PRELIMINARY WORST-CASE ACCIDENT ANALYSIS TO SUPPORT THE CONCEPTUAL DESIGN OF A POTENTIAL REPOSITORY IN TUFF[a]

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ABSTRACT

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is conducting investigations to determine the suitability of a site at Yucca Mountain for development as a high level waste repository. In support of the conceptual design, a preliminary analysis has been performed to identify events that could cause radiological releases from the surface facilities during the operations period. Accidental releases were modeled as short-duration release plumes, dispersed under averaged climatic conditions, using the AIRDOS-EPA code. The consequences of these accidents, in 50-yr integrated dose commitments to operations personnel, to the maximally exposed member of the public, and to the general population in the surrounding area were calculated. The risk to the general public from each event was also assessed. All postulated accidents result in doses to members of the public that are lower than the 0.5 rem/accident limit set by the NRC in 10 CFR 60. For those accidents that do not involve both fire and breach of waste canisters, doses to operations personnel are within the NRC limit for routine operations of 5 rem/yr set in 10 CFR 20. Accidents that involve fire and breach of waste canisters may cause doses to some operations personnel that are in excess of this limit.

BACKGROUND

A preliminary safety assessment of the surface facility at a potential nuclear waste repository was performed in support of the conceptual design effort for a repository at Yucca Mountain, Nevada. This paper summarizes the results of the safety assessment.[1] The site being investigated by the Nevada Nuclear Waste Storage Investigations (NNWSI) Project lies on and adjacent to the Nevada Test Site (NTS) (Fig. 1). Using preliminary meteorological data, site location, and repository design information,[2] the safety of operations personnel and the population in nonrestricted areas was examined by postulating several potentially hazardous events involving spent fuel and commercial high level waste (CHLW). The possible worst-case scenarios from among these events will be analyzed again later, using more complete and site-specific information.

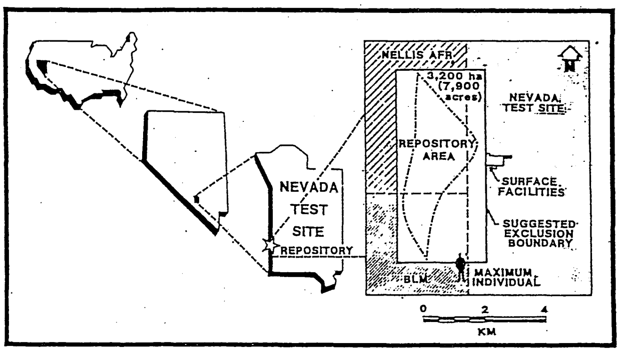

Fig. 1. General area for potential NNWSI geologic repository.

METHODOLOGY

Accident Screening

A probabilistic risk assessment approach was adopted for the repository surface facility accident analysis and risk assessment.[3] All external events specific to the site and plant type were identified

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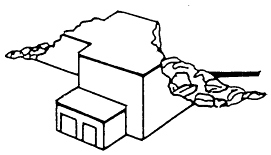
according to a standard list.[3] The events include natural phenomena and external man-made accidents. The development of operations-specific accidents was based on repository waste handling procedures. Each event was reviewed against screening criteria to identify the bounding cases. Nine potentially hazardous events were identified as requiring detailed analysis. The release scenarios used to evaluate these initiating events are described below.

Flood

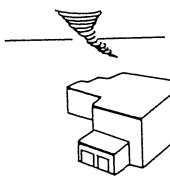
One possible location for the surface facility is transected by the upper reach of Drillhole Wash. This location is within the 100-yr flood plain.[4] A deluge is postulated that produces the 100-yr flood, which overruns and suspends material from the decontamination sludge pit.

Earthquake



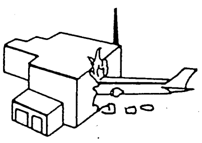
The most probable peak ground acceleration at the site is 0.4 g; the calculation is based on a rupture of the Bare Mountain Fault.[5] It is postulated that the ground motion causes electrical power failure. The negative atmospheric pressure in the hot cells where fuel assemblies are consolidated is lost, allowing released fission gases from failed fuel rods to contaminate the surface facility.

