduced by long-term relocation of the population away from contaminated areas, by prohibiting the consumption of contaminated foodstuff, by prohibiting the production of crops, including dairy and meat products, on contaminated farmland, by decontamination of contaminated land and buildings, or by permanently prohibiting the reoccupation or use of land or property which cannot be decontaminated in a certain period of time in a cost-effective manner.

Level 3 PRAs that have been done in the past [8] take the site-specific protective actions into account to demonstrate that the plant meets the QHOs of the safety goals. However, each of the protective actions, both in the short as well as the long term, involves costs to society. The sum of these costs is usually termed as the "offsite damage costs." Probabilistic consequence assessment models [9] developed for level 3 PRAs have been used to assess these costs based on site-specific input data on meteorology, population, evacuation routes, farmland use, property values, etc., and assumptions about the magnitude, rate, and timing of releases during severe accidents.

Based on these considerations, it appears that offsite costs of severe accidents could be one metric that could be used as a surrogate risk measure for developing a safety goal since it is virtually certain that in a severe reactor accident, stringent long-term protective actions will be taken to reduce offsite health effects among the general public in the vicinity of the affected plant or site, which, in turn, will lead to significant offsite costs. Other candidates for possible surrogate risk metrics include: the number of people in the offsite population temporarily or permanently relocated and the time period of relocation, or the amount of land area contaminated by the release in terms of a certain threshold level of the extent of contamination (e.g. Bq per m^2). This paper explores the use of offsite cost as a risk metric.

As indicated above, in developing the existing safety goals, the Commission looked at consequences in terms of the offsite public health effects and, to set a goal, they considered these health effects in terms of small percentages of the background rate of similar health effects in the

U.S. as a whole. Thus, early fatalities due to reactor accidents were compared to accidental death rates and latent cancer fatalities to cancer fatality rates and the risk goal in each case was set at 0.1 percent of the background rate to demonstrate the Commission's expectation that nuclear risks should pose no significant additional risk.

To develop a safety goal based on offsite costs, one option is to compare the accident costs of severe accidents to those incurred in natural phenomena such as hurricanes, floods, and seismic events that occur frequently with varying severities, involve fairly extended relocations of affected populations, and also have significant cost impacts. In this paper, hurricane costs have been used mainly because there is a credible and consistent data source on the damage costs and severity of hurricanes over an extended time period that can be utilized as a basis for comparison with the costs of severe accidents.

3 HURRICANE DAMAGE COSTS IN THE U.S.: 1900-2005

Pielke and associates [10] have estimated longitudinally consistent estimates of normalized total direct economic damage costs related hurricanes along the U.S. Gulf and Atlantic coasts from 1900-2005. Their methodology for estimating the normalized damage costs allows for adjustments to the historical damage costs by factors related to inflation, wealth, and population:

$$D_{2005} = D_y * I_y * RWPC_y * P_{2005/y}$$

Where, D_{2005} = normalized damages in 2005 dollars; D_y = reported damages in the year-of-occurrence dollars; I_y = inflation adjustment; $RWPC_y$ = real wealth per capita adjustment; and $P_{2005/y}$ = coastal county population adjustment. Detailed discussion of these factors and how they were arrived at is provided in Reference [10]. Table 1 shows the damage costs of the 20 most costly hurricanes with costs above $15 billion (in 2005 dollars) based on the data in Table 3 of Reference [10].

Table 1: Normalized Damage Costs of the 20 Most Costly Hurricanes 1900-2005

Rank	Hurricane	Year	State	Category	Normalized Costs (2005 US$ billion)
1	Greater Miami	1926	FL, AL	4-3	157.0
2	Katrina	2005	LA, MS	3	81.0
3	Galveston	1900	TX	4	78.0
4	Galveston	1915	TX	4	61.7
5	Andrew	1992	FL-LA	5-3	57.7
6	New England	1938	CT, MA, NY, RI	3	39.2
7	11	1944	FL	3	38.7
8	Lake Okeechobee	1928	FL	4	33.6
9	Donna	1960	FL-NC, NY	4-3	29.6
10	Camille	1969	LA, MS	5	21.2
11	Betsy	1965	FL-LA	3-3	20.7
12	Wilma	2005	FL	3	20.6

13	Agnes	1972	FL-CT, NY	1-1	17.5
14	Diane	1955	NC	1	17.2
15	4	1947	FL-LA, MS	4-3	16.8
16	Hazel	1954	NC, SC	4	16.5
17	Charley	2004	FL	4	16.3
18	Carol	1954	CT, NY, RI	3	16.1
19	Ivan	2004	FL	3	15.5
20	Hugo	1989	SC	4	15.3

