Radiological Substance Release

Accidental conditions where reactor core damage causes release of radiation. This event does not include releases caused by malicious acts.

Data Summary

In the following table, note that the low and high likelihoods do not correspond to the low and high impacts. In addition, low and high impacts are not necessarily correlated with each other between different impact categories.

Category	Description	Metric	Low	Best	High
Health and Safety	Fatalities[1]	Number of Fatalities	0[2]	230[3]	2200[4]
	Injuries and Illnesses[5]	Number of Injuries or Illnesses	0[2]	240[3]	2300[4]
Economic	Direct Economic Loss	U.S. Dollars (2011)	$7.5B[6]	$8.6B[3]	$16B[4]
	Indirect Economic Loss	U.S. Dollars (2011)	$9.4B[6]	$11B[3]	$23B[4,7]
Social	Social Displacement[8]	People Displaced from Home ≥ 2 Days	76,000	147,000	500,000
Psychological	Psychological Distress	Qualitative Bins	See text		
Environmental	Environmental Impact	Qualitative Bins[9]	Moderate[10]		
LIKELIHOOD	Frequency of Events	Number of Events per Year	6 e-3[11]	9 e-3[3]	1 e-2[12]

[1] Latent cancer fatalities: deaths resulting from cancer that became active after a latent period following exposure to radiation.
[2] The case with zero fatalities is drawn from the Three Mile Island core meltdown (Perham, 1980). A value of 58 fatalities and 61 illnesses would result from the most frequent, lowest impact scenarios that were outlined in each of the license renewal reports. Despite choosing the lowest impact events outlined in the report, some reports only contained somewhat rare, medium impact events, raising the overall expected fatalities. Therefore, the use of the Three Mile Island accident was selected as a more representative example of the most likely results of core damage accident.
[3] The Best estimates use a simulation of the expected core damage frequencies obtained from the license renewal applications for a number of individual reactors available from the public website of the Nuclear Regulatory Commission (United States Nuclear Regulatory Commission). The data from the license renewal applications is used to perform cost/benefit analyses on reactor upgrades and the baseline data was not developed for use in a general risk assessment. Currently, this is the most recent publicly available data and adequate for order of magnitude estimates of the SNRA. An alternative analysis was also conducted using fatality, injury, and core damage frequency data from NUREG-1150, and the best estimates from this analysis were within the same order of magnitude as the results obtained using data from license renewal applications (United States Nuclear Regulatory Commission, 1990). The expected impacts are weighted by the likelihood of a core damage accident for each reactor using a Crystal Ball simulation. The details are explained in the Additional Relevant Information section.
[4] The High impact estimates also come from the license renewal applications (United States Nuclear Regulatory Commission). The impacts correspond to the highest impact scenarios outlined in the report. These usually involve a large, early release and assume that there is not enough time for successful evacuation. The frequency of these events is typically one to two orders of magnitude less than the frequency of any core damage event. Note that the likelihood values in the table do not correspond to the impacts for the High and Low categories.
[5] Latent cancer morbidities.
[6] The Low values of economic damage are determined from the results of the most frequent types of core damage accidents in each report as discussed in Footnote 2. The economic costs are mostly fixed values associated with business interruption and are consistent with the $1B in decontamination costs from the shutdown of Reactor 2 at Three Mile Island (*New York Times*, 1993). The replacement power costs assumed in the model should be applicable here.
[7] The current cost estimates for the Fukushima disaster are in the hundreds of billions of dollars. This includes the damage directly from the earthquake and the tsunami as well as the nuclear power plant disaster (Japanese Ministry of Economy, Trade, and Industry).
[8] The low and best estimates reflect published estimates of displacement from the Three Mile Island incident. The high estimate reflects published estimates of displacement from the Chernobyl incident (see text).
[9] The United States Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event. The comments and rankings presented in this Risk Summary Sheet have not undergone review by the EPA and only represent the opinions of the group.

