

**Report To The Massachusetts Attorney General On The Potential Consequences Of A Spent-Fuel-Pool Fire At The Pilgrim Or Vermont Yankee Nuclear Plant.**

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**Personal Background.** I am a nuclear physicist who has studied the consequences of both real and hypothetical nuclear accidents, as well as strategies for mitigation. I am a regular member of panels and boards of the National Research Council of the National Academy of Sciences and an advisor to the Division of Engineering and Physical Sciences. After receiving my Ph.D. in nuclear physics from Columbia University, I taught environmental studies at Holy Cross College. Next, I did research at Princeton's Center For Energy and Environmental Studies modeling the consequences of nuclear accidents. I then spent 15 years at the National Audubon Society as Senior Policy Scientist, and ultimately as Chief Scientist and Vice President. Currently, I am senior scientist at Consulting in the Public Interest, providing scientific assistance to not-for-profits, universities, government, and injured plaintiffs.

I am the author of over 100 articles and reports that span a diverse range of topics. I am a regular peer reviewer of articles for scientific journals. One of my specialties is geographic exposure modeling of toxic releases (Beyea and Hatch 1999). My reconstruction of exposures following the TMI accident has been used in radiation epidemiologic studies (Hatch et al. 1990; Hatch et al. 1991). My reconstructions of historical exposures to traffic pollution (Beyea et al.; Beyea et al. 2005) are being used in two ongoing epidemiologic studies of breast cancer (Gammon et al. 2002), (Nie et al. 2005). I am a co-author of studies on risks and consequences of spent-fuel-pool fires (Alvarez et al. 2003a), (Beyea et al. 2004a), (Beyea 1979). I presented a briefing on this work to a committee of the National Research Council that was studying risks of spent fuel.

**Introduction** I have been asked by the Office of the Attorney General, Commonwealth of Massachusetts, to consider the consequences of releases of radioactivity from spent-fuel-pool fires at the Pilgrim and Vermont Yankee nuclear plants, as part of a relicensing proceeding. In my report I consider important new information on the consequences of releases of radioactivity, in general, and spent-fuel-pool fires, in particular, that was not available to the analysts who prepared earlier documents that are relevant to these proceedings. For example, this new information, which deals with damage costs and radiation risks, was not available prior to the publication of the Environmental Reports for Pilgrim and Vermont Yankee; it was not available prior to the publication of the generic relicensing environmental impact statement (NUREG 1996); and, some of it was not available prior to the filing of Entergy's license renewal application. Consequently, these earlier documents are incomplete from the scientific perspective.

I have addressed the consequences of releases from spent-fuel pools prior to these proceedings (Alvarez et al. 2003a), (Beyea et al. 2004a), (Beyea 1979), in some cases in collaboration with Gordon Thompson, Ph.D., who is filing a separate report in these proceedings. The work we have done has led to a study of the National Research Council<sup>1</sup> and has generated considerable debate and commentary (Alvarez et al. 2003b; Alvarez et al. 2003c; Beyea et al. 2004b)). We have revised our calculations to account for criticisms we thought were valid and easily addressable. In particular, Edwin Lyman, Frank von Hippel and I, in our most recent published work (Beyea et al. 2004a), which forms the backbone of this report on Pilgrim and Vermont Yankee, have specifically responded to criticisms by NRC staff concerning the use of constant population densities around nuclear plants (Alvarez et al. 2003c). In this report, I have addressed additional limitations that raised concerns about our earlier work in some circles. Although critiques of our independent work indicate that there are differences among analysts on the quantity of radioactivity that might be released in a spent-fuel-pool fire and the probability of such releases, there is a consensus among the technical community that this problem needs to be addressed.<sup>2,3</sup>

For my report, I have considered releases of 10% and 100% of the pool inventory, using methodologies outlined in (Alvarez et al. 2003a) and (Beyea et al. 2004a). I have also provided

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<sup>1</sup> For a discussion of the relationship between our study and the National Research Council's report (NatRC 2005), see remarks of Kevin Crowley before the Council on Foreign Relations (Crowley 2005).

<sup>2</sup> Allan Benjamin, lead author of the original 1979 spent-fuel paper from Sandia Laboratory, was a reviewer of our 2003 paper in SG&S. He provided a public commentary on it, in which he stated, "In summary, the authors are to be commended for identifying a problem that needs to be addressed, and for scoping the boundaries of that problem. However, they fall short of demonstrating that their proposed solution is cost effective or that it is optimal." (Benjamin 2003). Whether or not we "fell short" in demonstrating cost effectiveness or optimality is not the issue at this stage in the relicensing proceedings.

<sup>3</sup> It was in 2005, after the relicensing GEIS was completed, that the National Research Council (NatRC) released its study on risks of spent-fuel-pool fires.

"The committee judges that successful terrorist attacks on spent fuel pools, though difficult, are possible.

... If an attack leads to a propagating zirconium cladding fire, it could result in the release of large amounts of radioactive material.

... Additional analyses are needed to understand more fully the vulnerabilities and consequences of events that could lead to propagating zirconium cladding fires.

... it appears to be feasible to reduce the likelihood of a zirconium cladding fire by rearranging spent fuel assemblies in the pool and making provision for water-spray systems that would be able to cool the fuel, even if the pool or overlying building were severely damaged.

...Dry cask storage has inherent security advantages over spent fuel pool storage, but it can only be used to store older spent fuel.

The committee judges, however, that further engineering analyses and cost-benefit studies would be needed before decisions on this and other mitigative measures are taken." (NatRC 2005)

I note that such engineering analyses and cost-benefit studies have not been published by the applicants.

additional calculations that a) fill in some gaps left in earlier work, and b) take into account new information that has recently become available. 10% and 100% are the release fractions recommended for consideration by Gordon Thompson in his report. I have read his report and find it consistent with my knowledge of this field. These release fractions match earlier published work by Thompson, myself, and co-authors (Alvarez et al. 2003a), (Beyea et al. 2004a). They also are consistent in order of magnitude with values considered appropriate by the analyst who did the original work on releases from spent-fuel pools.<sup>4</sup> In addition to a 10% and 100% release fraction, I have also considered (briefly) a smaller release. I have presented general formulas that can be used to estimate consequences for a wide range of releases, other than 10% or 100%.

Thompson finds the inventory of Cesium-137 to be somewhat higher at Pilgrim and Vermont Yankee than the default inventory for a generic reactor considered in (Alvarez et al. 2003a). The differences are not major. I have reviewed Thompson's analysis and find his values reasonable for me to use.

Thompson has estimated the heat rate of a spent-fuel-pool fire to be higher at Pilgrim and Vermont Yankee than estimated for a generic spent-fuel pool in (Alvarez et al. 2003a). The difference in resulting plume rise is within one standard deviation for plume rise, using standard formulas, so it has not been necessary for me to modify my calculations with respect to plume rise.

Before submitting a report on consequences of a 10% and 100% release, I have made an independent assessment to assure myself that such releases are probable enough to be more than a mathematical exercise. I have already noted that many analysts have found that the generic, spent-fuel-pool problem needs to be addressed. In addition, I have reviewed the treatment of release probabilities in the companion report of Gordon Thompson, Ph.D. I find his analysis reasonable and conservative. I am certainly comfortable relying on his plant-specific probability numbers for this proceeding. I note that his estimate of the probability of a release caused by a malicious act increases his total probability estimate by only a factor of 6. A factor of 6 increase is modest, given the ingenuity that terrorists have shown in the past. Thompson's plant-specific numbers are consistent with generic probability analyses that were part of a scoping cost-benefit analysis that my colleagues and I made in 2003 (Alvarez et al.

