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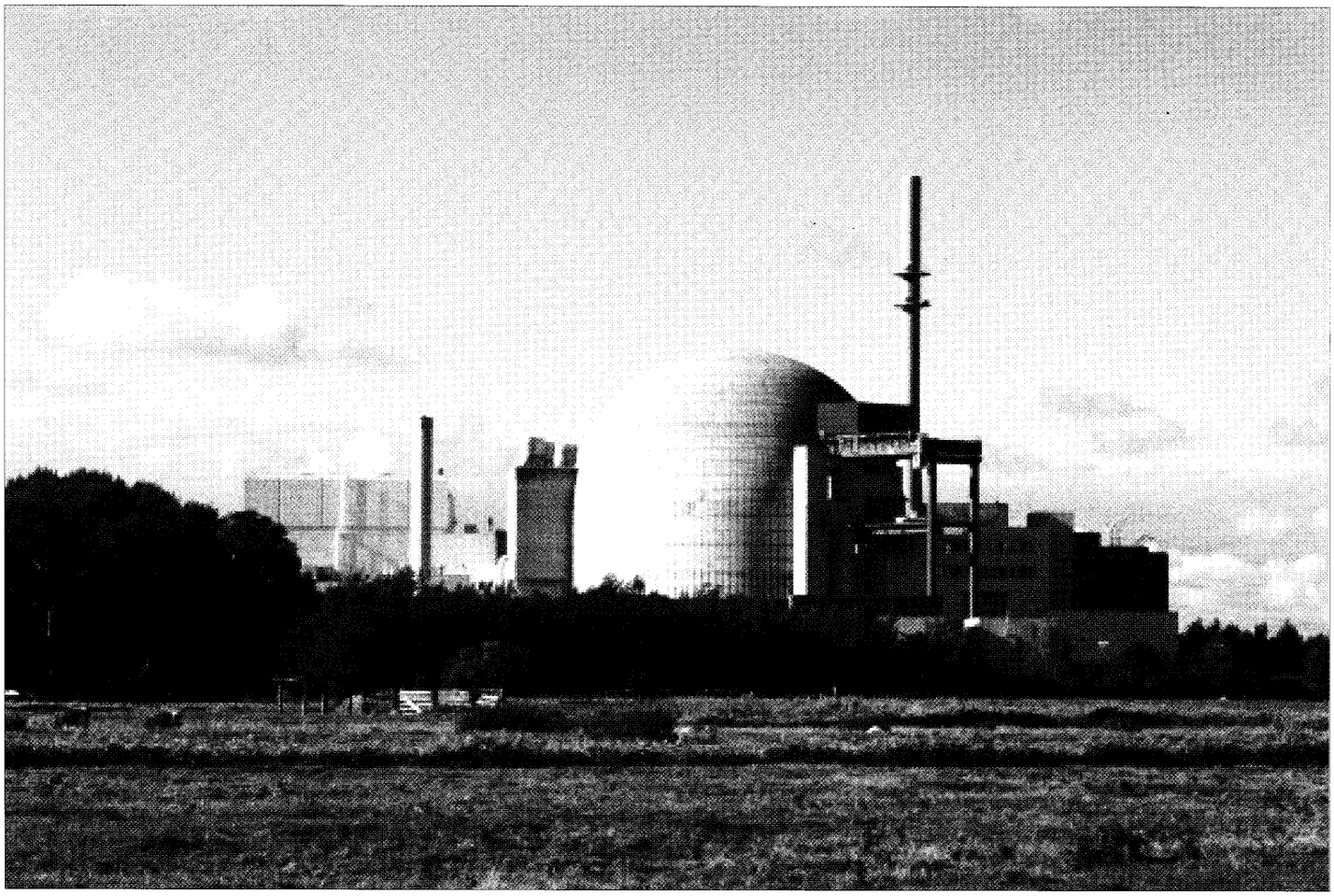

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Es werden Ergebnisse von Untersuchungen zur Bestimmung radiologischer Freisetzungen in die Umwelt bei schweren Störfällen im Hinblick auf verschiedene Folgen außerhalb des Anlagenstandorts behandelt. Neben der Freisetzung von Jod erweisen sich Freisetzungen von Tellur, Barium, Cer, Cäsium, Curium, Lanthan, Molybdän, Niob, Plutonium, Ruthen, Strontium, Yttrium und (radioaktivem) Zirkon, unter der Annahme einer gleich starken und vollständigen Freisetzung dieser Nuklide, als wichtig im Hinblick auf gesundheitliche Folgen mit früher Todesfolge. Berücksichtigt man allerdings die Bedingungen, unter denen Spaltprodukte freigesetzt werden, spielen nur die Nuklide Jod, Cäsium, Tellur und, in untergeordnetem Maße, Molybdän, Strontium und Barium eine Rolle, da quantitativ bedeutsame Freisetzungen anderer Nuklide nicht zu erwarten sind. Für latente Auswirkungen auf die Gesundheit wird nachgewiesen, dass die Americium-, Cäsium-, Cobalt-, Curium- und Plutoniumnuklide eine Rolle spielen, sofern eine gleich starke, vollständige Freisetzung vorausgesetzt wird. Auch hier sind bei schweren Störfällen große Freisetzungen dieser Nuklide, ausgenommen Cäsium, nicht zu erwarten. Deshalb bleibt Cäsium eines der Nuklide, deren Bedeutung bei den Langzeitwirkungen schwerer Störfälle von größter Bedeutung ist. Edelgase erweisen sich als unbedeutend. Im Bericht werden auch die verschiedenen Folgen unterschiedlicher Definitionen des Begriffs *„große Freisetzung"* auf Grund der Ergebnisse von probabilistischen Sicherheitsanalysen der Stufe 2 für typische Leichtwasserreaktoren behandelt. Es zeigt sich, dass die Definition von auf der Grundlage von latenten Effekten beruhenden Alternativen restriktiver ist als die auf der Grundlage von Frühfolgen beruhende. Für große Reaktoren sind die auf der Basis von einfachen Freisetzungsschwellen definierten Alternativen im Allgemeinen weniger vieldeutig und leichter zu bestimmen, umzusetzen und zu verifizieren.

Importance of Severe Accident Radiological Releases and Definition of Large Release

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1. Introduction

A spectrum of fission products of varying chemical and isotopic composition are expected to be produced inside the fuel during the operation of Light Water Reactors (LWRs). These fission products are excessively *"neutron rich,"* that is, they contain too many neutrons to be stable; therefore, they decay with emission of one or more negative β-rays, while a large proportion of the radioactive fission products also emit γ-rays. In addition to a large number of fission product nuclides, there are other radioactive products that result from activation of reactor control and structural material, and from transformation of fuel into other actinides.

The radiation associated with fission and activation product decay, particularly the γ-rays, present serious biological hazard, and if they are released from the fuel and transported to the environment, they would have significant health and environmental consequences.

The risk associated with severe core damage accidents in LWRs is typically dominated by accidents involving large radiological releases due to containment bypass or failure, some time during the accident. Therefore, the present approach to implementation of a risk informed nuclear regulatory framework in a number of countries requires a comparison of the various plant-specific risk measures (and changes in these risk measures) with appropriate goals, objectives and/or thresholds for regulatory actions.

Some of the commonly reported risk measures include:

- Risk of core damage
- Risk of radiological releases
- Risk of early fatalities
- Risk of latent fatalities
- Risk of radiation exposure
- Economic risk

Other risk measures that have been defined include the likelihood of containment failure, the frequency of large radiological releases, the risk of ground contamination, and the risk of injuries resulting from exposure to radiation.