Tornado



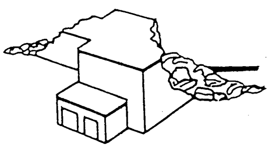
The design safety tornado for NTS has a maximum windspeed of 338 km/hr (210 mph).[6] Such an event could cause electrical power failure, disrupting the atmospheric protection system. Air from the hot cells, which is contaminated with fission gases leaked through failed fuel rods, is assumed to contaminate the surface facility.

Aircraft Impact



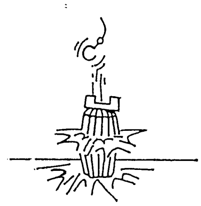
A large aircraft is assumed to strike the surface facility, penetrate a hot cell, and rupture canisters stored for emplacement underground. An aviation-fuel fire volatilizes fission gases and solid fuel-rod material in a ground-level release.

Underground Nuclear Explosive Test



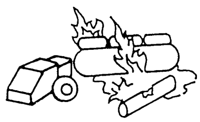
An underground nuclear test explosion conducted elsewhere on the NTS is assumed to produce a peak acceleration at the surface facility sufficient to cause electrical power failure. Through human error, canisters contained in a hot cell might not be secured properly. A consequence could be failure of hot cell atmospheric containment and the release of fission gases into the surface facility.

Fuel Assembly Drop in Hot Cell



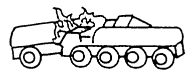
During repackaging operations, an assumed equipment malfunction allows a pressurized water reactor (PWR) fuel rod assembly to be dropped inside a hot cell. The shock causes 20% of the fuel rods to rupture and fission gases and some particulate matter to escape. This release is vented through the atmospheric protection system via the stack.

Transportation Accident and Fire at Loading Dock



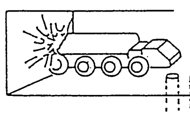
A truck transporting canistered HLW to the surface facility is assumed to be involved in a severe accident at the loading dock. The shipping cask and canister are breached, and a diesel-fuel fire volatilizes fission gases and other radioactive material in a ground-level release. Both spent fuel and vitrified CHLW are considered.

Transportation Accident and Fire on the Waste Handling Ramp



A transporter vehicle moving a waste emplacement canister down the access ramp into the repository is assumed to collide with another transporter. The impact causes the canister to rupture, and a diesel-fuel fire volatilizes fission gases and other radioactive material. The ventilation system moves the release cloud down the ramp, through a waste emplacement drift, and out the upcast shaft.

Transportation Accident and Fire in the Repository Emplacement Drift



A transporter carrying a waste emplacement canister is assumed to collide with the emplacement drift wall. The impact causes the canister to rupture, and a diesel-fuel fire volatilizes the fission gases and other radionuclides. The ventilation system moves the release cloud through the emplacement drift and out the upcast shaft.

Dose Calculations, Health Effects, and Risk Assessment

The methods used in calculating doses for this study are consistent with requirements of Reg. Guide 1.109.[7] Whole-body dose calculations are based on the ICRP-2[8] recommendations. Each of the calculated dose commitments reported in this study is made up of an acute exposure and a chronic exposure component. The acute exposure is the amount of radiation received during the accident from direct exposure to radioactive materials. The chronic exposure is the amount of radiation received after the accident from radioactive materials that have been incorporated into the body. Chronic exposures are more easily tolerated by the body because of its recuperative capacity than are acute exposures. Depending on the radionuclides involved, this chronic exposure can be received primarily in the first year after the accident, as from Ru-106, or be distributed more equally over the 50 yr for which dose is calculated, as from Pu-241. Radionuclide releases and subsequent human exposures are modeled using the AIRDOS-EPA Code.[9] The airborne releases are treated as short-duration release plumes that diffuse following a modified Gaussian distribution driven by wind. Both ground-level and stack-height releases are considered. Because of the unavailability of site-specific detailed meteorological data, information from the Yucca Flat Weather Station summarized from April 1957 to December 1964[18] was used. This station is approximately 25 mi northeast of the Yucca Mountain area currently considered for the repository surface facilities. Meteorological data being collected at the potential repository location will be used for the final analysis of the possible worst-case accidents.