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<sup>4</sup> Allan Benjamin, lead author of the original 1979 paper from Sandia Laboratory, was a reviewer of our 2003 paper in SG&S. He provided a public commentary on it, in which he stated, "Although there is clear evidence that some of the fuel would melt in such a situation, we don't know how much. Since we don't, it is conservative and appropriate to assume that a large fraction of the fission product inventory could become released to the environment. Whether that fraction is 0.20 or 1.00 doesn't change the fact that the release would be unacceptable." (Benjamin 2003)

2003a). Our analysis suggests that even using older probability numbers, and without considering threats of terrorism or new data on radiation risks to be discussed later, moving older fuel to dry cask storage is nearly cost-effective.<sup>5</sup> The Nuclear Regulatory Commission's response to the issues raised by the report of the National Research Council (NatRC 2005) and our paper in *Science and Global Security* (SG&S)(Alvarez et al. 2003a) is discussed in (Dorman 2005). The NRC does not appear to be addressing the scenarios of most concern to me, such as those addressed by Thompson in his report for Pilgrim and Vermont Yankee. The Commission essentially sees the spent-fuel pool problem as a non-issue that is diverting resources from more important areas. However, the basis for the Commission's overall judgment is secret, presenting a challenge in relicensing proceedings to independent scientists like myself, who are not allowed to review the secret analysis. Should I simply accept the Commission's judgment without review and remain silent to avoid any chance of providing useful information to terrorists? The problem with such a stance is that I do not believe the Commission (or any government agency) can best protect the public against terrorism in the absence of vigorous pressure from, and critical analysis by, a range of stakeholders. It would be irresponsible to say nothing, but equally irresponsible to say too much. I hope the balance I have struck in this report is the right one. I certainly conclude from all of the analysis carried out, both by me, Thompson, and others, and the lack of response by the NRC to date, that computing the consequences of large releases of Cesium-137 in regulatory proceedings is responsible and in the public interest.

Another reason that I find it important to make consequence calculations in these proceedings is that the NRC's own Inspector General has observed that the NRC appears to have informally established an unreasonably high burden of requiring absolute proof of a safety problem (IG 2003). Considerable evidence is available that a correspondingly high barrier has been set for alternatives to pool storage at reactors, based on comments by NRC staff on our 2003 paper and by my reading of (Dorman 2005). Thus, independent analysts may be the only vehicle for computing state-of-the-art consequences, if the NRC is reluctant to commission such calculations or require applicants to make them.

**Consequences of a release.** The first realistic study of the economic and land use consequences of

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<sup>5</sup> The approach I took for our 2003 report, when it came to dealing with terrorism, was to think of scenarios that a terrorist group might come up with using the technical means I thought would be reasonably available to them. Since at least one of those generic scenarios I came up with seemed plausible, I considered at the time, and still do, that we need to understand the consequences of spent-fuel-pool fires.

releases of long-lived radioactivity that tried to go beyond bounding calculations was published in 1996 (Chanin and Murfin 1996). This work appeared in the same year of publication of the relicensing GEIS (NUREG 1996), so would not likely have been considered in the GEIS. More recently, in 2003 and 2004, estimates of the long-term health consequences of releases from spent-fuel fires were published by our group of independent analysts, as noted above. Some NRC Commissioners have referred to staff analyses refuting our published results, but such analyses have never been made public, as far as I am aware. If the new staff analysis does exist, it was also prepared after the GEIS and so should be incorporated into the EIS for Pilgrim and Vermont Yankee. The staff analysis that has been published is sobering and only applies specifically to decommissioning (Collins and Hubbard 2001).

For this report, components of damage costs not previously considered at other sites have been included. For instance, new damage cost and latent cancer calculations have been made to extend the work by Beyea, Lyman, and von Hippel to areas contaminated by resuspension. Results from “wedge model” calculations (discussed below) have been used for this purpose. Loss of property value outside remediated areas have also been considered, again with reliance on the wedge model. Approximate correction has been made for wind-rose effects, something that was not done in (Beyea et al. 2004a). In addition, I have made cost and latent cancer estimates, assuming that the latest radiation mortality studies are used in the calculations. As for the standard components of damage calculations, I have scaled, interpolated or extrapolated from values computed for other sites as reported in (Beyea et al. 2004a). Since the MACCS2 model was run in the paper by Beyea, Lyman, and von Hippel, with the parameter values listed there, the results in this report on Pilgrim and Vermont Yankee are based on the MACCS2 model.

The models included in the MACCS2 code are based largely on methodologies originally developed for the 1975 Reactor Safety Study (NUREG 1975), as refined in the CRAC2 code (Kocher et al. 1987; Ritchie et al. 1984). See (Young and Chanin 1996). A simpler approach to consequence analysis (wedge model) was developed by an American Physical Society group that reviewed the Reactor Safety Study (APS 1975). The wedge-model provides quick estimates of consequences that usually gives similar results to more detailed models, such as MACCS2, provided one uses appropriate effective parameters. The wedge model may underestimate acute consequences in situations where changing weather classes dominates health effects, but that is not a major issue for releases of cesium-137, where the risk is from long-term exposure.

Details of the calculations made for this report are given in Appendix I. Tables with

quantitative results appear in a subsequent section. Reliance on output from the MACCS2 computer code or the wedge model to estimate consequences from releases of Cesium-137 in this report does not necessarily imply endorsement of the use of these methodologies in other contexts, nor endorsements of the parameter sets that applicants or others may use with them. All models have strengths and weaknesses that must not be forgotten by modelers. MACCS2 does not appear to have undergone extensive field validation (Young and Chanin 1997), but sensitivity studies have been undertaken (Helton et al. 1995; McKay and Beckman 1994), (Neymotin 1994) and a large number of expert elicitations have been carried out that provide uncertainty distribution for input parameters (Goossens et al. 1997; Harper et al. 1993; Little et al. 1997; USNRC 1995). The model has been used in a limited number of peer-reviewed publications. Edwin Lyman, who ran the MACCS2 code for (Beyea et al. 2004a) has probably the greatest number of peer-reviewed papers using MACCS2.

For late health effects, which are of interest in this report, the deposition velocity has been found to be a major parameter affecting MACCS results (Helton et al. 1995). Because the uncertainty distribution for deposition velocity is quite broad (USNRC 1995), the variance in the MACCS2 predictions for cancers (and damage costs) could be large. When possible, I prefer to rely on exposure models that have been tested against field data, such as those I have developed in recent years (Beyea et al.). However, by relying on results from MACCS2 in these proceedings with respect to consequences from releases of Cesium-137, I hope to avoid distracting debate over models.

In the next section, I present results of consequence calculations using standard cancer risk coefficients. In subsequent sections, I discuss major new studies on cancer risks from radiation that suggest the risk coefficients used in most versions of MACCS2 are way too low. I then present consequence calculations using higher cancer coefficients and discuss some of the implications for cost benefit analyses. Finally, I discuss some new developments in dispersion modeling at coastal sites. I suggest that the applicant at Pilgrim should undertake sensitivity studies using appropriate computer codes to see if this new knowledge of meteorology modifies cost-benefit computations.

### **Quantitative damage estimates for releases from Pilgrim and Vermont Yankee, assuming standard cancer risk coefficients:**

This section presents a subset of consequence estimates for hypothetical releases of Cesium-137 from spent-fuel pools at Pilgrim and Vermont Yankee. Estimates are presented for economic costs and latent cancers. Variance in the estimates are not considered for the contention phase. Details of the

estimates are given in the Table footnotes and in Appendix I. Political, psychological, and social impacts of hypothetical releases are not considered, although they could obviously be significant. For instance, there appears to exist a “radiation syndrome” that affects a subset of exposed populations, causing debilitating psychiatric symptoms (Vyner 1983). Psychological effects of radiation disasters are expected to be most serious for children (CEH 2003).

Releases of 10% and ~100% of the radiocesium in the spent-fuel pools at both Pilgrim and Vermont Yankee are considered. Results are presented in this section using the standard risk coefficients assumed in (Beyea et al. 2004a). Releases lower than 10% of the Cesium-137 inventory, even releases too low to justify remediation, could have costs associated with loss in property value in the range of 10 to 100 billion dollars.