Event Background

An accidental radiological release could come from a nuclear power plant accident or public exposure to lost or stolen radioactive sources. Most recorded exposure deaths and illnesses involve patients in medical accidents, workers and scientists working with radiological materials, or releases for criminal purposes (Johnston's Archive, 2010; Mohtadi, 2006; Streeper, Lombardi, & Cantrell, 2008). There have been a few accidental releases of lost material worldwide, but the documented exposures of this type are small and less likely to happen in the United States considering the standards regulating the maintenance and transport of radioactive material. Given the consequences of a large, radiological release from a power plant, this analysis focuses on nuclear power plant accidents.

A national-level power plant accident is defined in this scenario as any accident which damages the reactor core. The risk to the public and environment based on this type of accident is highly dependent on radiation containment and the location of the reactor. Accidents causing a radiological release from spent fuel are not considered in this summary sheet as their fatality and illness risk has been calculated to be more than an order of magnitude less than that of a core damage accident (United States Nuclear Regulatory Commission (T.E. Collins, G. Hubbard), 2001).

Assumptions

Fatalities and Illnesses/Injuries

Health and safety impacts were estimated based on the following assumptions:

- The fatalities and illnesses involved in a nuclear reactor accident are latent cancer fatalities and illnesses, determined as an increase over expected background illnesses and fatalities in an unexposed population. These would occur over the lifetimes of the exposed population with no expected deaths immediately after exposure.
- The fatalities and cancer illnesses were calculated from the dose consequence information in the license renewal applications available on the website of the Nuclear Regulatory Commission (United States Nuclear Regulatory Commission).
- The High and Low impact values use the largest impact release events and lowest impact events available in each report. Some reactors do not report the most likely scenarios, which make the Low impact values higher than would be expected for the most likely scenario. The most probable low impact scenario would be quite similar to the accident at Three Mile Island in 1979 in which it was determined that the radiological release would not raise the exposure of the population enough to cause an additional case of cancer above the expected background (Perham, 1980).

Estimates pertain to the potential for adverse effects on living organisms associated with pollution of the environment; they are grouped into high, moderate, low, and de minimus (none) categories.

[10] Experts provided both first and second choice categories, allowing the experts to express uncertainty in their judgments as well as reflect the range of potential effects that might result depending on the specifics of the event.

[11] This number is the 5th percentile of the core damage frequencies taking into account variability across the different reactors and the uncertainty of a single reactor. Note that this frequency incorporates the uncertainty and variability of the expectation and does not directly correspond to the Low impact values.

[12] This number is the 95th percentile of the core damage frequencies taking into account variability across the different reactors and the uncertainty of a single reactor. This does not correspond to the High impact values which have likelihoods one to two orders of magnitude lower than the Best CDF value.

- All of the impact estimates assume that the accident is confined to a single reactor. Damage to multiple reactors could cause higher impacts. Also, the impacts associated with external events could be greater than those for internal events (the basis for impacts in NRC models) due to potential difficulties in evacuation.

Economic Loss

Economic impacts were estimated based on the following assumptions:

- The costs associated with a nuclear power plant accident listed with the license renewal application at the website of the Nuclear Regulatory Commission (United States Nuclear Regulatory Commission) include the offsite costs associated with land remediation and business interruption for areas affected outside of the power plant, the direct costs of decontamination and disposal at the power plant site, and the cost to replace the power that would have been generated at the plant.
- The offsite costs vary depending on the size of the release. The cost of onsite decontamination and disposal as well as the cost of using a different power generator are assumed fixed.
- In determining the overall economic impacts for a radiological release incident, the SNRA project team used an approach to estimating direct, indirect, and induced economic losses. The definitions for direct, indirect, and induced costs are listed in Table 1 below:

Table 1. Definitions for Direct, Indirect, and Induced Costs

Direct Costs include: • **Decontamination, Disposal, and Physical Destruction:** DDP costs covered the repair, replacement and environmental clean-up which are considered expenditures by the government. It was assumed the government would recoup this spending through tax increases, causing a reduction of household spending of that same amount. However, this spending would be received as income by some sectors, such as waste management and environmental consulting services. The increase in spending into the waste management and environmental consulting services is treated as increase in annual output for these sectors. • **Business Interruption:** Business interruption impacts considered losses due to decreased output at the target area, along with other increases and decreases to related sectors due to behavioral changes resulting from the event. • **Loss in Spending from Fatalities:** This SNRA project team estimated a loss of spending of $42,500 for each fatality. In addition, $6,000 is included in increased output for mortuary services for each fatality. • **Medical Costs:** Costs of medical mitigation were considered to be borne through private spending and insurance companies, while the hospital sector received an offsetting increase in output.
Indirect Costs include: • Costs incurred by the suppliers and vendors in the associated expenditure sectors for the

