Watts Bar Nuclear Plant Severe Reactor Accident Analysis

Prepared for:

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Executive Summary

Tennessee Valley Authority (TVA) is preparing a Supplemental Environmental Impact Statement for the Watts Bar Nuclear (WBN) Plant site that includes future operation of Watts Bar Unit 2. This analysis was performed to estimate the human health impacts from potential accidents at the site. The term "accident" refers to any unintentional event (i.e., outside the normal or expected plant operation envelope) that results in a release or a potential for a release of radioactive material to the environment. The Nuclear Regulatory Commission (NRC) categorizes accidents as either design basis or severe. Design basis accidents are those for which the risk is great enough that NRC requires plant design and construction to prevent unacceptable accident consequences. Severe accidents are those that NRC considers too unlikely to warrant design controls.

TVA maintains a probabilistic safety assessment model to use in evaluating the most significant risks of radiological release from WBN fuel into the reactor and from the reactor into the containment structure. In 1995, both TVA and NRC concluded that, except for a few procedural changes implemented as part of the WBN operation, none of the Severe Accident Mitigation design alternatives were beneficial to further mitigating the risk of severe accidents. Since then, TVA has implemented the industry-required design and corresponding mitigating action changes as required by NRC for continued operation of WBN Unit 1, and is expected to implement them for operation of Unit 2. The design changes have already been implemented in the WBN Unit 1 probabilistic safety assessment model. The analysis is based on the WBN Unit 1 probabilistic safety assessment model, which considered applicable for Unit 2 operations because of its similarity to Unit 1. Only severe reactor accident scenarios leading to core damage and containment bypass or failure are considered, here. Accident scenarios that do not lead to containment bypass or failure are not presented because the public and environmental consequences would be significantly less.

The MACCS2 computer code (Version 1.13.1) was used to perform probabilistic analyses of radiological impacts. The generic input parameters given with the MACCS2 computer code that were used in the NRC's severe accident analysis (NUREG-1150) formed the basis for the analysis. These generic data values were supplemented with parameters specific to Watts Bar nuclear plant and the surrounding area. Site-specific data included population distribution, economic parameters, and agricultural product. Plant-specific release data included nuclide release, release duration, release energy (thermal content), release frequency, and release category (i.e., early release, late release). The behavior of the population during a release (evacuation parameters) was based on declaration of a general emergency and the emergency planning zone (EPZ) evacuation time. These data in combination with site specific meteorology were used to simulate the probability distribution of impact risks (exposure and fatalities) to the surrounding 80-kilometer (within 50 miles) population.

Table ES-1 summarizes the consequences of the beyond design-basis accident, with mean meteorological conditions, to the maximally exposed offsite individual, and an average individual member of population residing within an 80-kilometer (50-mile) radius of the reactor site. The analysis assumed that a site emergency would have been declared early in the accident sequence and that all nonessential site personnel would have evacuated the site in accordance with site emergency procedures before any radiological releases to the environment occurred. In addition, emergency action guidelines would have been implemented to initiate evacuation of 99.5 percent of the public within 16 kilometers (10 miles) of the plant. The location of the maximally exposed offsite individual may or may not be at the site boundary for these accident sequences because emergency action guidelines would have been

implemented and the population would be evacuating from the path of the radiological plume released by the accident.

Table ES–1 Severe Reactor Accident Annual Risks

Release Category (frequency per reactor year)	*Maximally Exposed Offsite Individual*		*Average Individual Member of Population within 80 Kilometers (50 miles)*	
	Dose Risk [a] *(rem/year)*	*Cancer Fatality* [b]	*Dose Risk* [a] *(rem/year)*	*Cancer Fatality* [b]
I - Early Containment failure (3.4×10^{-7})	2.2×10^{-5}	2.6×10^{-8}	1.8×10^{-7}	1.1×10^{-10}
II - Containment Bypass (1.4×10^{-6})	2.2×10^{-5}	1.3×10^{-8}	8.2×10^{-7}	4.9×10^{-10}
III - Late Containment Failure (3.0×10^{-6})	4.6×10^{-7}	2.8×10^{-10}	1.3×10^{-7}	7.8×10^{-11}

[a] Includes the likelihood of occurrence of each release category.
[b] Increased likelihood of cancer fatality per year.