The concept of Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) has been considered as suitable metrics for use in risk-informed regulatory decisions /1/. However, the definition of *"large release"* and the associated time of release relative to reactor shutdown and core damage (i. e., early and/or late) have implications that have not been reported.

Difficulties exist in defining *"large"* release frequencies, since there are a spectrum of fission product releases that are estimated as likely to occur following severe accidents, with their expected release quantities ranging over several orders of magnitude and occurring at various times following accident initiation.

The objectives of the present paper are two fold: (1) to present an updated study that shows the significance of radionuclides than can potentially release following severe accidents in terms of off-site consequences, and (2) to analyze the potential implications of using different definition of *"large release"* based on results of level-2 Probabilistic Safety Assessments (PSAs) for typical Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs) with different plant site characteristics.

2. Importance of Severe Accident Radiological Releases

Following severe reactor accidents, potentially large quantities of fission products, actinides and light nuclide activation products could be released to the environment. The potential importance to human heath effects from release of a radioactive nuclide is dependent on the following factors:

1. The abundance of radionuclide in the reactor at the time of the accident,
2. The half-life of radionuclide,
3. The fraction of the inventory of the radionuclide that is released, and

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4. The radiological health consequences of the radionuclide, including any progenies (daughter nuclides) after release from the fuel inside the reactor.

Various studies have been conducted to determine the relative importance of radioactive nuclides in a reactor core to the offsite consequences, including WASH-1400. These studies have identified iodine and tellurium radioisotopes to be the most important in terms of their early health effects (i. e., early fatalities and early injuries) and the cesium radioisotopes as the most important with respect to their long-term effects (i. e., latent cancer fatalities, ground contamination, and economic losses). These conclusions were driven by the assumption of relatively large release fractions for these nuclides. A study /2, 3/ during the early development of the MACCS computer code /4/ concluded that other nuclides such as lanthanum, neptunium, and radioactive zirconium could be as important to early effects as those of iodine and tellurium nuclides /2, 3/. For the long-term effects, the list included, in addition to cesium, ruthenium, curium, plutonium, and cerium /2-3/.

The various modeling changes to the MACCS2 code has put into question the validity of some of the conclusions in Reference /2/. Therefore, as part of the present study, a new evaluation of the relative importance of the various released radionuclides as a result of severe accidents, has been undertaken as discussed below.

In developing the relative importance of the various released radionuclides following severe accidents, the MACCS Version 2.12, or MACCS2, /4/ computer code has been used assuming:

- An end of cycle core inventory for a 3 578 MW (t) BWR that is scaled to the thermal power of 2 952 MW (t) for the present reference nuclear power plant.
- A selected list of 60 isotopes that is included in the MACCS2 computer code that encompasses 25 nuclides.
- One hundred percent release for each of the 25 nuclides has been considered.
- A non-buoyant release for each nuclide at the ground level (i. e., the plume thermal energy was assumed to be zero).
- The human health consequences from nuclides released include contributions from daughter products as modeled in MACCS2.
- A uniform release of each nuclide one hour after accident initiation.
- A dry deposition velocity of 0.01 m/s for all nuclides, except noble gases.
- Bin sampling of one full year of site-specific meteorology data.
- Radiation protection factors associated with normal activities (0.75 cloud shine, 0.45 ground shine, and 1.0 for inhalation).
- No credit to emergency protective actions, and the early dose is calculated for 24 hours of exposures to the contaminated land.
- No credit to long-term protective actions, and the long-term dose decay only by weathering (i. e., no credit to decontamination and relocation).
- Long-term exposures begin seven days after deposition and persist for the full duration of contamination.

The exposure pathways that have been considered include ground shine (i. e., exposure due to proximity to radioactive material deposited on the ground), cloud shine (i. e., exposure due to immersion in a cloud of radioactive material) and inhalation (i. e., exposure due to breathing contaminated air) for early exposure, and ground shine, resuspension and inhalation, for long-term exposure. It should be noted that, because of the above assumptions, the estimated doses that will be presented below are not representative of any realistic accident scenario.

The selected radionuclide inventory for a BWR plant operating at 3 578 MW (t) at the time of accident is listed in *Table I*[a]. The selected list of isotopes represents a fraction of the total isotopes that would be in the core at the time of accident. These isotopes are considered risk-significant, and are a subclass of the entire core inventory. Using the power-scaling factor of 0.825 (the ratio of the present reference plant thermal power of 2 952 MW(t) to that of the MACCS2 standard BWR operating at 3 578 MW(t) in an equilibrium cycle), the core inventory for the reference plant can be calculated by multiplying the values listed in *Table I* by 0.825.

Using MACCS2 and the above assumptions, the relative importance of the 25 nuclides (comprising of 60 isotopes) was determined for both the early and the long-term effects. For the early effects, whole body doses, early fatalities, bone marrow (red marrow) dose and latent cancers were calculated. For the long-term effects, the latent cancer fatalities, and the long-term direct exposure (ground shine and resuspension) were calculated. *Table II* summarizes the results for the aforementioned effects. It is clear from this

Nuclide/Isotope(s)[a]		Isotope abundance		Nuclide		Isotopes		Isotope abundance		Nuclide	
Name		Bq	Grams	Bq	Grams	Name		Bq	Grams	Bq	Grams
Americium, **Am**	Am-241	2.90E+14	2.31E+03	2.9E+14	2.31E+03	Neptunium, **Np**	Np-239	7.52E+19	8.84E+03	7.52E+19	8.84E+03
Antimony, **Sb**	Sb-127	3.08E+17	3.12E+01	1.38E+18	3.63E+01	Plutonium, **Pu**	Pu-238	5.23E+15	8.31E+03	2.94E+17	8.56E+05
	Sb-129	1.07E+18	5.14E+00				Pu-239	1.32E+15	5.75E+05		
Barium, **Ba**	Ba-139	6.62E+18	1.09E+01	1.31E+19	2.74E+03		Pu240	1.66E+15	1.95E+05		
	Ba-140	6.52E+18	2.41E+03				Pu241	2.86E+17	7.73E+04		
Cerium, **Ce**	Ce-141	5.92E+18	5.71E+03	1.55E+19	3.84E+04	Praseodymium, **Pr**	Pr-143	5.64E+18	2.28E+03	5.64E+18	2.28E+03
	Ce-143	5.76E+18	2.36E+02			Rhodium, **Rh**	Rh-105	2.43E+18	7.82E+01	2.43E+18	7.82E+01
	Ce-144	3.84E+18	3.24E+04			Rubidium, **Rb**	Rb-86	1.86E+15	6.21E-01	1.86E+15	6.21E-01
Cesium, **Cs**	Cs-134	5.59E+17	1.16E+04	1.04E+18	1.16E+05	Ruthenium, **Ru**	Ru-103	4.88E+18	4.12E+03	9.46E+18	1.50E+04
	Cs-136	1.50E+17	5.55E+01				Ru-105	3.25E+18	1.31E+01		
	Cs-137	3.35E+17	1.04E+05				Ru-106	1.33E+18	1.09E+04		
Cobalt, **Co**	Co-58	2.02E+16	1.71E+01	4.44E+16	6.12E+02	Strontium, **Sr**	Sr-89	3.67E+18	3.42E+03	1.37E+19	5.37E+04
	Co-60	2.42E+16	5.95E+02				Sr-90	2.60E+17	5.02E+04		
Curium, **Cm**	Cm-242	7.67E+16	6.28E+02	8.08E+16	2.01E+03		Sr-91	4.77E+18	3.58E+01		
	Cm-244	4.14E+15	1.38E+03				Sr-92	5.00E+18	1.04E+01		
Iodine, **I**	I-131	3.42E+18	7.70E+02	3.02E+19	1.02E+03	Technetium, **Tc**	Tc-99m	5.55E+18	2.83E+01	5.55E+18	2.83E+01
	I-132	5.02E+18	1.36E+01			Tellurium, **Te**	Te-127	2.98E+17	3.10E+00	7.05E+18	8.19E+02
	I-133	7.17E+18	1.76E+02				Te-127m	4.01E+16	1.15E+02		
	I-134	7.85E+18	7.86E+00				Te-129	1.00E+18	1.29E+00		
	I-135	6.75E+18	5.21E+01				Te-129m	2.63E+17	2.37E+02		
Krypton, **Kr**	Kr-85	3.32E+16	2.30E+03	6.39E+18	2.31E+03		Te-131m	5.06E+17	1.71E+01		
	Kr-85m	1.21E+18	3.99E+00				Te-132	4.94E+18	4.45E+02		
	Kr-87	2.19E+18	2.11E+00			Xenon, **Xe**	Xe-133	7.18E+18	1.02E+03	8.89E+18	1.04E+03
	Kr-88	2.96E+18	6.38E+00				Xe-135	1.71E+18	1.78E+01		
Lanthanum, **La**	La-140	6.66E+18	3.21E+02	1.87E+19	3.33E+02	Yttrium, **Y**	Y-90	2.78E+17	1.39E+01	1.55E+19	4.92E+03
	La-141	6.14E+18	4.89E-01				Y-91	4.48E+18	4.84E+03		
	La-142	5.92E+18	1.12E+01				Y-92	5.00E+18	1.41E+01		
Molybdenum, **Mo**	Mo-99	6.44E+18	3.63E+02	6.44E+18	3.63E+02		Y-93	5.70E+18	4.67E+01		
Niobium, **Nb**	Nb-95	5.58E+18	3.87E+03	5.58E+18	3.87E+03	Zirconium, **Zr**	Zr-95	5.90E+18	7.59E+03	1.2E+19	7.68E+03
Neodymium, **Nd**	Nd-147	2.52E+18	8.41E+02	2.52E+18	8.41E+02		Zr-97	6.08E+18	8.65E+01		