The damage estimates shown in the Tables are much less than the GDP of the US, which is about 12 trillion per year. However, some of the numbers exceed the annual payment on the national debt, which is about 350 billion dollars per year, indicating that government borrowing to cover the damage payments from a spent-fuel-pool fire could represent a major perturbation on the economy. Thus, significant macroeconomic effects could be expected depending on the state of the economy at the time of any hypothetical release. The regional impacts would be expected to be the most serious. Estimating such effects are beyond the scope of this report.

The Tables include numbers in some cells to 3-significant figures. This does not imply any comparable level of accuracy.



**Table 1. Cost estimates for a release of 10% of spent-fuel pool inventory of radioactive Cesium-137 assuming no change in cancer risk coefficient (billions of dollars)**

Category	Pilgrim	Vermont Yankee	Comment
Direct costs <sup>a)</sup>	49	39	
Indirect administrative costs <sup>b)</sup>	49	39	
Loss in property values adjacent to treated areas <sup>c)</sup>	7-74	9-87	
Costs associated with cleanup or demolition of downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings. <sup>d)</sup>	??	??	Particularly important for Pilgrim, with its proximity to Boston
Total	> 105-171	> 87-165	

a) As estimated from computations with MACCS2 at comparable sites with the parameters given in (Beyea et al. 2004a). Reduction by 1/3<sup>rd</sup> to account for wind rose effects.

b) Based on Chanin and Murfin. "We believe . . . that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs." (Chanin and Murfin 1996), p. 6-3. The factor might not be as great in the current case, however, because of economies of scale. We assume that litigation costs offset any economies of scale.

c) Assumes 5% loss in property value for an area surrounding the plume that includes 1 to 10 times as many persons as are in the (0.24 radian) plume extending out to 250 miles (see Appendix I). A similar 5% loss in property value is assumed in the plume from 250-1000 miles. \$132,000 in property value assumed per capita (Beyea et al. 2004a). Although not included in this total for the contention phase, loss in property value upon sale by government of remediated property should be included here. MACCS2 assumes no such loss.

d) We have not attempted an estimate for this category in the contention phase.

**Table 2. Cost estimates for a release of ~100% of spent-fuel pool inventory of Cs-137 assuming no increase in cancer risk coefficient (billions of dollars)**

Category	Pilgrim	Vermont Yankee	Comment
Direct costs <sup>a)</sup>	163	173	
Indirect administrative costs <sup>b)</sup>	163	173	
Loss in property values adjacent to treated areas <sup>c)</sup>	16-162	17-172	
Costs associated with cleanup or demolition of downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings. <sup>d)</sup>	??	??	Particularly important for Pilgrim, with its proximity to Boston
<b>Total</b>	<b>&gt; 342-488</b>	<b>&gt; 364-518</b>	

a) As estimated from computations with MACCS2 at comparable sites with the parameters given in (Beyea et al. 2004a). Figures reduced by 1/3<sup>rd</sup> to account for wind rose effects.

b) Based on Chanin and Murfin. “We believe . . . that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs.” (Chanin and Murfin 1996), p. 6-3. The factor might not be as great in the current case, however, because of economies of scale. We assume that litigation costs offset the economies of scale.

c) Assumes 5% loss in property value for an area including 1 to 10 times as many persons as are in a 0.24 radian plume extending out to 700 miles (see text). A similar 5% loss in property value is assumed in the plume from 700-1000 miles. \$132,000 in property value assumed per capita (Beyea et al. 2004a). Although not included in this total for the contention phase, loss in property value upon sale by government of remediated property should be included here. MACCS2 assumes no such loss.

d) We have not attempted an estimate for this category in the contention phase.

Note that the latent cancer estimates in Table 3, below, are lower limits, because they only include the cancers from Cesium-137. This approximation ignores shorter isotopes in the fresh fuel in the pool, especially Cesium-134 (Benjamin 2003).

**Table 3. Estimates for latent cancers following releases from the spent-fuel pools at either Pilgrim or Vermont Yankee (assuming no increase in cancer risk number)**

Category	10% release	~100% release
Latent cancers in main plume path from residual contamination <sup>a)</sup>	1300	4000
Latent cancers from deposited resuspension <sup>b)</sup>	1300	4000
<b>Total</b>	<b>2,700</b>	<b>8,000</b>

a) Based on typical numbers for plants analyzed in (Beyea et al. 2004a). Figures reduced by 1/3<sup>rd</sup> to account for wind rose effects. Cancers in the direct plume are reduced by more than a factor of ten from decontamination and deconstruction.

b) Assumes 10% resuspension and redistribution of deposited Cesium-137 resulting from a) wind removal in the first few weeks, and b) remediation/demolition efforts over successive years. It is possible that even the resuspended Cesium would produce concentrations high enough to justify remediation, with a corresponding reduction in projected cancers. However, clean-up costs would be increased.

I have not been able to incorporate new understanding of the flow of air over and around the New England Coastline that has been achieved in recent years. Still, this new knowledge should be taken into account in EISs for coastal facilities. Releases from Pilgrim headed initially out to sea will remain tightly concentrated due to reduced turbulence until winds blow the puffs back over land (Zagar et al.), (Angevine et al. 2006). This can lead to hot spots of radioactivity in unexpected locations (Angevine et al. 2004). Dismissing radioactivity blowing out to sea is inappropriate. Reduction of turbulence on transport from Pilgrim across the water to Boston should also be studied. Although incorporating such meteorological understanding into a PSA or equivalent at Pilgrim would not be likely to make more than a factor of two difference in risk, the change could bring more SAMAs into play and would be significant in an absolute sense, when combined with the increase arising from incorporation of new values of radiation dose conversion coefficients (discussed below). The program

CALPUFF (Scire et al. 2000) has the capability to account for reduced turbulence over ocean water and could be used in sensitivity studies to see how important the phenomenon is at Pilgrim.

**New cancer risk coefficients** There have been increases in the value of the cancer risk assigned to low doses of radiation that should be taken into account in EISs. These increases have been steady since 1972,<sup>6</sup> which makes the original EISs out of date. In addition, there has been a marked increase in the value of the cancer mortality risk per unit of radiation at low doses (2-to-3 rem average) as a result of recent studies published on a) radiation workers (Cardis et al. 2005) and b) the Techa River cohort (Krestinina et al. 2005). Both studies give similar values for low dose, protracted exposure, namely about 1 cancer death per Sievert (100 rem).

*Worker study:* The average dose for the workers was 2-rem. The authors of this large, international study of radiation workers included major figures in the field of radiation studies. The authors state, “On the basis of these estimates, 1-2% of deaths from cancer among workers in this cohort may be attributable to radiation.” Although it can be misleading to interpret epidemiologic data in this way (Beyea and Greenland 1999), because it implies to non-experts a single-cause model of cancer, there is no doubt that a 1-2% increase in cancer mortality for a worker population is unusually high.

*Techa River Cohort:* The results for the Techa River cohort are equally striking, showing a strong linear effect down to a few rads. The average dose was 3 rads. The authors, who once again include major figures in the field of radiation studies, state: “It is estimated that about 2.5% of the solid cancer deaths...are associated with the radiation exposure.” As in the worker population, an increase in solid cancer deaths of 2.5% from a dose of 3 rads is extraordinarily high compared to past estimates.

Such high risk coefficients imply that background radiation itself must increase cancer mortality by 3-5%.<sup>7</sup> (It has long been known that background radon concentrations may well increase lung cancer rates by 10% or more (Lubin et al. 1995), (Darby et al. 2005).) Critics of studies like those by

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<sup>6</sup> For instance, there was a large increase in the risk coefficients estimated between the 1980 BEIR III report and the 1990 BEIR V report. See Table 4-4 of (National Research Council 1990), where the lifetime risk estimates increased by a factor of 4.6-19, depending on the risk model.

<sup>7</sup> Assuming 0.1 rem per year background, which ignores the “equivalent” dose to the lung from radon. It is more difficult to compare rates of lung cancer, because the interaction of smoking and radiation has been found to lie between a linear and relative model. Therefore, such interactions must be taken into account, before drawing conclusions about area-wide differences, or lack of differences, in lung cancer rates.