The source terms and exposure pathways were used to calculate 50-yr whole-body equivalent dose commitments for the operations personnel and population residing within 50 mi (80 km) of the site. The maximally exposed member of the public is located 2.5 mi (4 km) southwest of the surface facility on Bureau of Land Management land (Fig. 1). This location assumes that the minimum amount of land is withdrawn from public access, 7,900 acres (3,200 ha).[11] The maximum individual dose is calculated by assuming that the entire release plume passes directly over this individual at average wind velocity. The operations personnel doses are calculated assuming total and instantaneous mixing of the release plume in an enclosed building space or in a minimum-volume hypothetical hemisphere for releases that occur outside the facility.

The population dose commitment is the sum of the population doses calculated for each radial interval and sector within the 80-km (50-mi) area surrounding the potential repository site (Fig. 1). The average annual atmospheric dispersion factor based on daily averaged meteorological data and radionuclide depletion for each zone is used to calculate the individual dose per zone. This average individual dose is then multiplied by the calculated population in each zone to give the total population dose in man-rem. The population distribution within the study area was calculated assuming an even distribution of county populations among the sectors. Dose commitments for operations personnel were compared with the 10 CFR 20 exposure limit for routine operations of 5 rem/yr, 3 rem/quarter.[12] Dose commitments to the maximally exposed individual were compared with the accidental dose limit specified in 10 CFR 60 for the general public of 0.5 rem/accident.[13]

Dose commitments were converted to estimated health effects as another measure of accident consequence. Health effects are the excess cancer deaths predicted in a population exposed to a specified dose of low-level radiation. The conservative BEIR III linear, nonthreshold model[14] that correlates 10^6 man-rem with 75-230 excess cancer deaths was used.

Risk is the product of the consequence of an event (dose commitment) and the probability of the event's occurrence. The probability of occurrence of each accidental radionuclide release was estimated by making an extremely conservative assumption: the probability is assumed to be that of the initiating event, disregarding the probability of failure of containment barriers that would isolate radioactive material from the accessible environment. Because insufficient information was available to make a complete assessment of failure probabilities, the assessment was based on this conservative assumption. Probabilities will be refined when more detailed information is developed.

RESULTS AND DISCUSSION

Dose Commitments, Health Effects, and Risk to the General Public

The results of the dose calculations, conversion to health effects, and probabilities of occurrence are given in Table I. All dose commitments to the maximally exposed individual and to the general public are less than the 0.5 rem/accident limit set in 10 CFR 60. The largest dose commitment to the maximally exposed individual is 0.328 rem, resulting from the aircraft impact scenario. Of this amount, approximately 8% or 2.6×10^{-2} rem is an acute dose and 92% or 3.02×10^{-1} rem is a chronic dose commitment. The acute dose is received during the time of direct exposure to the release plume. Short-term health effects in people have not been observed below acute doses of about 25 rem. The chronic dose is received over 50 years and is due to decay of radionculides incorporated into the body. The effect of chronic doses has been assessed using the BEIR III relationship of dose to health effects. Dose to the estimated population of 19,908 living within 50 mi (80 km) of the aircraft impact scenario is 121 man-rem. In comparison, the background radiation effects from cosmic and terrestrial radiation in the same area is 0.09-0.10 rem/yr to an individual[15] or 1,800-2,000 man-rem/yr to the population. Less than one additional cancer death is estimated in the population living in the study area from any accident assessed. This analysis indicates that the radiation effect on the general population from potentially hazardous events could not be distinguished from background radiation effects.

Upper limits to the probabilities of occurrence per year determined for each scenario range from 1×10^{-2} for flooding to $<9.1 \times 10^{-11}$ for tornado.[1] The probability of each accident involving canister breach and fire (i.e., accident at the loading dock, waste handling ramp, and the emplacement drift) is the product of two probabilities: the probability that the accident would occur and the probability that the accident would be severe enough to cause the release of radioactive materials. The latter probability is 1×10^{-7} per year.[16] The former probability will be determined in future studies, but because it must be <1.0, the overall probability of each accident is $<1 \times 10^{-7}$ per year. Estimates of risk range from 8.21×10^{-6} man-rem/yr for the accident in which a fuel assembly drops in the hot cell, to 1.32×10^{-14} man-rem/yr for the transportation accident and fire on the waste handling ramp and in the emplacement drift scenarios.