[a] The isotopic inventories are reproduced from NUREG/CR-4467 /2/

Tab. I. Selected radionuclide inventory of a 3 578 MW(t) BWR plant at the time of accident initiation.

Nuclides	Nuclide inventory (PBq)	Early Effects[a]				Long-Term Effects			Total Latent Cancer Fatalities
		Early Fatalities	Latent Cancer Fatalities	Red Marrow Dose (Sv)	Total Dose (Sv)	Latent Cancer fatalities	Direct Dose (Sv)	Ground Shine Dose (Sv)	
Americium, **Am**	2.39E-01	0.0	325	113400	7790	674	22300	93.5	999
Antimony, **Sb**	1.14E+03	0.07	27.4	199	340	7.15	158	154	34.6
Barium, **Ba**	1.09E+04	30	360	4730	5250	5110	115000	115000	5470
Cerium, **Ce**	1.28E+04	69.1	12000	3730	92300	12600	162000	25400	24600
Cesium, **Cs**	8.61E+02	5.56	164	2900	3130	**45300**	**1020000**	**1010000**	**45464**
Cobalt, **Co**	3.66E+01	0	27	138	383	2140	46900	46100	2167
Curium, **Cm**	6.67E+01	34.6	9570	154000	142000	10400	275000	18.7	19970
Iodine, **I**	2.49E+04	46.3	398	3730	12300	203	4770	4420	601
Krypton, **Kr**	5.27E+03	0.524	8.56	152	135	0	0	0.0	8.56
Lanthanum, **La**	1.54E+04	58.6	493	5760	8060	30.7	684	677	523.7
Molybdenum, **Mo**	5.31E+03	8.31	244	745	2310	24.8	588	581	268.8
Niobium, **Nb**	4.60E+03	25.1	286	2840	4650	4490	99400	98700	4776
Neodymium, **Nd**	2.07E+03	0.189	143	209	1240	96.4	2200	2110	239.4
Neptunium, **Np**	**6.20E+04**	**71.1**	1870	7870	16600	161	3440	2340	2031
Plutonium, **Pu**	2.43E+02	3.53	21400	203000	232000	33400	692000	2650	54800
Praseodymium, **Pr**	4.64+03	4.92	374	18.5	2770	48.3	1210	892	422.3
Rhodium, **Rh**	2.00e+3	7.65E-05	21	73.2	196	0.219	4.93	4.88	21.22
Rubidium, **Rb**	1.53E+00	0	0.044	1.05	0.905	0.107	3.29	3.16	0.151
Ruthenium, **Ru**	7.80E+03	36.7	5440	2470	43100	11300	226000	159000	16740
Strontium, **Sr**	1.13E+04	28.6	382	23500	6210	2290	111000	100000	2672
Technetium, **Tc**	4.58E+03	7.19E-05	4.24	61.4	86.5	0	0	0.0	4.24
Tellurium, **Te**	5.81E+03	51.5	472	6270	9440	303	6860	6660	775
Xenon, **Xe**	7.33E+03	0	5.2	72.1	125	0	0	0.0	5.2
Yttrium, **Y**	1.28E+04	35.8	2720	461	19500	970	21200	11100	2618
Zirconium, **Zr**	9.88E+03	52.3	1230	9020	12900	20070	444000	384000	18426

[a] These consequences are estimated for a distance up to 16 km.

Tab. II. Individual nuclide releases to the environment and their corresponding human health effects for the present reference plant.

table that cesium is the dominating contributor to latent effects, while neptunium is the dominant contributor to the early fatalities. In order to get a better perspective of the relative importance of these nuclides, the nuclides unit health effects per Peta Becquerel (PBq) (10^{15} Bq, or 27.027 kilo-curies) of release for early and latent consequences are presented in *Table III*. This table shows that per PBq of release, curium, and plutonium are the most important to both early and latent effects. Americium is the most important for latent cancer fatality effects, surpassing both curium and plutonium. However, in a reactor accident, the activity of these actinide nuclides in a typical release is orders of magnitudes smaller than the activity of the volatile radionuclides (i. e., I, Cs and Te).

Table IV shows the importance of various nuclides in a hypothetical reactor accident leading to their total (100 %) release, normalized with respect to iodine for early fatalities and dose; and with respect to