Cardis et al. and by Krestinina et al. argue that such big effects, if they were real, should show up in cancer statistics in places like Colorado, where background radiation is high, when compared to areas of the country where background radiation is lower. However, crude statistical analysis that does not adjust for covariates at an individual level is unlikely to be very reliable (Lubin 1998). Also, there is an issue of the confounding effect of hypoxia (Weinberg et al. 1987). Hypoxia also varies with altitude.

Because the average dose in these two new studies is so low and so close to background radiation dose, there is no way to escape the linear non-threshold model. Even were a hypothetical hormesis effect to lead to a minimum risk at background levels (5 rem lifetime dose), the risk has to rise again after another 2-3 rem dose, based on the studies by Cardis et al. and Krestinina et al.

Could the increased risk numbers be due to a systematic underestimate or underreporting of doses? Random errors in doses would tend, in most cases, to reduce the strength of associations (Carroll et al. 1998), (Thomas et al. 1993). On the other hand, if dose errors were not random, but were proportionately underestimated or proportionately underreported in the worker studies and the Techa River cohort, then the risk coefficients could be inflated. For this to happen in both studies would be a coincidence. And in the radiation worker study, the results for Hanford do not support the missing-dose hypothesis, even though we know the neutron doses were likely underreported at Hanford (CohenAssociates 2005). In fact, the cancer risk numbers at Hanford were lower than average, not higher (Cardis et al. 2005). Finally, should the Techa River cohort dose estimates be too low that would mean that modern dose reconstruction techniques are underestimating doses, suggesting that other modern dose estimation techniques, such as those used in MACCS2 (Chanin and Young 1997), the standard NRC consequence code, could well be too low. In that case, an upward adjustment of doses would be required, if the risk coefficients were kept the same. Certainly, from a public health point of view, the arguments are strong for making use of the new risk coefficients, one way or another, with programs like MACCS2 and other consequence codes.

Recent press reports around the anniversary of the Chernobyl accident seemed to suggest that effects of radiation doses were lower than expected. Not at all. The “new” estimates of 4,000 projected fatalities were merely a re-interpretation of a study from the 1990s. No longer were 5,000 projected cancers outside the most highly contaminated regions counted. Also, another 7,000 cancers projected to occur in Europe were not noted by the press (Cardis et al. 2006). A summary of all of these estimates can be found in (Cardis et al. 2006). Were the new risk coefficients discussed earlier applied to the population dose estimates, the projected numbers of fatalities from the Chernobyl releases would

climb much higher.

The confusion over the Chernobyl numbers appears to be traceable to a typo in a highly publicized IAEA report (Forum 2005) that relied on a WHO report for its cancer numbers (WHO 2005). The WHO report stated that the “Expert Group” concluded that there may be up to 4 000 additional cancer deaths among the three *highest* exposed groups over their lifetime (emphasis added). This was translated in the IAEA report to, “The total number of people that could have died or could die in the future due to Chornobyl originated exposure over the lifetime of emergency workers and residents of *most* contaminated areas is estimated to be around 4 000.” (Emphasis added.) In fact, in my view, the last clause should have referred to “residents of *the* most contaminated areas...”<sup>8</sup>

Impact of new cancer risks. As a result of these two radiation studies, all probabilistic safety analyses prepared prior to them need to be revisited. These new studies should change the threshold for adoption of severe accident mitigation alternatives (SAMA). For instance, the current Environmental Report for Pilgrim assigns a value of \$2,000 per person rem in deciding whether a proposed SAMA is cost effective. According to the results of the study by Cardis et al., \$2,000 per rem implies a valuation of \$200,000 per cancer death before discounting, which is way to low.<sup>9</sup> The same low valuation of life would arise from use of the risk numbers derived from the Techa River cohort (Krestinina et al. 2005). As a result, the SAMA analyses prepared for the Pilgrim and Vermont Yankee facilities need to be redone, even without inclusion of spent-fuel-pool fires as a risk to be addressed. Presumably, a number of additional SAMAs that were previously rejected by the applicant's methodology will now become cost effective. In addition to affecting the existing SAMA calculations, the new cancer risk coefficients make the consideration in an EIS of mitigation measures for spent-fuel-pool fires especially important.

In addition to providing motivation for a reanalysis of past PSAs and SAMA thresholds, the results of these new epidemiologic studies throw into doubt the entire basis of the NRC culture, which maintains that the linear non-threshold theory (LNT) is conservative, providing a margin of safety. Although it has always been known that the dose-response at doses below the 25-rad average dose of the Atomic Bomb survivors could be supralinear, as opposed to sublinear, the possibility has not been

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8 Note that the IAEA stands by its original wording, not accepting it as a typo. Personal Communication, 2006, D. Kinley, IAEA public information, Vienna.

9 \$50,000 net present value for a cancer death occurring 20 years from now, based on the 7% per year discount rate assumed in the Pilgrim Environmental Report, which leads to a factor of 4 reduction in present value for a cancer induced 20 years from now.

given much attention in the radiation protection community until now.<sup>10</sup> This is not the time for *pro forma* treatment of licensing applications. Whereas it would be unreasonable to require an applicant to redo analysis after every new paper is published in the scientific literature, the increase at low doses is very dramatic in this case. It represents a 5-fold increase over the risk estimated in BEIR VII (NRC 2005). Based on information in (Little 1998), it appears to represent a factor of 10 over the standard value used in the MACCS2 computer code, which is the code on which the applicants' analyses are based. With such a high reported increase, public health considerations have to take precedence over applicant convenience. The paper by Cardis et al., at the very minimum, demands that a thorough analysis be made of mitigation and alternatives to spent-fuel pool storage.

For example, application of the new risk coefficients would drive the risk of spent-fuel-pool accidents during decommissioning (without even considering terrorist threats) above the NRC's safety goal. See Figures ES-1, ES-2 of (Collins and Hubbard 2001).

### **Quantitative damage estimates for releases from Pilgrim and Vermont Yankee, assuming cancer risk coefficients are increased to accommodate the new epidemiologic studies:**

This section presents a subset of consequence estimates for hypothetical releases of Cesium-137 from spent-fuel pools at Pilgrim and Vermont Yankee, assuming a 3-fold increase in cancer risk coefficients to conservatively account for the latest studies on radiation risk at low dose. To account for some weighting of other studies, I have chosen a value lower than the factor of 5-to-10 increase that is suggested by the study of (Cardis et al. 2005).<sup>11</sup>

As with earlier Tables, estimates are presented for economic costs and latent cancers. Variance in the estimates are not considered for the contention phase. See the Table footnotes and Appendix I for details. Political, psychological, and social impacts of hypothetical releases are not considered, although they could obviously be significant. As stated earlier, there appears to exist a “radiation syndrome” that affects a subset of exposed populations, causing debilitating psychiatric symptoms (Vyner 1983). Psychological effects of radiation disasters are expected to be most serious for children (CEH 2003).

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<sup>10</sup> There has been some discussion, however, that the A-Bomb survivor data produces low risk coefficients due to a healthy survivor effect (Stewart and Kneale 1993; Stewart and Kneale 1999). In addition, I have always wondered about the lowest dose data in Pierce, which seems to show a supralinear effect below 5 rem (Pierce et al. 1996), page 9.

<sup>11</sup> Part of the factor of 5 comes from the use of a dose and dose rate effectiveness factor, which is commonly used with the MACCS2 code, as in (Beyea et al. 2004a).

Once again, releases lower than 10% of the Cesium-137 inventory, even releases too low to justify remediation, could have costs associated with loss in property value in the range of 10 to 100 billion dollars.

The damage estimates shown in the Tables are much less than the GDP of the US, which is about 12 trillion per year. However, some of the numbers are considerably larger than the annual payment on the national debt, which is about 350 billion dollars per year, indicating that government borrowing to cover the damage payments from a spent-fuel-pool fire could represent a major perturbation on the economy. Thus, once again, significant macroeconomic effects could be expected depending on the state of the economy at the time of any hypothetical release. The regional impacts would be expected to be the most serious. Estimating such effects are beyond the scope of this report.