industries impacted by the direct costs above.
Induced Costs include: • The induced costs are those incurred due to reduced spending by households with members employed in any of the directly or indirectly affected industries. Induced costs can also include substitution effects or likely transfers of economic activity from one set of sectors to another set, such as avoidance of air or other travel or altered transportation mode preferences to other sectors following an attack on the commercial air transport sector.

- In order to apply this model to the set of costs available, the offsite, disposal and decontamination, and alternate power generation costs must be binned into the above direct costs categories.
- Because the offsite costs are assumed to mostly be due to business interruption, they are placed in that category. The alternative power generation would also be a business interruption cost. Both of these values are several billion dollars and expected to contain the majority of business interruption costs from the accident.
- Onsite decontamination and disposal should be the primary area where this type of work would need to be conducted, so these costs are directly used for the decontamination, disposal, and physical destruction category.

Social Displacement

For the purposes of the SNRA, social displacement was defined as the number of people forced to leave home for a period of two days or longer. Note that there are limitations to this measure of social displacement, as the significant differences between temporary evacuations and permanent displacement due to property destruction are not captured.

- For the accidental Radiological Substance Release event, the low and best estimates reflect published estimates of displacement from the Three Mile Island incident. This displacement represented voluntary evacuation by individuals and families rather than a mandatory evacuation order: the SNRA's social displacement metric counts all people displaced from homes for two or more days, whether the displacement was directed or not.[13] The high estimate reflects published estimates of displacement from the Chernobyl incident.[14]

Psychological Distress

Psychological impacts for the SNRA focus on *significant distress* and *prolonged distress*, which can encompass a variety of outcomes serious enough to impair daily role functioning and quality of life. An index for significant distress was created that reflected empirical findings that the scope and severity of an event is more important than the type of event. The equation for this index uses the fatalities, injuries, and displacement associated with an event as primary inputs; a factor elicited from subject matter experts weights the index for differing psychological impact

[13] Sources for the low and best estimates of displacement due to Accidental Radiological Substance Release are Cutter, Susan, and Kent Barnes. 1982. "Evacuation Behavior and Three Mile Island." *Disasters* 6.2: 116-124.; and Soffer, Yechiel, Dagan Schwartz, Avishay Goldberg, Maxim Henenfeld and Yaron Bar-Dayan. 2008. "Population Evacuations in Industrial Accidents: A Review of the Literature about Four Major Events." *Prehospital and Disaster Medicine* 23.3: 276-281.

[14] Soffer, Yechiel, Dagan Schwartz, Avishay Goldberg, Maxim Henenfeld and Yaron Bar-Dayan. 2008. "Population Evacuations in Industrial Accidents: A Review of the Literature about Four Major Events." *Prehospital and Disaster Medicine* 23.3: 276-281.

based on the type of event, but as a secondary input.[15] The numerical outputs of this index formula were used to assign events to bins of a risk matrix for a semi-quantitative analysis of psychological risk in the SNRA.

Environmental Impact

The United States Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event. Estimates are based on the following assumptions:

- Experts were elicited to provide estimates in the environmental impact category based on assumptions. Actual environmental/ecological harm that occurs as a result of the events described in a given scenario may vary considerably, and will depend on numerous variables (such as chemical or biological agent, contamination extent, persistence and toxicity—both chronic and acute toxicity—or infectivity).
- EPA defined environmental consequence (impact)[16] as the potential for adverse effects on living organisms associated with pollution of the environment by effluents, emissions, wastes, or accidental chemical releases; energy use; or the depletion of natural resources.
- Experts identified the best estimate for environmental impacts as “moderate.” Nuclear power plant disruption could cause radioactive airborne releases that could travel for large distances and settle into down-range eco-systems, with possible disruptions. In addition, releases into water bodies may have impacts on aquatic life.