Nuclides	Nuclide's inventory (PBq)	Early Effects per PBq[a]				Long-Term Effects per PBq			Total Latent Cancer Fatalities per PBq
		Early Fatalities	Latent Cancer Fatalities	Red Marrow Dose (Sv)	Total Dose (Sv)	Latent Cancer fatalities	Direct Dose (Sv)	Ground Shine Dose (Sv)	
Americium, **Am**	2.39E-01	0.00E+00	**1.36E+03**	**4.73E+04**	**3.26E+04**	**2.82E+03**	9.33E+04	3.91E+02	**4.18E+03**
Antimony, **Sb**	1.10E+03	6.36E-05	2.49E-02	1.81E-01	3.09E-01	6.50E-03	1.44E-01	1.40E-01	3.15E-02
Barium, **Ba**	1.09E+04	2.75E-03	3.30E-02	4.34E-01	4.82E-01	4.69E-01	1.06E+01	1.06E+01	5.02E-01
Cerium, **Ce**	1.28E+04	5.40E-03	9.38E-01	2.91E-01	7.21E+00	9.84E-01	1.27E+01	1.98E+00	1.92E+00
Cesium, **Cs**	8.61E+02	6.46E-03	1.90E-01	3.37E+00	3.64E+00	5.26E+01	1.18E+03	1.17E+03	5.28E+01
Cobalt, **Co**	3.66E+01	0.00E+00	7.38E-01	3.77E+00	1.05E+01	5.85E+01	1.28E+03	1.26E+03	5.92E+01
Curium, **Cm**	6.67E+01	**5.19E-01**	**1.43E+02**	**2.31E+03**	**2.13E+03**	**1.56E+02**	4.12E+03	2.80E-01	**2.99E+02**
Iodine, **I**	2.49E+04	1.86E-03	1.60E-02	1.50E-01	4.94E-01	8.15E-03	1.92E-01	1.78E-01	2.41E-02
Krypton, **Kr**	5.27E+03	9.94E-05	1.62E-03	2.88E-02	2.56E-02	0.00E+00	0.00E+00	0.00E+00	1.62E-03
Lanthanum, **La**	1.54E+04	3.81E-03	3.20E-02	3.74E-01	5.23E-01	1.99E-03	4.44E-02	4.40E-02	3.40E-02
Molybdenum, **Mo**	5.31E+03	1.57E-03	4.60E-02	1.40E-01	4.35E-01	4.67E-03	1.11E-01	1.09E-01	5.06E-02
Niobium, **Nb**	4.60E+03	5.46E-03	6.22E-02	6.17E-01	1.01E+00	9.76E-01	2.16E+01	2.15E+01	1.04E+00
Neodymium, **Nd**	2.07E+03	9.13E-05	6.91E-02	1.01E-01	5.99E-01	4.66E-02	1.06E+00	1.02E+00	1.16E-01
Neptunium, **Np**	6.20E+04	1.15E-03	3.02E-02	1.27E-01	2.68E-01	2.60E-03	5.55E-02	3.77E-02	3.28E-02
Plutonium, **Pu**	2.43E+02	**1.45E-02**	**8.81E+01**	**8.35E+02**	**9.55E+02**	**1.37E+02**	2.85E+03	1.09E+01	**2.26E+02**
Praseodymium, **Pr**	4.64E+03	1.06E-03	8.06E-02	3.99E-03	5.97E-01	1.04E-02	2.61E-01	1.92E-01	9.10E-02
Rhodium, **Rh**	2.00E+3	3.83E-08	1.05E-02	3.66E-02	9.80E-02	1.10E-04	2.47E-03	2.44E-03	1.06E-02
Rubidium, **Rb**	1.53E+00	0.00E+00	2.88E-02	6.86E-01	5.92E-01	6.99E-02	2.15E+00	2.07E+00	9.87E-02
Ruthenium, **Ru**	7.80E+03	4.71E-03	6.97E-01	3.17E-01	5.53E+00	1.45E+00	2.90E+01	2.04E+01	2.15E+00
Strontium, **Sr**	1.13E+04	2.53E-03	3.38E-02	2.08E+00	5.50E-01	2.03E-01	9.82E+00	8.85E+00	2.36E-01
Technetium, **Tc**	4.58E+03	1.57E-08	9.26E-04	1.34E-02	1.89E-02	0.00E+00	0.00E+00	0.00E+00	9.26E-04
Tellurium, **Te**	5.81E+03	8.86E-03	8.12E-02	1.08E+00	1.62E+00	5.22E-02	1.18E+00	1.15E+00	1.33E-01
Xenon, **Xe**	7.33E+03	0.00E+00	7.09E-04	9.84E-03	1.71E-02	0.00E+00	0.00E+00	0.00E+00	7.09E-04
Yttrium, **Y**	1.28E+04	2.80E-03	2.13E-01	3.60E-02	1.52E+00	7.58E-02	1.66E+00	8.67E-01	2.05E-01
Zirconium, **Zr**	9.88E+03	5.29E-03	1.24E-01	9.13E-01	1.31E+00	2.03E+00	4.49E+01	3.89E+01	1.87E+00

[a] These consequences are estimated for a distance up to 16 km.

Tab. III. Individual nuclide unit health effects per Peta Becquerel of release for the present reference plant.

Nuclides	Nuclide inventory (PBq)	Early Effects Relative to Iodine[a]		Long-Term Effects Relative to Cesium			
		Early Fatalities	Early Dose[b]	Latent Cancer Fatalities (Early)	Latent Cancer Fatalities (Late)	Long-term Dose	Total Latent Cancer Fatalities
Americium, **Am**	2.39E-01	0.00E+00	6.60E+04	7.14E+03	5.36E+01	7.88E+01	7.92E+01
Antimony, **Sb**	1.14E+03	3.42E-02	6.26E-01	1.31E-01	1.24E-04	1.21E-04	5.96E-04
Barium, **Ba**	1.09E+04	1.48E+00	9.75E-01	1.73E-01	8.91E-03	8.91E-03	9.50E-03
Cerium, **Ce**	1.28E+04	2.90E+00	1.46E+01	4.92E+00	1.87E-02	1.07E-02	3.64E-02
Cesium, Cs	8.61E+02	3.47E+00	7.36E+00	**1.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**
Cobalt, **Co**	3.66E+01	0.00E+00	2.12E+01	3.87E+00	1.11E+00	1.08E+00	1.12E+00
Curium, **Cm**	6.67E+01	2.79E+02	4.31E+03	7.53E+02	2.96E+00	3.48E+00	5.67E+00
Iodine, I	2.49E+04	**1.00E+00**	**1.00E+00**	8.39E-02	1.55E-04	1.62E-04	4.57E-04
Krypton, **Kr**	5.27E+03	5.35E-02	5.19E-02	8.53E-03	0.00E+00	0.00E+00	3.08E-05
Lanthanum, **La**	1.54E+04	2.05E+00	1.06E+00	1.68E-01	3.79E-05	3.75E-05	6.44E-04
Molybdenum, **Mo**	5.31E+03	8.42E-01	8.81E-01	2.41E-01	8.88E-05	9.35E-05	9.59E-04
Niobium, **Nb**	4.60E+03	2.93E+00	2.05E+00	3.26E-01	1.86E-02	1.82E-02	1.97E-02
Neodymium, **Nd**	2.07E+03	4.91E-02	1.21E+00	3.63E-01	8.85E-04	8.97E-04	2.19E-03
Neptunium, **Np**	6.20E+04	6.17E-01	5.42E-01	1.58E-01	4.94E-05	4.68E-05	6.20E-04
Plutonium, **Pu**	2.43E+02	7.81E+00	1.93E+03	4.62E+02	2.61E+00	2.40E+00	4.27E+00
Praseodymium, **Pr**	4.64+03	5.70E-01	1.21E+00	4.23E-01	1.98E-04	2.20E-04	1.72E-03
Rhodium, **Rh**	2.00E+3	2.06E-05	1.98E-01	5.51E-02	2.08E-06	2.08E-06	2.01E-04
Rubidium, **Rb**	1.53E+00	0.00E+00	1.20E+00	1.51E-01	1.33E-03	1.82E-03	1.87E-03
Ruthenium, **Ru**	7.80E+03	2.53E+00	1.12E+01	3.66E+00	2.75E-02	2.45E-02	4.06E-02
Strontium, **Sr**	1.13E+04	1.36E+00	1.11E+00	1.77E-01	3.85E-03	8.29E-03	4.48E-03
Technetium, **Tc**	4.58E+03	8.44E-06	3.82E-02	4.86E-03	0.00E+00	0.00E+00	1.75E-05
Tellurium, **Te**	5.81E+03	4.77E+00	3.29E+00	4.27E-01	9.91E-04	9.97E-04	2.53E-03
Xenon, **Xe**	7.33E+03	0.00E+00	3.45E-02	3.72E-03	0.00E+00	0.00E+00	1.34E-05
Yttrium, **Y**	1.28E+04	1.50E+00	3.08E+00	1.12E+00	1.44E-03	1.40E-03	3.87E-03
Zirconium, **Zr**	9.88E+03	2.85E+00	2.64E+00	6.54E-01	3.86E-02	3.79E-02	3.53E-02

[a] These consequences are estimated for a distance up to 16 km.
[b] This is a whole body dose received during early exposure.