The Tables include numbers in some cells to 3-significant figures. This does not imply any comparable level of accuracy.



**Table 4. Cost estimates for a release of 10% of spent-fuel-pool inventory of Cs-137 assuming 3-fold increase in cancer risk coefficient (billions of dollars)**

Category	Pilgrim	Vermont Yankee	Comment
Direct costs <sup>a)</sup>	89	79	
Indirect administrative costs <sup>b)</sup>	89	79	
Loss in property values adjacent to treated areas <sup>c)</sup>	> 7-74	> 9-87	
Costs associated with cleanup or demolition of downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings. <sup>d)</sup>	??	??	Particularly important for Pilgrim, with its proximity to Boston
<b>Total</b>	<b>&gt; 186-253</b>	<b>&gt; 167-245</b>	

a) As estimated from computations with MACCS2 at comparable sites with the parameters given in (Beyea et al. 2004a). An increase in the cancer risk numbers is mathematically equivalent to an increase in release magnitude, which is how the numbers in the Table were computed. Figures reduced by 1/3<sup>rd</sup> to account for wind rose effects.

b) Based on Chanin and Murfin. “We believe . . . that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs.” (Chanin and Murfin 1996), p. 6-3. The factor might not be as great in the current case, however, because of economies of scale. We assume that litigation costs offset the economies of scale.

c) Assumed to be at least as great as the figures calculated in Table 1, where the cancer risk coefficient was left unchanged. Although not included in this total for the contention phase, loss in property value upon sale by government of remediated property should be included here. MACCS2 assumes no such loss.

d) We have not attempted an estimate for this category in the contention phase.

**Table 5. Cost estimates for a release of ~100% of spent-fuel-pool inventory of Cs-137 assuming a three-fold increase in cancer risk coefficient (billions of dollars)**

Category	Pilgrim	Vermont Yankee	Comment
Direct costs <sup>a)</sup>	283	353	
Indirect administrative costs <sup>b)</sup>	283	353	
Loss in property values adjacent to treated areas <sup>c)</sup>	16-162	17-172	
Costs associated with cleanup or demolition of downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings <sup>d)</sup>	??	??	Particularly important for Pilgrim, with its proximity to Boston
Costs due to delays in implementing remediation and deconstruction <sup>d)</sup>	??	???	
Total	> 582-728	> 723-878	

a) As estimated from computations with MACCS2 at comparable sites with the parameters given in (Beyea et al. 2004a). An increase in the cancer risk numbers is mathematically equivalent to an increase in release magnitude, which is how the numbers in the Table were computed. Figures reduced by 1/3<sup>rd</sup> to account for wind rose effects.

b) Based on Chanin and Murfin. “We believe . . . that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs.” (Chanin and Murfin 1996), p. 6-3. The factor might not be as great in the current case, however, because of economies of scale. We assume that litigation costs offset the economies of scale.

c) Assumed to be at least as great as the figures calculated in Table 2, where the cancer risk coefficient was left unchanged. Although not included in this total for the contention phase, loss in property value upon sale by government of remediated property should be included here. MACCS2 assumes no such loss.

d) We have not attempted an estimate for this category in the contention phase.

Note that the latent cancer estimates in Table 6, below, are lower limits, because they only include the cancers from Cesium-137. This approximation ignores shorter isotopes in the fresh fuel in the pool, especially Cesium-134 (Benjamin 2003).

**Table 6. Estimates for latent cancers following releases from the spent-fuel pools at either Pilgrim or Vermont Yankee (assuming a 3-fold increase in cancer risk number)**

Category	10% release	~100% release
Latent cancers in main plume path from residual contamination <sup>a)</sup>	4,000	12,000
Latent cancers from deposited resuspension <sup>b)</sup>	4,000	12,000
<b>Total</b>	<b>8,000</b>	<b>24,000</b>

a) Based on typical numbers for plants analyzed in (Beyea et al. 2004a) multiplied by a factor of 3. Figures reduced by 1/3<sup>rd</sup> to account for wind rose effects. Cancers in the direct plume are reduced by more than a factor of ten from decontamination and deconstruction.

b) Assumes 10% resuspension and redistribution of deposited Cesium-137 resulting from a) wind removal in the first few weeks, and b) remediation/deconstruction efforts over successive years. It is possible that even the resuspended Cesium would produce concentrations high enough to justify remediation, with a corresponding reduction in projected cancers. However, clean-up costs would be increased.

**Regulatory implications.** The results in Tables 1-6, along with the discussion in the text suggest that: The applicant should withdraw and revise its Environmental Reports for Pilgrim and Vermont Yankee. The NRC should prepare supplements to the August 1979 Generic Environmental Impact Statement on handling and storage of spent fuel (NUREG-0575), and the May 1996 GEIS on license renewal (NUREG-1437). The revised documents should consider the new cancer risk coefficients published by Cardis et al. and Kristinina et al. For both reactor accidents and spent-fuel-pool fires, when relevant, the documents should consider loss of property value outside remediated areas. They should consider wind-driven resuspension, especially from remediation activities, that carries radioactivity to new areas in the immediate weeks and years following the release. Although MACCS2 does not directly account

for such refinements, it may be possible to mimic their effects in the program.<sup>12</sup> In their economic calculations, the revised documents should include administrative and litigation costs associated with clean up and demolition. The ER for Pilgrim should consider the reduced turbulence over ocean water, including transport directly over water to the Boston area. The NUREG supplements should consider the impacts of coastal meteorology for reactors on the East and West Coasts. The program CALPUFF can be used to deal with dispersion over coastal waters.

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<sup>12</sup> This might be done by adding on extra plume segments to the end of a standard run, with varying delay times, and a total added release equal to the assumed resuspension fraction times the initial release. This will tend to produce the mathematical equivalent of resuspended material being carried in directions different from the main plume.

## Appendix I.

Variance in estimates are not considered in this report for the contention phase.

Based on the report of Gordon Thompson, the inventories at Pilgrim and Vermont Yankee are somewhat higher than the 35 MCi considered in (Beyea et al. 2004a). For Pilgrim, Dr. Thompson estimates 44 MCi; for Vermont Yankee, 39 MCi.

Thompson has also estimated a hotter heat rate for releases at Pilgrim and Vermont Yankee than was assumed in the calculations in (Beyea et al. 2004a). 106-128 MW vs 40 MW. Plume rise varies as the  $1/3^{\text{rd}}$  power of the heat rate in the standard “Briggs” formula for plume rise (Parks 1997), which implies a 50% greater rise than would have been calculated in the MACCS2 program that was used in the paper by Beyea, Lyman and von Hippel. For the contention phase of these proceedings, this difference has been ignored, since a 50% increase in plume rise is within 1-standard deviation of the value predicted by the formula (Irwin and Hanna 2004).

Rather than make new MACCS2 calculations for the contention phase of these proceedings, the azimuthally-averaged radial population distributions for both Pilgrim and Vermont Yankee have been compared as a function of distance with those for which economic and latent cancer consequences have been calculated in (Beyea et al. 2004a). It is the radial population numbers that drive the economic damage costs and cancer numbers. Figures 1 and 2 show the azimuthally-averaged radial population distributions for Pilgrim and Vermont Yankee for two different maximum distances. The CensusCD computer program (Geolytics 2002) was used to generate these population distributions. The same program was used in (Beyea et al. 2004a) for the five reactors, Catawba, Indian Point, LaSalle, Palo Verde, and TMI.

The effect of variation in wind direction at Pilgrim is to reduce the average damages and latent fatalities. Wind rose data taken from the Pilgrim FSAR shown in Figure 5 for the 300 foot tower suggest a reduction factor of 0.666 for that facility. See caption for Figure 5. I did not find similar data for a high tower in the FSAR for Vermont Yankee, so I have used the 0.666 factor determined for Pilgrim. Wind flows at the surface given in the Vermont Yankee FSAR are not particularly relevant to a hot release during a fire, since the plume will be elevated. The variance with angle appears to be quite large, because the population figures change with release angle, as shown in Figures 3 and 4.