Source: Reference [10]

4 SEVERE REACTOR ACCIDENT COSTS

In using the hurricane damage cost data as a background for a safety goal, the first step is to establish a comparison and, if possible, an approximate congruence between the hurricane damage costs established by Pielke et al and the costs of severe reactor accidents estimated in some Level 3 PRAs. For the latter, information has been taken from the estimated offsite costs of severe reactor accidents at one of the plants that was evaluated in the NUREG-1150 program [11], and which was later analyzed in more detail in a subsequent publication [12] devoted to considerations of value-impact analysis and the monetary value of averted dose. Table 2 shows the offsite damage costs at 50 miles from the point of release (this is the distance of the plume exposure zone used to calculate ingestion doses for achieving compliance with the EPA Protective Action Guides, PAGs) and at 100 miles, respectively, for Unit 1 of the (now closed) Zion nuclear power plant, a four loop PWR with a large dry containment, that is located in the vicinity of Chicago, IL. These calculations are taken from those estimated in Tables 4.18 and 4.19 of Reference 12, escalated from 1990 $ (in which the original calculations were done) to 2005 $ using the Bureau of Labor Statistics consumer price index inflator [13].

The consequences that are shown in Table 2 are for 15 highest consequence mean source terms that were evaluated in Reference [12] using the MACCS probabilistic consequence assessment code based on the NUREG-1150 methodology revealed in Reference [11]. Each source term is characterized by a set of variables which includes: fractional releases from the core inventory of nine radionuclide groups (noble gases, iodine, cesium, tellurium, barium, strontium, ruthenium, cerium, and lanthanum), timing and duration of release, and the height and energy of the release. The source terms were placed into groups based on their potential for early and latent health effects, and the mean source term from each of 25 groups was selected for more detailed analysis with the MACCS consequence code.

The source terms that were reported in the NUREG-1150 study for Zion are based on accident sequences initiated by internal events while the plant is at full-power operation. These source terms cover a wide spectrum of accidents from loss-of-coolant accidents to containment bypass, anticipated transients without scram, and station blackout events and a correspondingly wide range of releases and consequences ranging from minor releases with little consequences to large releases with major consequences. Hence, these source terms are believed to be a reasonably representative sample of the range of releases which could arise from (internally initiated) severe accidents at a U.S. nuclear power plant.

Table 2: Offsite Damage Costs at 50 and 100 Miles of the 15 Largest Releases at Zion (Based on NUREG-1150 Source Terms)

Release #	Offsite Damage Costs (2005 US $ billion)	
	50 miles	100 miles
1	58.8	83.3
2	52.4	74.1
3	52.4	72.8
4	47.9	64.7
5	41.6	56.7
6	37.8	50.3
7	35.6	49.2
8	33.9	45.6
9	30.9	42.0
10	27.6	36.3
11	22.4	28.4
12	20.4	24.5
13	17.9	21.9
14	15.0	17.0
15	13.2	15.9

Source: Reference [12]; the estimates in 1990 dollars in Ref. [12] were updated to 2005 dollars using the CPI inflator in Reference [13].

In performing the consequence calculations, the various assumptions used, such as for emergency response actions (delay time, evacuation speed, etc.) as well as the long-term protective actions were the same as those used in the NUREG-1150 study. The long-term protective action assumption used in NUREG-1150 were to interdict, i.e. prohibit re-occupancy of, land which could give a projected dose to an individual via the groundshine and resuspension inhalation pathways of more than 4 rem (0.04 Sv) in 5 years (2 rem in the first year and 500 millirem per year for the next 4 years). It is important also to realize that a significant fraction of the offsite costs arise from long-term protective actions which, in turn, depend on the criteria adopted for the allowable levels of long-term exposure of affected populations that would permit reoccupation of previously contaminated land and property. Thus offsite costs and latent health effects are inversely related and this has been explored in some earlier studies. [14]

Banning of contaminated food and interdiction of contaminated farmland for crop and dairy production, and their associated costs, was based on the EPA PAGs for exposure of offsite populations from ingestion of the food groups and crops modeled in the MACCS code (believed to be representative of an average U.S. diet).

This brief description of MACCS offsite cost calculations is provided mainly as context for the figures shown in Table 2 which are based, except for the CPI inflator, on the version of the model at the time of the NUREG-1150 calculations.

In the meantime, the MACCS2 version of the code that includes an improved food model has been released [15, 16] and a number of other changes have been made to provide an extended range of options for the user. An improved economic model is also believed to be under consideration. However, while these changes may lead to somewhat different figures for offsite costs of severe accidents, they are not likely to affect the substance of the argument offered here, which is based on establishing an approximate congruence between the offsite damage costs of severe reactor accidents and those attributed to the occurrence of hurricanes.