Tab. IV. Relative importance of individual nuclides.

cesium for latent (long-term) health effects (i. e., latent cancer fatalities and the long-term dose). *Table IV* shows that when equal activity releases per nuclide are considered, iodine would not be a major contributor to early health effects. In terms of total effective dose from the exposure to plume and a short duration of exposure (e. g., 24 hour) to the ground contamination (i. e., total dose-early), 14-out-of-25 nuclides would have higher dose consequences than that of iodine.

This table identifies those nuclides that have similar or more contributing effects than that of iodine nuclide for the early effects. In addition to iodine, it is seen that tellurium, barium, cerium, cesium, curium, lanthanum, molybdenum, niobium, plutonium, ruthenium, strontium, yttrium and (radioactive) zirconium are important to early fatality health effects, provided a complete release of these nuclides were to be postulated; however, even under the most severe accidents involving potentially large releases (e. g., containment bypass scenarios), and in the absence of any release mitigation, the radiological releases are dominated by volatile nuclides of iodine, cesium, and tellurium, and to a lesser extent, by the release of nuclides of molybdenum, strontium, and barium. While quantitatively significant releases of the other nuclides that are shown to be important in terms of early health effects, are not envisioned.

On the other hand, *Table IV* also shows that latent health effects are dominated by nuclides of americium, cesium, cobalt, curium, and plutonium (note that also important are nuclides of ruthenium, strontium, yttrium, and cerium due to exposure to the plume), if a complete release of these nuclides were to be postulated. Here again, during severe accidents, quantitatively large releases for the aforementioned nuclides other than cesium are not likely. Therefore, cesium remains as the nuclide of greatest significance from a standpoint of long-term effects, for severe accidents. Furthermore, in terms of either early or latent health effects, noble gases are shown to be of little significance.

Also, since emergency actions (i. e., evacuation or relocations), long-term protective measures, and the effects of plume buoyancy, have not been considered in the analysis, the normalization results shown in *Table IV* remove down wind distance as a factor in the relative importance of each nuclide.

2.1 Early Fatalities

Following severe accidents, the consequences in terms of early fatalities are limited to the immediate areas surrounding the plant. Since the early fatalities are a direct function of the acute dose, with a threshold value causing fatality, the number of the fatalities would not be proportional to the total dose received by the population. In general, the individual residing nearest to the site would receive the highest dose, and as the distance increases, the acute dose becomes smaller, which results in a lower number of potential early fatalities. *Figure 1* shows that more than 95 % of the total early fatalities occur in less than 5 kilometers from the point of release. Since the consequences in terms of early fatalities are most pronounced in the immediate vicinity of the plant, MACCS2 calculations show at close distances, tellurium and iodine have similar contribution to early fatality health effects.

2.2 Latent Fatalities

Latent cancer fatalities are proportional to the total population exposure. In contrast to early fatalities where the number of fatalities decreases as distance increases and reaches a fixed value within a short distance (e. g., less than 16 kilometers), latent cancer fatalities increase with before the distance and population (see *Figure 2*). As indicated earlier, the contribution from cesium release dominates all the latent cancer fatality health effects. Note that the impact of radioactive decay and daughter build-up on latent fatalities and population dose, in the long-term, is not significant.

2.3 Ground Contamination and Regulatory Criteria

Ground contamination level down wind from an accidental release of radioactive material is a function of its deposition rate and decay rate. Nuclides with heavier masses and larger particle dimensions than one micron would have a greater rate of deposition onto ground and thus produce higher levels of ground contamination relative to the initial airborne concentration. The effect of higher deposition rate is a higher contamination level near the point of release. Nuclides with short half-lives would lead to lower levels of contamination as the plume travels down wind. Therefore, nuclides with a few-hour

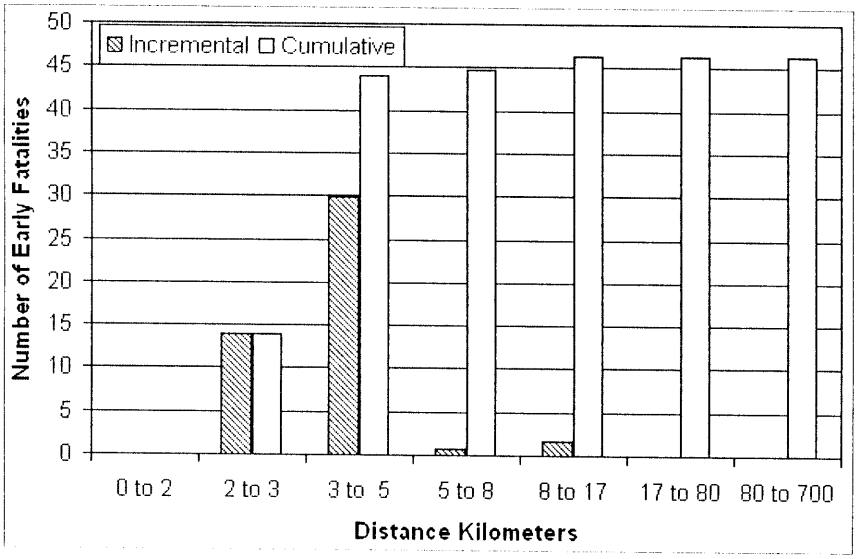

Fig. 1. Early fatalities versus distance due to 100 % release of iodine to the environment.

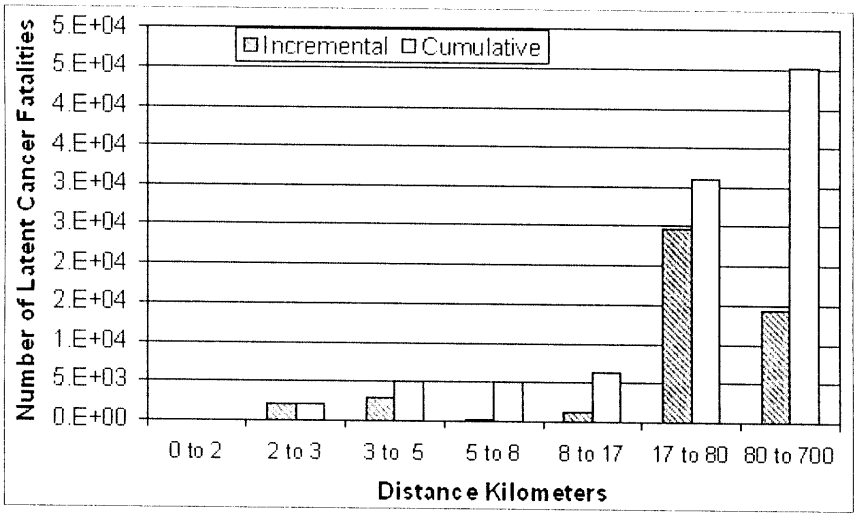

Fig. 2. Latent cancer fatalities versus distance from the plant due to 100 % release of cesium.