Key Mitigating Factors

The impacts caused by a nuclear release are currently mitigated through several preparedness strategies. Monitoring systems indicate the need for individuals in the designated evacuation zone to evacuate to the recommended safe distance. The monitoring and warning systems are regularly tested to ensure that they are functioning properly when an event occurs. Additionally, evacuation and safe routes are identified and communicated to individuals residing or working in the evacuation zones. Further, a properly prepared and deployed response team could potentially aid in limiting exposure to the radiological substance and reducing the size of the contaminated area.

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[15] The Significant Distress Index is calculated from these inputs using a formula proposed by subject matter experts consulted for the SNRA project: $N_{SD} = C_{EF} \times (5\ Fat + Inj + ½\ D)$, where N_{SD} represents the number of persons significantly distressed, C_{EF} is the expert assessed Event Familiarity Factor, *Fat* is the number of fatalities, *Inj* is the number of injuries and/or illnesses, and *D* is the number of persons displaced (Social Displacement). In words, this formula suggests that there are 5 significantly distressed persons for each life lost; 1 for each person injured; and 1 for each 2 people displaced. This formula was constructed to reflect the empirical finding that the most severe stressor of a disaster is losing a loved one, followed by injury, followed by displacement. Uncertainty was captured by applying the index formula to the low, best, and high estimates of these three human impact metrics.

The Event Familiarity Factor is intended to capture the extent to which the event entails an ongoing threat with uncertainty regarding long term effects, is unfamiliar, or that people dread, exacerbating psychological impacts. This factor, ranging from 1.0 for familiar events to 1.3 for unfamiliar events, was provided by subject matter experts for each national-level event included in the SNRA: accidental Radiological Substance Release was given a C_{EF} of 1.1.

The numerical estimates calculated from this formula are reported in Appendix G. The semi-quantitative risk matrix is discussed in the Findings (Psychological Distress Risk).

[16] The 2011 SNRA referred to impacts as ‘consequences’ because of prior usage in quantitative risk assessment (Kaplan and Garrick [1981, March], On the quantitative definition of risk: *Risk Analysis* 1(1) 11-32). Except where it will cause confusion, ‘impact’ is used synonymously in this document because of pre-existing connotations of the word ‘consequence’ within FEMA.

Additional Relevant Information

The frequencies of radiological releases were determined by Core Damage Frequency (CDF)[17] results provided in license renewal applications, which are available at the website of the Nuclear Regulatory Commission (United States Nuclear Regulatory Commission). Of the 104 active nuclear reactors in the United States, 81 have either completed applications for license renewal or have applications that are currently under review. As part of this license renewal process, each reactor includes an environmental report with a Severe Accident Mitigation Alternatives (SAMA) analysis, which is where the CDFs can be found. Information for reactors that do not have current license renewal applications is not available, but it was assumed that the data available on the 81 reactors with current renewal application is representative of the remaining reactors without current license renewal applications. Therefore, in accordance with this assumption, the mean internal CDFs[18] are drawn from the distribution of the 81 reactors whose information is available.

Regarding the SAMA data in the license renewal applications, it is important to note that data from SAMA analyses are developed and used to perform cost/benefit analyses on reactor upgrades, not to perform general risk assessments. However, SAMA data are the best publicly available data for our purposes and are adequate for the order-of-magnitude estimates of the SNRA. The NRC is currently re-evaluating severe accident impacts using two pilot plants. Preliminary results from this State-of-the-Art Reactor Consequence Analysis (which is still in progress[19]) indicate that selected accident scenarios could reasonably be mitigated, either preventing core damage or delaying/reducing the radiation release. For scenarios assumed to proceed without mitigation, accidents progress more slowly and result in smaller and more delayed radiological releases than previously predicted (e.g. in NUREG-1150) (Gauntt, 2008).