For economic damages from the 10% releases, we are interested in populations out to 250 miles

(based on wedge model calculations). For the ~100% releases, the corresponding distance is 700 miles. The Pilgrim population figures best match Catawba out to 250 miles. For Vermont Yankee the population figures best match Lasalle out to 250 miles. Out to 700 miles, both Pilgrim and Vermont Yankee are most similar to Lasalle, although I discount the Lasalle cost figures to account for the lower population values of Pilgrim and Vermont Yankee.

Table 7, shows the relevant costs extracted from Table 3 of (Beyea et al. 2004a) and adjusted as indicated in the Table footnotes. These numbers were then fit to a power law function of release magnitude. The corresponding functions were used to generate costs estimates for the Pilgrim and Vermont Yankee releases estimated by Thompson, which differ somewhat from the releases assumed for a spent-fuel fire in (Beyea et al. 2004a).

<i>Table 7. Assigning damage cost estimates in billions of dollars based on Table 3 of (Beyea et al. 2004a)</i>		
Release magnitude	Pilgrim	Vermont Yankee
3.5 MCi	71 <sup>a)</sup>	54 <sup>b)</sup>
35 MCi	219 <sup>c)</sup>	243 <sup>d)</sup>
a) Cost figure for Catawba for a 3.5 MCi release. b) Cost figure for Lasalle for a 3.5 MCi release. c) Cost figure for Lasalle for a 35 MCi release reduced by 20% d) Cost figure for Lasalle for a 35 MCi release reduced by 10%		

Extrapolated and interpolated direct damage costs for Pilgrim and Vermont Yankee were computed from the following formulas:

Pilgrim:  $\text{Damages} = 0.66 * 35 * (\text{release in MCi})^{0.5}$

Vermont Yankee:  $\text{Damages} = 0.66 * 24 * (\text{release in MCi})^{0.65}$

The factor of 0.66 comes from wind-rose effects.

Administrative costs are taken equal to direct costs, following the suggestion of (Chanin and Murfin 1996). Property loss estimates are discussed below.

Estimates of losses in property value. It is assumed that an area exists around the “main portion” of the plume, where potential property buyers would be concerned about residual risk. (The main portion of the plume is defined as the area where remediation or demolition takes place.) Outside the main plume, contamination would still be measurable. Lack of trust in statements by government would translate into loss in property values. All things being equal, persons would wish to live as far away from contaminated areas as possible.

Note that radioactive deposition would extend into these non-remediated areas, both from the immediate release and from resuspension in the weeks and years after the release and from subsequent demolition and remediation efforts. People would be accumulating long-term radiation doses, which government sources would say are too trivial to worry about. Expert opinion would differ on the seriousness of the long-term exposures. Confidence in government would likely drop over time based on revelations of government failings. If past patterns are followed, government leaders would early on feel compelled to downplay the true situation to prevent panic. Although it is hard to see how they could act otherwise, it is also hard to see how citizens enthusiasm for purchasing property in the vicinity of the main plume would not be weakened.

How much would property values decline? Based on expert reports filed in litigation concerning the Rocky Flats nuclear weapons facility, and the jury decision favorable to plaintiffs in that litigation (2006), I assume a 5% loss in property value for property lying within measurable contours of contamination. This is quite conservative, since the jury accepted Plaintiffs' expert assessment that residential values dropped by 7%,<sup>13</sup> vacant land by 30%, and commercial land by 53%. For the calculations in this report, I define the main, remediated plume as a 0.24 wedge extending out to 250 miles for the 10% release and 700 miles for the ~100% release.

Areas where property damage loss is assumed to take place extends outward from the plume to 1000 miles, which is where the damage calculations stop in (Beyea et al. 2004a). In addition, property in areas to the side of the plume are also expected to suffer a 5% loss in value. Because I have no firm basis for determining the distance to which property loss would extend, I have picked a ten-fold range. At the low end, as many people outside the main plume are assume to be affected as live in the main plume. At the high end, I pick ten times as many persons.

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13 The "residential" figure appears to be some sort of compromise. It's within a range reported by expert Radke's year-by-year multiple regressions for 1988-95, but it's less than the 10% that expert Hunsperger ultimately estimated. Personal communication, 2006, Peter Nordberg, Berger and Montague.

MACCS2 accounts for inhalation of resuspended material at the location where radioactivity is deposited (Chanin et al. 2004), Section 2, page 6-14. However, MACCS2 does not allow for redistribution of resuspended material to new locations. Yet, 10% of radioactivity deposited on vegetation may be blown off in the first few weeks,<sup>14</sup> with additional resuspension over decades,<sup>15</sup> increased dramatically by anthropogenic activity during clean up and remediation (Schershakov 1997). I adopt a net resuspension factor for Cesium-137 of 10% over the long term, which should be a conservative choice in this context.<sup>16</sup> To account for the latent cancers that would be caused by this redistribution of radioactivity, I have made the approximation that no such re-deposited material would be high enough to generate remediation. (If this assumption is violated, the number of latent cancers from redistributed radioactivity would go down, but it would then be necessary to increase clean-up costs.)

Based on wedge model calculations, I know that remediation reduces latent cancers by a factor of 10 or more. Thus, the contribution from redistributed radiation to total cancers, under the assumptions I have made, should be more than the direct contribution from the remediated plume (10% X 10 = 100%). A more precise calculation could be obtained by running MACCS2 in a special way, even though MACCS2 does not directly handle redistributed radioactivity. (MACCS2 only allows straight-line plume segments and does not allow wind trajectories (Chanin et al. 2004), Section 5, page 1-4.) However, MACCS2 does allow multiple straight-line segments with different starting times (Chanin et al. 2004), Section 2, page 6-14. If MACCS2 was run with extra plume segments added on to the end of a standard release sequence, with varying delay times, and a total added release equal to

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<sup>14</sup> (NUREG 1975), Appendix VI. Radioiodine after weapons fallout shows very rapid decline over periods of days, some of which must be due to wind action (NCI 1997), Table 4.8. The half-life for small particles is longer, about 14 days (Prohl et al. 1995). Resuspension *factors* in the early days after the Chernobyl accident have shown very high values, including  $2.4 \times 10^{-4} \text{ m}^{-1}$  at one day after deposition (Schershakov 1997). Such a high rate could not be maintained without completely exhausting the surface concentration in a very short time. The resuspension factor has been estimated to drop as an inverse power of time in days, with an exponent of 0.5-to-1.67 (Schershakov 1997). At issue is the size of the resuspended material, because some radioactivity might deposit on relatively large particles on vegetation that are easily removed by wind.

<sup>15</sup> Resuspension *rates* measured for Chernobyl radiocesium are also high ( $1 \times 10^{-8} \text{ s}^{-1}$ ) (Schershakov 1997). When such a high uplift rate is totaled for periods of years, a 10% net loss is quite reasonable, although resuspension rates were measured to decrease by an order of magnitude over time (Schershakov 1997). Studies by my colleagues and I have indicated that underground material is brought to the surface by animal burrowing (Morrison et al. 1997; Smallwood et al. 1998), where it is subject to wind resuspension. Thus, movement into the soil of radiocesium does not keep it away from the surface forever. Smallwood has estimated from his measurements in California and Colorado that about 0.5 % of underground radioactivity should be brought to the surface each year by animal burrowing, including ant burrowing (Smallwood, personal communication, 1998). How relevant this number is to the East Coast is not known.

<sup>16</sup> Because of lack of data on particle sizes, analysts may differ as to how much resuspended material would be in particle sizes large enough to travel outside the main plume before remediation. However, most land area would not be remediated. In any case, it will be important for the field of contamination consequence analysis to have debates on this subject.



the assumed resuspension fraction times the initial release, then MACCS2 will produce as output the mathematical equivalent of resuspended material being carried in directions different from the main plume.

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Figure 1.