Worker Doses

Dose commitments to operations personnel are less than the 5 rem/yr dose limit for all accidents that do not involve canister breach and fire. The primary factors in the accidents where this dose limit is exceeded are high temperatures and heavy mechanical shock. Elevated temperatures caused by fire volatilize the halogens, volatile solids, and some of the heavy radionuclides.[17,18] The greatest dose commitment to a single worker is 334 rem received by a loading dock worker adjacent to the transportation accident and fire at the loading dock. Because of the preliminary ventilation design, a radionuclide release in the access ramp may expose workers in the waste emplacement drift. The estimated individual emplacement worker dose commitment related to transportation accident and fire on the ramp is 49.8 rem for the horizontal emplacement design, 12.8 rem for the vertical

TABLE I

Estimated Population Dose Commitments from Postulated Accidents

Scenario[b]	Probability of Event (event/yr)	Maximum Individual[a] Whole-Body Equivalent Dose (rem)	General Population: Population Exposed (number)	General Population: Whole-Body[a] Equivalent Dose (man-rem)	Range of Health Effects[d]
Exposure Limit 10 CFR 60		0.5 rem/accident whole-body dose			
Background		9.00×10^{-2} rem/yr	19,908	1.80×10^{3}	
Natural Phenomena					
Flood	1.0×10^{-2}	1.59×10^{-5}	29[c]	4.61×10^{-4}	3.46×10^{-8} to 1.06×10^{-7}
Earthquake	$<1.3 \times 10^{-3}$	2.34×10^{-4}	19,908	3.07×10^{-3}	2.31×10^{-7} to 7.07×10^{-7}
Tornado	$<9.1 \times 10^{-11}$	2.34×10^{-4}	19,908	3.07×10^{-3}	2.31×10^{-7} to 7.07×10^{-7}
Man-Made External Events					
Underground nuclear explosive test	1.0×10^{-3}	2.34×10^{-4}	19,908	3.07×10^{-3}	2.31×10^{-7} to 7.07×10^{-7}
Aircraft impact	$<2.0 \times 10^{-10}$	3.28×10^{-1}	19,908	1.21×10^{2}	9.04×10^{-3} to 2.77×10^{-2}
Operational Accidents					
Fuel assembly drop in hot cell	1.0×10^{-1}	5.14×10^{-6}	19,908	8.21×10^{-5}	6.16×10^{-9} to 1.89×10^{-8}
Transportation accident and fire at loading dock					
Spent fuel	$<1.0 \times 10^{-7}$	2.42×10^{-4}	19,908	4.04×10^{-3}	3.03×10^{-7} to 9.30×10^{-7}
CHLW	$<1.0 \times 10^{-7}$	4.35×10^{-5}	19,908	4.76×10^{-4}	3.57×10^{-8} to 1.09×10^{-7}
Transportation accident and fire on waste handling ramp	$<1.0 \times 10^{-7}$	9.64×10^{-9}	19,908	1.32×10^{-7}	9.90×10^{-12} to 3.04×10^{-11}
Transportation accident and fire in repository emplacement drift	$<1.0 \times 1.0^{-7}$	9.64×10^{-9}	19,908	1.32×10^{-7}	9.90×10^{-12} to 3.04×10^{-11}

a. Each of the calculated dose commitments reported in this study is made up of an acute exposure and a chronic exposure component. Depending on the radionuclide involved, this chronic exposure can be received primarily in the first year after the accident, as from Ru-106, or be distributed more equally over the 50 yr for which dose is calculated, as from Pu-241.

b. Except for the transportation accident and fire at the loading dock where both spent fuel and CHLW are evaluated, all scenarios are based on spent fuel.

c. Only population in the zone directly south of Drillhole Wash is exposed.

d. Health effects are cancer deaths; 75-230 excess cancer deaths may be associated with 1×10^{6} man-rem radiation exposure.[14]

emplacement design. For those accidents that involve canister breach and fire, approximately 1% to 10% of the dose commitments are acute and the remaining 90% to 99% are chronic. The loading dock worker, for example, would receive a dose commitment of 4 rem (acute) and 330 rem (chronic) for a total of 334 rem. All of the dose commitment calculations for operations personnel are conservatively based on an exposure time of 1 hr. If the workers were exposed for only 30 min, then their average dose commitment would be approximately one-half the dose calculated for a 1-hr exposure. The estimated average dose commitments to operations personnel are given in Table II. Acute and chronic components of the dose commitments to operations personnel are given in Table III.