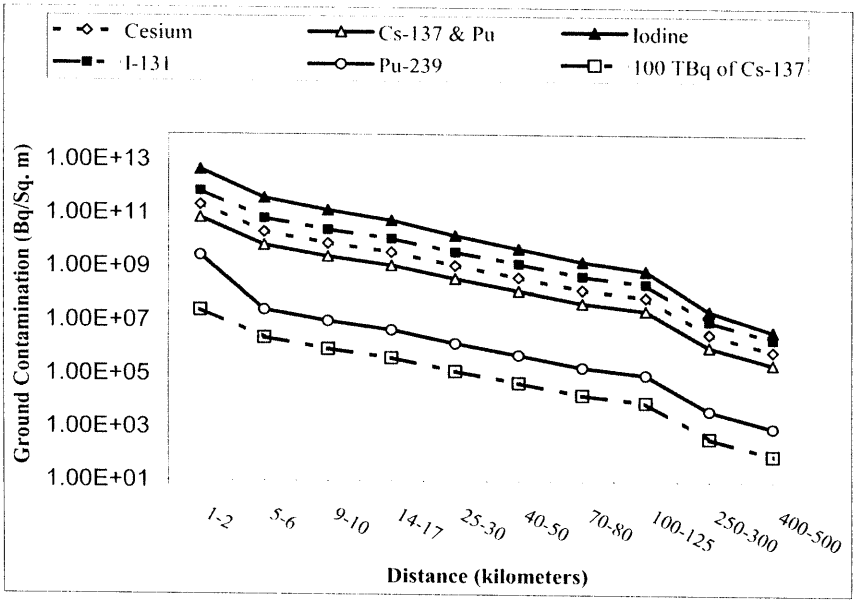

Fig. 3. Plume centerline ground contamination versus distance.

half-lives would be almost decayed completely within a few hundred kilometers from the point of release.

Analysis of the ground contamination levels versus distance shown in *Figure 3* indicates that cesium and plutonium have similar contamination levels relative to their initial release quantities whereas iodine has a lower value. This is because both cesium and plutonium nuclides include isotopes with long half-lives, whereas iodine isotopes except for iodine-131 (which has a half-life of about 8 days), have short half lives relative to the duration of the plume passage.

There are several criteria, which set limits on ground contamination, including:

1. The *U.S. Environmental Protection Agency (EPA)* provisions for relocation of population include:

– In 1977, *EPA* issued proposed guidelines on the dose limit from ground contamination, which requires that the surface contamination be limited to below 0.2 $\mu Ci/m^2$ /5/. A 0.2 $\mu Ci/m^2$ is equivalent to 7 400 Bq/m^2, a comparisons of the cesium-137 centerline ground contamination values to this criterion indicates that a release fraction of the order of 10^{-7} for a large power reactor would be needed in order not to require any relocation beyond 1 km of the plant. Therefore, this criterion is very restrictive and difficult to achieve even with substantial decontamination following a severe accident.

– In 1992, *EPA* issued protective action guidelines for nuclear incidents in which mitigative actions such as decontamination, or decontamination followed by temporary interdiction is to be undertaken based on the projected future dose /6/. An example of this is the limit of projected individual dose of 0.02 Sv in the first year following the accident. This would limit the cesium release fraction to about $4x10^{-6}$ for a large power reactor, in order to preclude such conditions beyond 1 km of the plant.

2. The criterion by the Finish Radiation and Nuclear Safety Authority /7/ to limit the releases to equivalent of 100 TBq (10^{14} Bq) of Cs-137, translates to cesium release fraction of about 10^{-4} or less.

3. Other criteria include those that have been examined by *Prêtre* /8/, which are based on land contamination due to Cs-137 (or other options). Under the condition of Cs-137 land contamination, relocation would occur if the Cs-137 contamination exceeds 40 Ci/km^2 ($1.5x10^6$ Bq/m^2). This criterion limits Cs-137 release fraction to less than $2x10^{-5}$ to preclude relocation beyond 1 km from the plant. This criterion is 200 times that of *EPA*-1977 criterion. Reference /8/ also discusses a number of other criteria.

Reference /3/ has discussed the impact of factors such as power level, reactor type, fuel burnup, and site and release characteristics on the potential offsite consequences of severe accidents. The differences in the relative importance of various radionuclides

notwithstanding, the present study, also confirms that for early exposure, only nuclides with short (few days) half-lives are of significance, and these inventories are not greatly impacted by reactor type, power level and fuel burnup. However, even though the inventory of long-lived radionuclides are affected by fuel cycle and burnup, nonetheless, this dependence is similar for all these nuclides, and the relative significance of these nuclides (in terms of latent effects and ground contamination) will not be significantly altered by these factors.

3. Definition of Large Release

Difficulties exist in defining *"large"* release frequencies, since there are a spectrum of fission product releases that are estimated as likely to occur following severe accidents, with their expected release quantities ranging over several orders of magnitude and occurring at various times following accident initiation.

The more prominent release characteristics as defined in various PSAs that can have a marked influence on the magnitude of releases consist of:

- Containment status and failure mode that include isolation failure; Steam Generator Tube Rupture (SGTR) (for PWRs) and other containment bypass events (e. g., interfacing systems LOCA); containment failure mode (e. g., leakage, rupture, etc.); containment venting; basemat penetration; and intact containment (i. e., release through preexisting leakage paths only).
- Time of containment failure that include before or near the time of vessel breach, late in the accident (many hours after core damage and vessel breach), and never (intact containment).
- Status of containment engineered safety systems (e. g., sprays for PWRs and some BWRs, pressure suppression pool in BWRs, etc.) that can be considered as active or not bypassed, and inactive or bypassed.
- Status of reactor lower containment/cavity region that include flooded with water on the long-term, or dry.

These characteristics have a profound impact on the magnitude of radiological releases into the environment. In general, bypass and early containment failure modes are expected to result in quantitatively significant releases (i. e., typically, involving release of volatile radionuclides in excess of 10 % of their initial core inventories). However, consequentially, some of the other listed release modes that have the potential for being large, may or may not be classified as such, depending on the threshold that is used to distinguish the *"large"* from the *"not large"* (i. e., low and medium releases).

The frequency of large radiological releases to the environment will be impacted by many factors, foremost, by the definition itself. For instance, if offsite fatalities or health effects are selected as part of the definition, then aside from the release magnitude, time, and other attributes of the release, the off-site emergency response countermeasures, will also have a significant and determining impact on triggering the *"large"* release threshold. Specifically, early fatalities in the immediate vicinity of the plants are most sensitive to the release magnitude, the time of release (after core damage), the thermal energy of release, the elevation of release, the population density, and the emergency response actions.

The following alternatives for the definition of large release (e. g., see /1/, /7/, /9/ and /10/) to estimate the large release frequency following postulated severe accidents, are noteworthy:

- A-1: Any releases that occur because of severe accidents that would entail an early containment failure (including containment isolation failure)
- A-2: Any releases that occur because of severe accidents that would entail early containment failure (including containment isolation failure) and containment bypass conditions
- A-3: Any release that would exceed specific thresholds in terms of fractional releases and timing of release
- A-4: Any releases that occur because of severe accidents that would entail 10 % or more of the initial core inventory of iodine
- A-5: Any releases that would exceed specific thresholds in terms of the activity associated with the release from the containment
- A-6: A collection of all releases that would result in one or more early fatalities offsite

The first four alternatives are solely based on the release thresholds, and can be readily calculated using the results of the level-2 PSAs. On the other hand, calculation of alternative A-5 requires the appropriate estimation of release activities. Estimation of release frequency using alternative A-6 requires off-site consequence calculations using MACCS2 or other similar computer codes (or other approximations) to determine the number of early fatalities in the immediate vicinity of the power plants (i. e., in the area outside the exclusion zone extending to about 2 km from the plant).