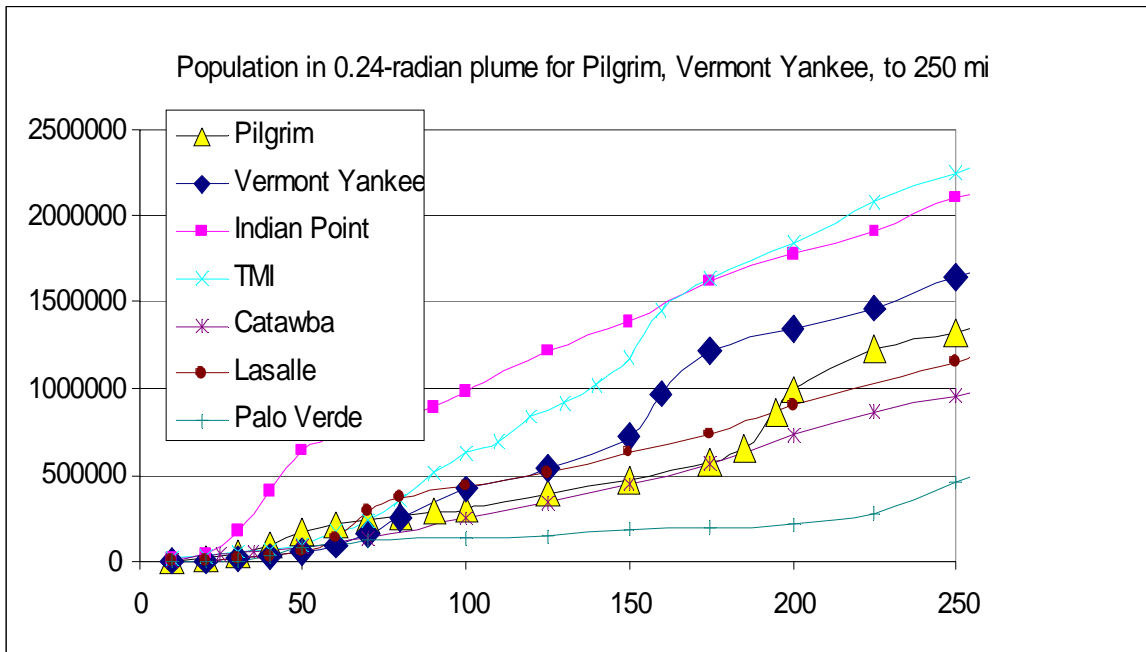


Figure 2.

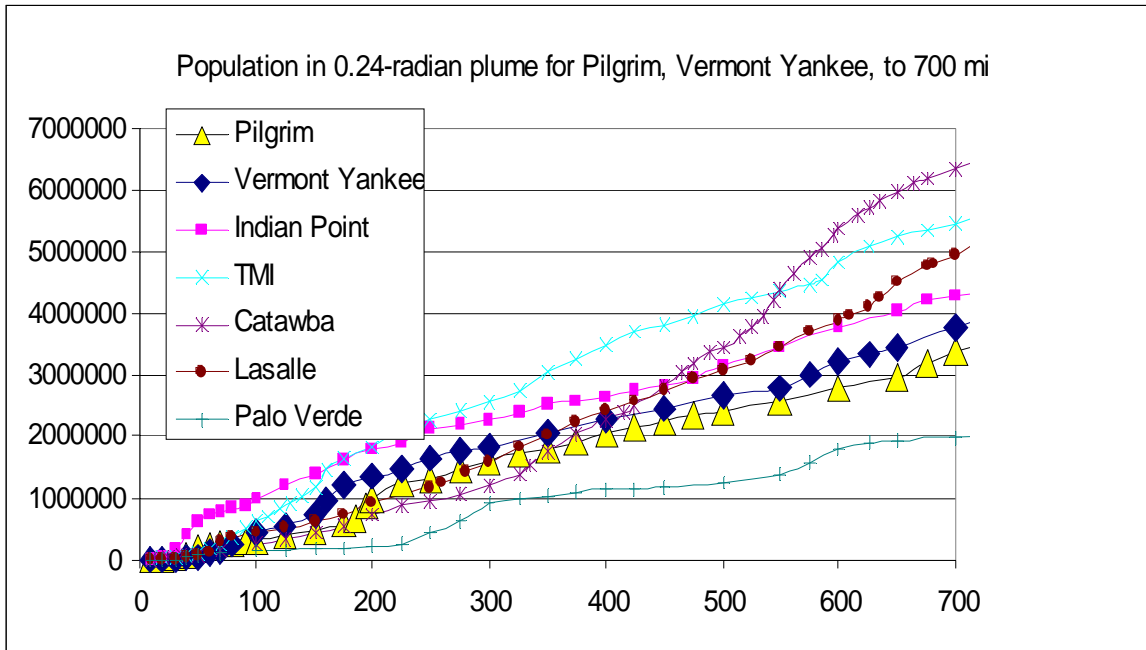


Figure 3. Calculated with the SECPOP 2000 computer code (Bixler et al. 2003).

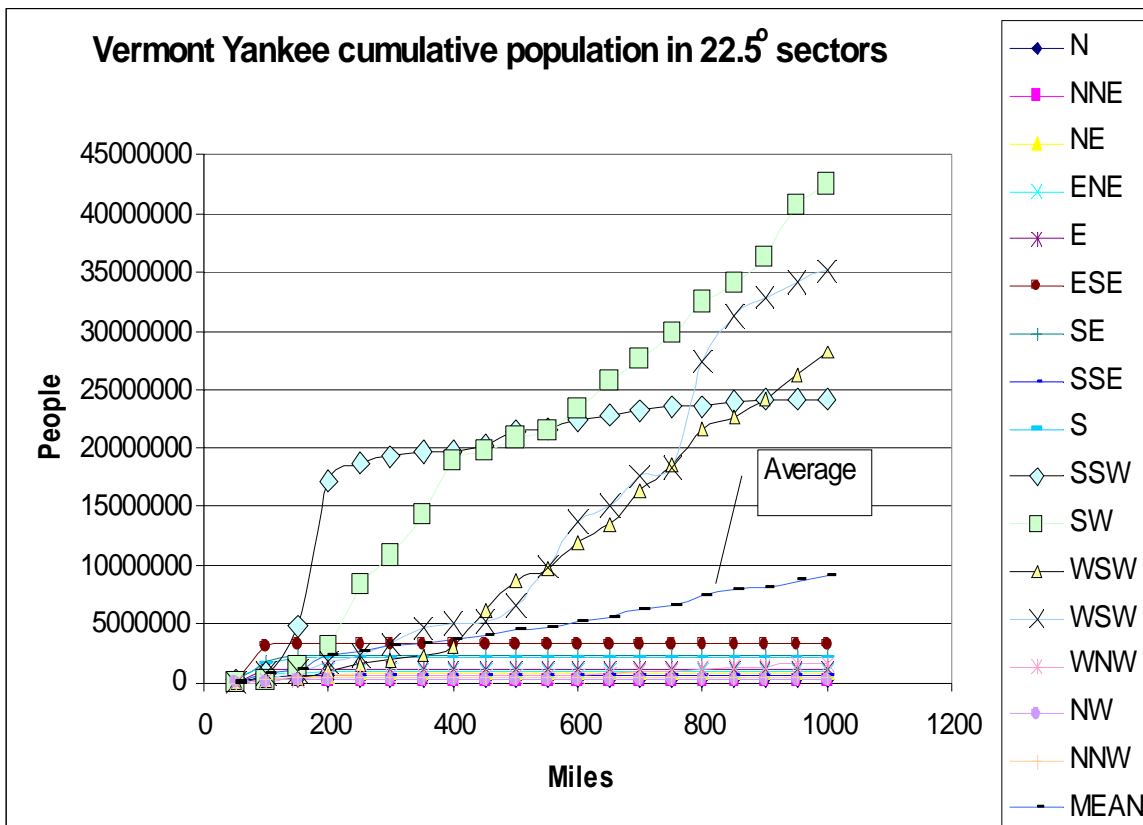




Figure 4. Calculated with the SECPOP 2000 computer code (Bixler et al. 2003).