CONCLUSIONS

According to the preliminary study, the potential repository site boundaries and design criteria used to construct other nuclear facilities appear adequate to protect the health of the general public during the operating period of the repository. The ventilation system for the ramp and underground waste emplacement area may require further evaluation because of the high potential worker doses calculated for these worst case accidents.

TABLE II

Estimated Operations Personnel Dose Commitments from Postulated Accidents

Scenario[a]	Probability of Event (event/yr)	Single Worker Whole-Body[b] Equivalent Dose (rem)	Workers Exposed (number)	Whole-Body[b] Equivalent Dose (man-rem)	Comments
Exposure Limit 10 CFR 20		5 rem/yr			
		3 rem/quarter			
Background		9.00×10^{-2} rem/yr	414[c]	3.73×10^{-1}	
			434[c]	3.91×10^{-1}	
Natural Phenomena					
Flood	1.0×10^{-2}	1.80×10^{-11}	87	1.57×10^{-9}	Only waste handling facility workers are assumed to be exposed.
Earthquake	$<1.3 \times 10^{-3}$	5.71×10^{-1}	87	4.97×10^{1}	
Tornado	$<9.1 \times 10^{-11}$	5.71×10^{-1}	87	4.97×10^{1}	
Man-Made External Events					
Underground nuclear explosive test	1.0×10^{-3}	5.71×10^{-1}	87	4.97×10^{1}	
Aircraft impact	$<2.0 \times 10^{-10}$	6.16×10^{0}	327[c]	2.01×10^{3}	All waste handling facility workers are assumed killed. Other surface and subsurface personnel are assumed to be exposed as a consequence of the accident.
			347[c]	2.14×10^{3}	
Operational Accidents					
Fuel assembly drop in hot cell	$<1.0 \times 10^{-1}$	1.25×10^{-2}	414[c]	5.18×10^{0}	All surface and subsurface personnel are assumed to be exposed equally as a consequence of the accident.
			434[c]	5.43×10^{0}	
Transportation accident and fire at loading dock					
Spent fuel	$<1.0 \times 10^{-7}$	3.34×10^{2}	17	5.68×10^{3}	Workers at the waste handling facility loading dock receive the maximum dose; remaining personnel receive the smaller dose.
		4.45×10^{-2}	397[c]	1.77×10^{1}	
			417[c]	1.86×10^{1}	
CHLW	$<1.0 \times 10^{-7}$	3.84×10^{1}	17	6.53×10^{2}	
		4.98×10^{-3}	397[c]	1.98×10^{0}	
			417[c]	2.08×10^{0}	
Transportation accident and fire on waste handling ramp	$<1.0 \times 10^{-7}$	7.23×10^{1}	6	4.34×10^{2}	Workers in the waste handling ramp area receive the maximum dose.
		4.98×10^{1}	40[c]	2.00×10^{3}	Waste emplacement workers receive a smaller dose than workers in the ramp area. Remaining personnel above ground receive the smallest dose.
		1.28×10^{1}	60[c]	7.68×10^{2}	
		7.50×10^{-2}	368	2.76×10^{1}	

TABLE II

Estimated Operations Personnel Dose Commitments from Postulated Accidents (concluded)

Scenario[a]	Probability of Event (event/yr)	Single Worker Whole-Body[b] Equivalent Dose (rem)	Workers Exposed (number)	Whole-Body[b] Equivalent Dose (man-rem)	Comments
Transportation accident and fire in repository emplacement drift	$<1.0 \times 10^{-7}$	1.86×10^{2} 1.57×10^{1} 7.50×10^{-2}	40[c] 60[c] 374	7.44×10^{3} 9.42×10^{2} 2.81×10^{1}	Waste emplacement workers receive a greater dose than above-ground operations personnel.