5 COMPARISON OF HURRICANE AND REACTOR ACCIDENT COSTS

The entries in Table 1 show that five of the most costly hurricanes in the 1900-2005 period have normalized costs in excess of 50 billion dollars. The greater Miami storm of 1926 is the most costly with a normalized cost of $157 billion, with the next most costly, Katrina, of $ 81 billion and the lower three in this top category clustered in a range of about $ 58 to $ 78 billion. With regard to severe accident offsite costs, the figures in Table 2 show that both the 100 mile and 50 mile offsite damage costs are approximately of the same order of magnitude as the hurricane costs. At 100 miles, the largest six offsite damage costs range from about $ 50 billion to $ 83 billion, while at 50 miles, the five largest costs range from about $ 40 billion to about $ 60 billion.

In its Safety Goal Policy Statement, the Commission stated that the quantitative health objectives "are based on the principle that nuclear risks should not be a significant addition to other societal risks." [17] The main purpose of comparing hurricane costs with those of severe reactor accidents is to suggest that if, apart from health effects, costs of remediating the impacts of reactor accidents are also considered as a risk metric, then hurricanes may provide a suitable "other societal risk" against which the Commission expectations for nuclear power safety can be assessed. If this notion is accepted, one can then look at the data in Table 1 on the more than one hundred year record of hurricane occurrence to establish the frequency of the more devastating hurricanes as measured in terms of their cost impacts.

There is one major event, the Great Miami hurricane of 1926 that is approximately twice the estimated normalized cost of the next event, the Katrina storm of 2005, with another three that have costs ranging from about $58 billion to $81 billion. To establish the background rate of occurrence, one could then estimate the frequency of the most destructive hurricanes as lying in a range from 1 in 105 years (a rate of 9.5E-03 per year) to 5 in 105 years (a rate of 4.7E-02 per year).

Based on the establishment of this range of frequencies of the more destructive hurricanes, using their costs, as representing a measure of the background or "other societal risks," one can apply the same figure of 0.1 percent for the risks of nuclear power plant operation as representing an insignificant level of additional risk, that was used by the Commission in establishing the QHOs of the safety goal policy. By analogy, this would imply that the risk of releases from severe accidents should not exceed a range of 9.5E-6 to 4.7E-05 per year, i.e., about 1E-05 per year to about 5 E-05 per year, which can be rounded off to the more conservative figure of 1E-05 per year. Hence one could establish a safety goal of 1E-05 per year based on limiting the risk of significant offsite damage costs of reactor accidents. This can be recognized, of course as the limiting value currently used for LERF for the current fleet of operating plants. While this identity is fortuitous, what is surprising, however, and may even be somewhat reassuring, is that the frequencies of releases from accidents based on 0.1 percent of the background rate of hurricane occurrence should result in values that are close to those already in regulatory use, which were derived from entirely different premises.

6 CONCLUSIONS AND DISCUSSION

One motivation for establishing a goal based on the costs rather than the health effects of severe accidents, is that the Level 3 PRAs that were used (in programs such as NUREG-1150) to assess compliance with Safety Goals usually include emergency protective response measures such as evacuation and relocation, hence there is a trade-off between the health effects and the costs of the extent of protection provided. A possible benefit of deriving a safety goal in terms of release severity that uses cost as a risk metric is that it brings the safety goal derivation to a more technology neutral standpoint than the concepts of CDF and LERF that are more applicable to LWRs. For some future reactor designs, the surrogate risk measures, CDF and LERF, may not be useful risk metrics. In high temperature gas reactors (HTGRs), for example, there is no unique state comparable to core damage in LWRs. In some small, modular reactor (SMRs) designs, a LERF concept may be inapplicable due to the lack of a driver for an early release.

Developing a safety goal on a cost basis also has possible implications for alternative ways of carrying out regulatory analyses, e.g. of backfits, that are currently based on using a guideline for monetizing averted doses ($ per person-rem). In future analyses, this could be based straightforwardly on averted cost alone without having to assign a dollar cost to averted dose.

One source of some ambiguity in current discussions of the implications of the safety goal policy arises from the fact that the current safety goal policy statement refers to a "nuclear power plant" without specifying whether a plant refers to a single unit or all the units on a site. In future, one may have a mix of plants at a hybrid site consisting of current generation reactors, modular reactors, passive plants, etc., each with a different risk profile. A cost-based goal could be viewed more directly as pertaining to the site as a whole instead of to individual plants that could help to avoid these ambiguities of the current safety goal policy.

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