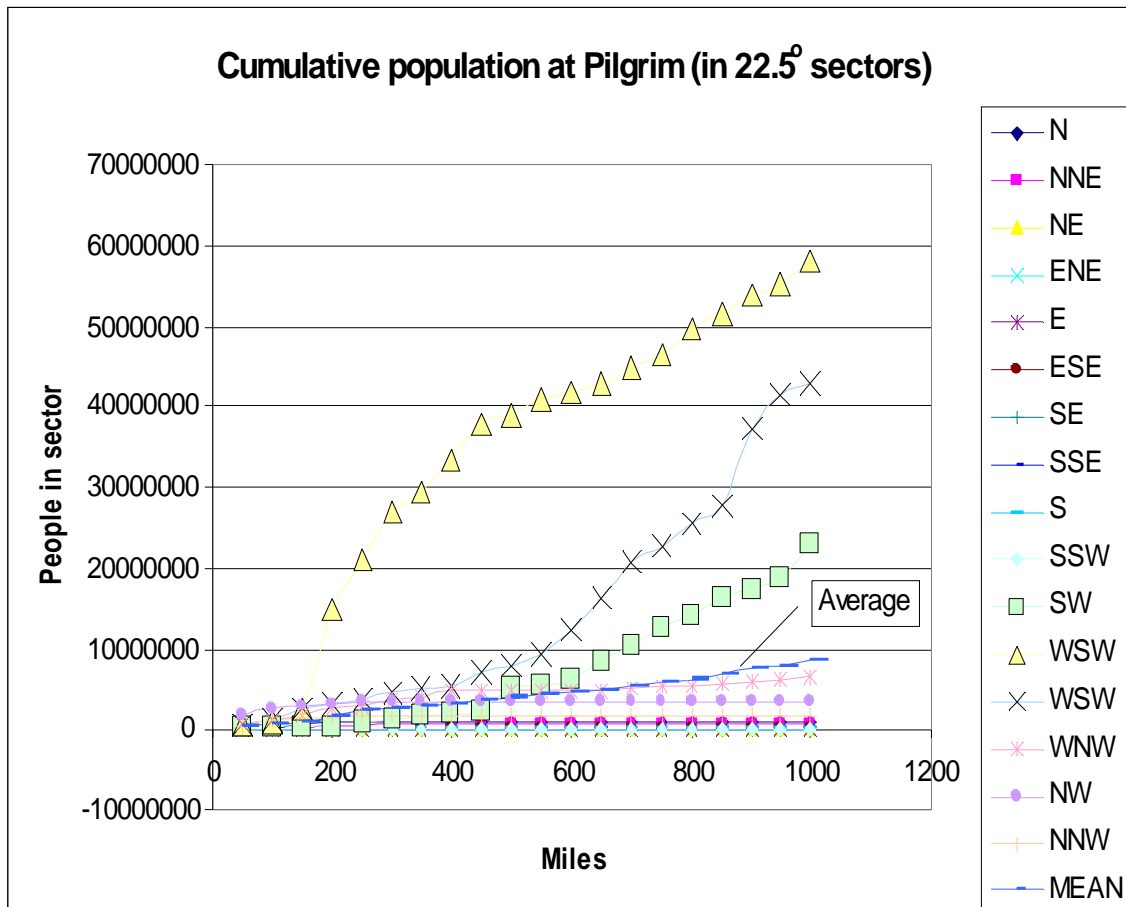


Figure 5: In the wind rose below for Pilgrim, an excess frequency beyond the 4% circle is shown for winds coming from the Southwest, which would blow out over the ocean. Ignoring return flows, such excess flows would not contribute to damage. The excess beyond the 4% circles is about 33% of the total year. Removing this excess leaves a roughly axially-symmetric flow, which matches the assumptions used in the paper by Beyea, Lyman, and von Hippel.

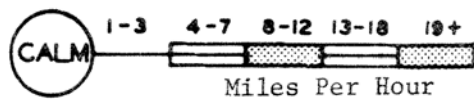
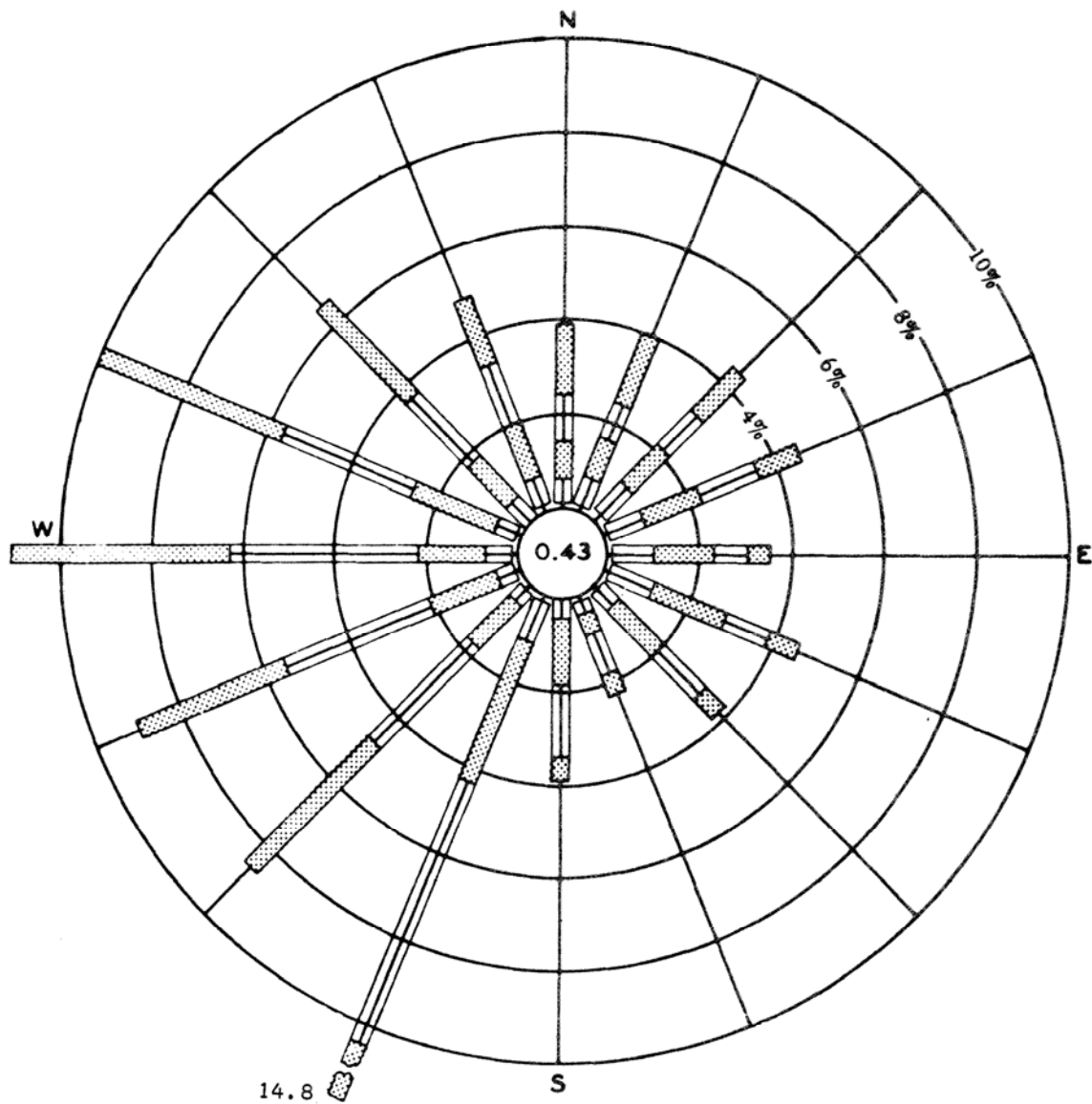


FIGURE 2.3-6  
 ELEVATION 300 FT. MSL  
 WIND ROSE ANNUAL  
 PILGRIM SITE  
 PILGRIM NUCLEAR POWER STATION  
 FINAL SAFETY ANALYSIS REPORT