Furthermore, each of the reactor license renewal applications includes the CDFs associated with internal events, which are accidents arising from plant activities, such as worker error or parts malfunctions. Uncertainty around these CDFs was collected for 15 license renewal applications, which report 5th and 95th percentiles along with mean CDFs. For example, in Reactor 1 this value is 2.10 for the ratio of the 95th percentile to the mean and 0.462 for the 5th percentile to the mean, and in Reactor 2 the ratio of the 95th percentile to the mean is 1.40, and the ratio of the 5th percentile to the mean is 0.687. However, uncertainty was collected in only 15 of the 81 CDFs (not all reports included these values), and the functions associated with the Monte Carlo runs that underlie the uncertainty are not reported. Therefore, to address this lack of information and assign uncertainty to all CDFs for all the reactors, the 15 available reports on uncertainty are used to calculate 15 separate ratios of the 95th percentile to mean and of the 5th percentile to mean. Also, it was assumed that the distributions of the 5th-mean and 95th-mean ratios for the available 15 cases would be representative of all reactors. Crystal Ball was used to find a statistical best fit for the distributions of these ratios. Then to assign uncertainty to all CDFs, the 15 reference values were used for their corresponding reactors and drew randomly from the best fit 95th-mean and 5th-mean distributions for all other reactors, multiplying their CDFs by the randomly assigned ratios in order to derive 5th and 95th percentile values for the CDFs. These

[17] **Core Damage Frequency (CDF)** - An expression of the likelihood that, given the way a reactor is designed and operated, an accident could cause the fuel in the reactor to be damaged (United States Nuclear Regulatory Commission, 2011).
[18] **Individual Plant Examination for External Events (IPEEE)** - While the "individual plant examination" takes into account events that could challenge the design from things that could go awry internally (in the sense that equipment might fail because components do not work as expected), the "individual plant examination for external events" considers challenges such as earthquakes, internal fires, and high winds (United States Nuclear Regulatory Commission, 2011).
[19] As of August 2011.

distributions were chosen independently for each of the reactors, and it was assumed that the uncertainty for each of the reactors is independent: the model does not simulate a systematic dependency among the reactors' uncertainties, which could push all of the reactors' CDFs in the same direction (high or low).

The frequency of core damage caused by external events (fire, earthquake, flood, plane crash, etc.) is included in some—but not all—of the applications. For the reactors where external CDFs are readily available, they have been included directly in the frequency calculation. In the examples examined, external CDFs including fire, seismic events, and high winds are frequencies that share the same order of magnitude as the internal CDFs. For example, for two given reactors, the internal CDFs are 1.79e-5 for Reactor 1 and 1.15e-5 for Reactor 2. The external CDF values are 5.01e-5 for Reactor 1 and 5.20e-5 for Reactor 2. For reactors without external CDFs, a lognormal distribution based on the selection of 18 known external CDF/internal CDF ratios is used to calculate the variation in external factors. (The lognormal distribution was chosen based on a Crystal Ball best fit.)

The other frequency of interest is the Large, Early Release Frequency (LERF).[20] For example, in Reactor 1 the CDF of 1.79e-5 corresponds to a LERF of 6.50e-7. Similarly in Reactor 2, the CDF of 1.15e-5 corresponds to a LERF of 9.43e-7. Any event with core damage is assumed to cross the threshold of national significance and influence national preparedness goals. Therefore, the CDF is the frequency listed in the risk characteristics table above, which will include all large, early release events. Based on the data from 16 reactors, the frequency of a large, early release is between one and two orders of magnitude lower than the frequency of a more general core damage event.

The results of the analysis using license renewal applications were compared to an alternative analysis that was conducted using fatality, injury, and core damage frequency data from NUREG-1150 (United States Nuclear Regulatory Commission, 1990.). The average of the core damage frequencies taken from NUREG-1150 was multiplied by 104 (the number of active nuclear reactors in the United States) and the fatalities and dose rates taken from NUREG-1150 were used to determine the comparability of the results of the two data sources. The best estimates from the NUREG-1150 analysis were within the same order of magnitude as the results obtained using data from license renewal applications.

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[20] **Large, Early Release Frequency (LERF)** - The frequency of those accidents leading to significant, unmitigated releases from containment in a time frame prior to effective evacuation of the close-in population such that there is a potential for early health effects. Such accidents generally include unscrubbed releases associated with early containment failure at or shortly after vessel breach, containment bypass events, or loss of containment (United States Nuclear Regulatory Commission, 2002).

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