The consideration of *"release fraction"* as an appropriate threshold for definition of LERF requires to be augmented by other factors since the actual quantitative releases into the environment are a function of core inventory (e. g., reactor rated power, fuel composition, fuel burnup, etc.). However, qualitatively, for a large power reactor (e. g., 1 000 MW(e)), releases involving a few percent (~3% of iodine equivalent) of the volatile fission products would produce measurable offsite consequences.

On the other hand Reference /9/ proposes the concept of *"cesium equivalence"* to define the large releases as those that exceed a given quantity of core radiological inventory measured as *"Cs-equivalent"*. This proposal for large release uses the frequency versus Cs-137 equivalent release that is in a form of a Complementary Cumulative Distribution Function (CCDF) shown in *Figure 4*, which defines releases exceeding about 10 kg (or 3.2×10^{16} Bq) of "cesium -137 equivalent", as those that are expected to have a frequency that is less than or equal to 10^{-6} per reactor-year. The limit for the release of radioactive materials arising from a severe accident is defined in Reference /7/. This requirement limits the releases from severe accidents to those that cause neither acute harmful health effects to the population near the nuclear power plants or any long-term restrictions on the use of extensive areas of land and water. For satisfying the requirement applied to long-term effects, the Reference /7/ criterion is such that to limit atmospheric releases of cesium-137 to 100 TBq (10^{14} Bq). In addition, Reference /7/ requires that the combined fall-out consisting of nuclides other than cesium-isotopes should not cause, in the long term, starting three months from the accident, any hazard greater than would be expected from a cesium release corresponding to 10^{14} Bq. This Cs-137 release criterion is at least about 300 times lower (i. e., more restrictive) than that proposed in Reference /9/.

Within the *U. S. Nuclear Regulatory Commission (NRC)* regulatory framework /1/, large early release is typically being used as a surrogate for the early fatality quantitative health objective of the *NRC* safety goal policy, where it is defined as *"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, and loss of containment isolation."* Results of studies performed to examine the implications of defining a *"large release"* source term that has the potential to result in one early fatality within one mile of the plant boundary have been reported /10/. The current NRC concept is geared towards early fatalities, while the concepts proposed in /7/ and /9/ are aimed at ground contamination and latent exposure.

4. Examination of Alternative Definitions on Plant-Specific Basis

The calculation of alternatives A-1 through A-4 is straightforward, and consists of summing the frequency of all release categories that result in release quantities exceeding the specified threshold, accounting for the relative time of release (to distinguish large releases that occur *"early"* from

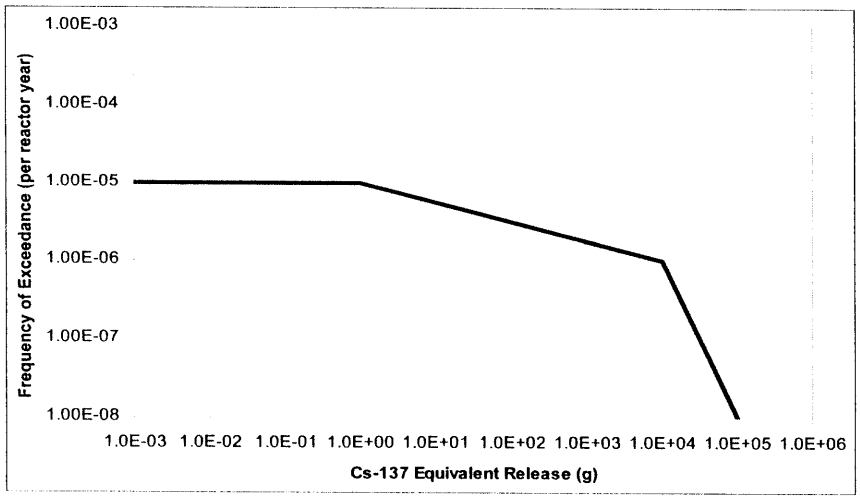

Fig. 4. Frequency consequence proposal of Reference /9/.

those large releases that occur *"late"* relative to time of damage).

Calculation of LERF and Large Release Frequency (LRF) based on alternative A-5 and using the threshold values of /7/ and /9/, involves additional analyses. To evaluate the Cs-137 equivalent health effects of all nuclides, a set of *"Cs-137 equivalent"* consequence weights were developed by performing a separate MACCS2 calculation where 100 % release of only the Cs-137 isotope was assumed in order to obtain the late direct dose and the number of latent cancer fatalities. This calculation showed that 2.76×10^{17} Bq of Cs-137 results in a late direct dose of 6.87×10^{5} Sv. Therefore, the unit late direct dose of Cs-137 is $6.87 \times 10^{5} / 2.76 \times 10^{17} = 2.49 \times 10^{-12}$ Sv/Bq. Furthermore, by normalizing the doses in terms of the corresponding nuclide inventory (isotope in the case of Cs-137 calculation), the resulting dose due to the release of 1 Bq of activity of each nuclide is calculated. The weights are then obtained by dividing the unit dose effects of the nuclides by that corresponding to Cs-137 isotope. Similar Cs-137 equivalent weights were also generated using latent cancer fatality health effect measures resulting from exposure to ground contamination starting 90 days after the release. These results are presented in *Table V.*

The calculation of release frequency using alternative A-6 involved performance of plant-specific MACCS2 calculations as well as a simplified formulation to determine the number of early fatalities within 2 km of the plant. The plant type, power level (relative to the MACCS2 standard power), and the site population differences are summarized in Table VI.

Using the results of plant-specific level-2 PSAs for typical LWRs, the frequency associated with each alternative definition of large release (including large early release) was estimated, and the results are summarized in *Table VII.* Note that the estimation of frequency associated with alternatives A-1 through A-4 is strictly based on the results of level-2 PSAs only. As such, these frequencies can be estimated by summing the frequency of each release bin/category that fulfils the threshold requirement of the definition. Only alternatives A-5 and A-6 require additional calculations, as described earlier.

It should be noted that the differences in the absolute frequencies listed in *Table VII*, including variations between the plants, which are also indicative of the specifics of the PSAs used are not of significance to the present analyses. However, on an individual plant level, the differences between the results for various release definitions, are indicative of the implications of using different characterization of large release, the threshold values, and in one case (i. e., alternative A-6), the site characteristics.