a. Except for transportation accident and fire at the loading dock where both spent fuel and CHLW are evaluated, all scenarios involve spent fuel.

b. Each of the calculated dose commitments reported in this study is made up of an acute exposure and a chronic exposure component. Depending on the radionuclides involved, this chronic exposure can be received primarily in the first year after the accident, as from Ru-106, or be distributed more equally over the 50 yr for which dose is calculated, as from Pu-241.

c. Horizontal emplacement of waste canisters requires an estimated 40 subsurface workers, vertical emplacement requires an estimated 60 subsurface workers.

TABLE III

Estimated Acute and Chronic Dose Commitments to Workers

		Single Worker Whole-Body Equivalent Dose					
		Acute[a]			Chronic[b]		
Scenario	Worker Location	Dose (rem)	Major Isotopes	Percent of Acute Dose	Dose (rem)	Major Isotopes	Percent of Chronic Dose
Natural Phenomena							
Flood	Drillhole Wash	1.8×10^{-11}	Co-60 Cs-134 Cs-137	31.9 43.8 24.0	NA[c]		
Earthquake	Surface facility	5.6×10^{-1}	Kr-85	99.9	5.8×10^{-3}	H-3 I-129	99.4 0.1
Tornado	Surface facility	5.6×10^{-1}	Kr-85	99.9	5.8×10^{-3}	H-3 I-129	99.4 0.1
External Man-Made Events							
Underground nuclear explosive test	Surface facility	5.6×10^{-1}	Kr-85	99.9	5.8×10^{-3}	H-3 I-129	99.4 0.1
Aircraft impact	Site--surface and subsurface	4.4×10^{-1}	Kr-85 Cs-134 Cs-137	80.8 12.0 1.0	5.7×10^{0}	H-3 Sr-90 Cs-134 Cs-137 Pu-238 Pu-241	0.6 1.0 67.7 21.8 5.3 3.8
Operational Accidents							
Fuel assembly drop in hot cell	Site--surface and subsurface	1.1×10^{-2}	Kr-85	99.9	1.2×10^{-3}	H-3	99.4
Transportation accident and fire at loading dock							
Spent fuel	Loading dock	5.5×10^{-2}	Sr-90 Y-90 Cs-134 Cs-137	12.0 60.6 11.1 14.9	3.3×10^{2}	Sr-90 Pu-238 Pu-239 Pu-241 Am-241 Cm-241	6.8 35.1 3.9 15.6 32.5 5.4

TABLE III

Estimated Acute and Chronic Dose Commitments to Workers (concluded)

		Single Worker Whole-Body Equivalent Dose					
		Acute[a]			Chronic[b]		
Scenario	Worker Location	Dose (rem)	Major Isotopes	Percent of Acute Dose	Dose (rem)	Major Isotopes	Percent of Chronic Dose
CHLW	Loading dock	6.2×10^{-3}	Sr-90	12.1	3.8×10^{1}	Sr-90	6.9
			Y-90	61.2		Pu-238	54.9
			Cs-134	11.1		Pu-239	8.9
			Cs-137	14.9		Pu-241	15.6
						Am-241	32.3
						Cm-244	5.8
Transportation accident and fire on waste handling ramp	Ramp	1.2×10^{-2}	Sr-90	12.0	7.1×10^{1}	Sr-90	6.8
			Y-90	60.6		Pu-238	35.1
			Cs-134	11.1		Pu-239	3.9
			Cs-137	14.9		Pu-241	15.6
						Am-241	32.5
						Cm-244	5.4
Transportation accident and fire in waste emplacment drift	Drift (horizontal emplacement)	3.0×10^{-2}	Sr-90	12.0	1.8×10^{2}	Sr-90	6.8
			Y-90	60.6		Pu-238	35.1
			Cs-134	11.1		Pu-239	3.9
			Cs-137	14.9		Pu-241	15.6
						Am-241	32.5
						Cm-244	5.4

a. Acute dose is exposure of the body surface by air immersion, cloudshine, and groundshine.
b. Chronic dose is inhalation and incorporation of radionuclides into the body.
c. NA = not applicable.

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