Table VII shows that:

1. Alternatives A-2 and A-4 result in similar LERF values, for a given plant; however, across plants, those that have a higher susceptibility to containment bypass have a greater LERF contribution.
2. Alternatives A-3 and A-5 can result in the inclusion of some of the late containment failure modes and late releases into the LRF estimates, as compared to the other alternatives, and these contributions are highly pronounced for some of the plants.
3. Alternative A-5 results in the highest contribution to LRF and LERF for all plants, considering the release limit as set forth in Reference /7/.
4. The LRF estimate based on the proposed Reference /9/ criterion is not significant for any of the plants. Furthermore, the use of the proposed Reference /9/ limit results in LERF estimates that are significantly larger than those of alternative A-6, for all the plants used in the present study, except for one plant.
5. In the majority of the plants, the use of alternative A-6 results in the lowest

Nuclide	Core Inventory (Bq)	Late Cancer Fatalities (After 90 days)	Latent Cancer Fatalities (LCF) per unit inventory	Cs-137 weights
Americium, Am	2.39E+14	496	2.08E-12	2.18E+01
Antimony, Sb	1.14E+18	0.139	1.22E-19	1.28E-06
Barium, Ba	1.08E+19	48.7	4.51E-18	4.73E-05
Cerium, Ce	1.28E+19	7440	5.81E-16	6.10E-03
Cesium, Cs	8.61E+17	38100	4.43E-14	4.64E-01
Cobalt, Co	3.66E+16	1780	4.86E-14	5.10E-01
Curium, Cm	6.67E+16	6670	1.00E-13	1.05E+00
Iodine, I	2.49E+19	0.137	5.50E-21	5.77E-08
Krypton, Kr	5.27E+18	0	0.00E+00	0.00E+00
Lanthanum, La	1.54E+19	0.432	2.81E-20	2.94E-07
Molybdenum, Mo	5.31E+18	0	0.00E+00	0.00E+00
Niobium, Nb	4.6E+18	756	1.64E-16	1.72E-03
Neodymium, Nd	2.08E+18	0.437	2.10E-19	2.20E-06
Neptunium, Np	6.2E+19	41.1	6.63E-19	6.96E-06
Plutonium, Pu	2.43E+17	24600	1.01E-13	1.06E+00
Praseodymium, Pr	4.65E+18	0.534	1.15E-19	1.21E-06
Rhodium, Rh	2E+18	0	0.00E+00	0.00E+00
Rubidium, Rb	1.53E+15	0.00421	2.75E-18	2.89E-05
Ruthenium, Ru	7.8E+18	6240	8.00E-16	8.39E-03
Strontium, Sr	1.13E+19	1870	1.65E-16	1.74E-03
Technetium, Tc	4.58E+18	0	0.00E+00	0.00E+00
Tellurium, Te	5.81E+18	7.45	1.28E-18	1.35E-05
Xenon, Xe	7.33E+18	0	0.00E+00	0.00E+00
Yttrium, Y	1.28E+19	242	1.89E-17	1.98E-04
Zirconium, Zr	9.88E+18	8110	8.21E-16	8.61E-03

Tab. V. Calculation of Cs-137 weights for Latent Cancer Fatalities from exposure to releases starting 90 days after accident initiation.

Plant		Plant & Site					
		1	2	3	4	5	6
Plant type		PWR	PWR	PWR	PWR	BWR	BWR
Power relative to MACCS2 standard[a] PWR or BWR		0.79	0.79	0.88	0.81	0.83	0.40
Population density (persons/km^2)	Within ~ 2 km of plant	~100	~35	~1[b]	~1[b]	~1[b]	~15
	Within immediate vicinity (in the ring of 2 to 16 km)	~20	~20	~5	~5	~10	~10

[a] MACCS2 standard PWR and BWR power level are 3412 MW(t), and 3578 MW(t), respectively.
[b] Actual population is zero but a population density of ~1 person per square kilometer is assumed

Tab. VI Plant type, power and site population differences.

Alternative		PWRs				BWRs	
		1	2	3	4	5	6
A-1		3.1×10^{-7a}	1.1×10^{-6a}	1.2×10^{-6a}	9.6×10^{-8a}	9.5×10^{-6a}	6×10^{-7}
A-2		1.8×10^{-6a}	1.0×10^{-5a}	1.6×10^{-6a}	2.5×10^{-6a}	2.2×10^{-6a}	7×10^{-7}
A-3		1.8×10^{-6a} [6.3×10^{-6}]	1.0×10^{-5a} [2.3×10^{-5}]	5.4×10^{-7a}	2.4×10^{-6a} [9.1×10^{-6}]	1.1×10^{-6a} [1.1×10^{-6}]	1×10^{-7a} [1.5×10^{-6}]
A-4		1.8×10^{-6a}	3.9×10^{-6a}	4.3×10^{-7a}	2.4×10^{-6a}	1.1×10^{-6a}	1×10^{-7a}
A-5	Ref [7]	1.8×10^{-6a} [5.3×10^{-6}]	1.0×10^{-5a} [2.4×10^{-5}]	1.6×10^{-6a} [1.3×10^{-5}]	2.4×10^{-6a} [1.3×10^{-5}]	1.1×10^{-6a} [1.8×10^{-6}]	7×10^{-7a} [2.1×10^{-6}]
	Ref [9]	1.8×10^{-6a}	3.9×10^{-6a}	5.4×10^{-7a}	2.4×10^{-6a}	1.1×10^{-6a} [1.1×10^{-6}]	1×10^{-7a}
A-6		1.8×10^{-6a}	1.0×10^{-5a} [1.30×10^{-5}]	0	0	1.1×10^{-7}	1×10^{-7a}

[a] Large Early Release Frequency (LERF). The numbers in the brackets refer to the total Large Release Frequency (LRF).

Tab. VII. Frequency of release (per reactor-year) using various alternatives for several typical light water reactors.

contribution to LERF estimates, even assuming a minimum population density of about one person per square kilometer in the area extending from the exclusion area (i. e., about 0.5 km) to about 2 km from the plant. However, alternative A-6 shows a significant LERF contribution for larger plants with a relatively higher population density. Obviously, this alternative is strongly affected by site population.

5. Conclusions

This paper has presented an updated study that shows the relative importance of various radionuclides that can potentially release following severe accidents, to offsite consequences, and an analysis of the potential implications of using different definition of *"large release"* based on results of typical level-2 PSAs for PWRs and BWRs at different plant sites.

The analyses have shown that in addition to iodine, the release of tellurium, barium, cerium, cesium, curium, lanthanum, molybdenum, niobium, plutonium, ruthenium, strontium, yttrium and (radioactive) zirconium are important to early fatality health effects, provided an equal and complete release of these nuclides were to be postulated; however, even under the most severe accidents involving potentially large releases (e. g., containment bypass scenarios), and in the absence of any release mitigation, the radiological releases are dominated by volatile nuclides of iodine, cesium, and tellurium, and to a lesser extent, by the release of nuclides of molybdenum, strontium, and barium. While quantitatively significant releases of the other nuclides that are shown to be important in terms of early health effects are not envisioned.

Furthermore, the analysis results for the latent health effects have also shown that these effects are dominated by nuclides of americium, cesium, cobalt, curium, and plutonium (note that also important are nuclides of ruthenium, strontium, yttrium, and cerium due to exposure to the plume), if an equal and complete release of these nuclides were to be postulated. Here again, during severe accidents, quantitatively large releases for the aforementioned nuclides other than cesium are not likely. Therefore, cesium remains as the nuclide of greatest significance from a standpoint of long-term effects, for severe accidents. The analyses also showed that the noble gases are of little significance in terms of either early or latent health effects.

The paper also examined the implications of using several alternatives to define the large (including large early) release frequency for risk-informed regulatory applications, ranging from simple criteria based on release class characteristics and threshold values, to those that are aimed at minimizing early (e. g., early fatalities) and latent (e. g., land contamination) radiological consequences.

The paper showed that alternatives that are based on latent effects are obviously more restrictive than those that are based on early fatality effects. Furthermore, for large power reactors, those alternatives that are defined on the basis of simple release class characteristics and threshold values are generally easier to implement and verify for regulatory applications (i. e., they are less susceptible to computational assumptions, and analytically straightforward to calculate).

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