The results presented in this table indicates that the highest risk to the maximally exposed offsite individual is one fatality every 38 million years (or 2.6×10^{-8} per year) and the highest risk to an average individual member of the public is one fatality every 2 billion years (or 4.9×10^{-10} per year). Overall, the risk results presented above are small. Completion and operation of WBN Unit 2 would not change the risks evaluated here because the likelihood of an accident that could affect both units and lead to radioactive releases beyond those analyzed here would be extremely low. This is consistent with the conclusions of NRC's Generic Environmental Impact Statement for License Renewal of Nuclear Plants, (GEIS). Accidents that could affect multiunit sites are initiated by external events. Severe accidents initiated by external events as tornadoes, floods, earthquakes, and fires traditionally have not been discussed in quantitative terms in final environmental statements and were not considered in the GEIS. In the GEIS, however, NRC staff did evaluate existing impact assessments performed by NRC and the industry at 44 nuclear plants in the United States and concluded that the risk from beyond-design-basis earthquakes at existing nuclear power plants is small. Additionally, the staff concluded that the risks from other external events are adequately addressed by a generic consideration of internally initiated severe accidents.

WATTS BAR NUCLEAR PLANT SEVERE REACTOR ACCIDENT ANALYSIS

1. Introduction

Tennessee Valley Authority (TVA) is preparing a supplemental environmental impact statement for the Watts Bar Nuclear (WBN) Plant site that includes future operation of Watts Bar Unit 2. This analysis is being performed to estimate the human health impacts from potential accidents at the site. The term "accident" refers to any unintentional event (i.e., outside the normal or expected plant operation envelope) that results in a release or a potential for a release of radioactive material to the environment. The Nuclear Regulatory Commission (NRC) categorizes accidents as either design-basis or severe. Design-basis accidents are those for which the risk is great enough that NRC requires plant design and construction to prevent unacceptable accident consequences. Severe accidents are those that NRC considers too unlikely to warrant design controls.

TVA maintains a probabilistic safety assessment (PSA) model to use in evaluating the most significant risks of radiological release from WBN fuel into the reactor and from the reactor into the containment structure. For the WBN Unit 1 Severe Accident Mitigation Design Alternative (SAMDA) analysis conducted in 1995, TVA used the PSA model output as input to an NRC-approved model that calculated economic costs and dose to the public from hypothesized releases from the containment structure into the environment. Using regulatory analysis techniques, TVA calculated the monetary value of the unmitigated WBN severe accident risks. TVA and NRC concluded that, except for a few procedural changes implemented as part of the WBN operation, none of the SAMDAs were beneficial to further mitigating the risk of severe accidents (NRC 1995). Since then, TVA has implemented the industry-required equipment design and corresponding mitigating action changes required by NRC for continued operation of WBN Unit 1 and is expected to implement them for operation of Unit 2. Therefore, prior to operation of Unit 2, the plant will meet all required designs and conditions for mitigating the risk of severe accidents.

Based on the statement of the work (TVA 2007), the analysis herein will follow a method similar to that used in the *Final Environmental Impact statement for the Production of Tritium in a Commercial Light Water Reactor* (CLWR EIS) (DOE 1999). TVA's analyses of design-basis accidents are described in the WBN Updated Final Safety Analysis Report and are not within the scope of this analysis. This analysis is limited to severe reactor accidents. The analyses presented here are based on the WBN Unit 1 PSA model, which is considered applicable for Unit 2 operations, because of the similarity to Unit 1 operations. Only severe reactor accident scenarios leading to core damage and containment bypass or failure are considered here. Accident scenarios that do not lead to containment bypass or failure are not presented because the public and environmental consequences would be significantly less. Three modes of containment failures are defined: containment bypass, early containment failure, and late containment failure (see **Table 1**).

The magnitude of the radioactive release to the atmosphere resulting from an accident depends on the timing of the reactor vessel failure and the containment failure. Source terms associated with various release categories describe the fractional releases for representative radionuclide groups, as well as the timing, duration, and energy of potential releases.

Table 1 Definition and Causes of Containment Failure Mode Classes

Failure mode	*Definition and Causes*
Containment Bypass	Involves failure of the pressure boundary between the high-pressure reactor coolant and low-pressure auxiliary system. For pressurized water reactors, steam generator tube rupture, either as an initiating event or as a result of severe accident conditions, will lead to containment bypass. In this scenario, if core damage occurs, a direct path to the environment can exist.
Early Containment Failure	Involves structure failure of the containment before, during, or slightly after (within a few hours of) reactor vessel failure. A variety of mechanisms can cause structure failure, including direct contact of core debris with containment, rapid pressure and temperature loads, hydrogen combustion, and fuel coolant interaction (ex-vessel steam explosion). Failure to isolate containment or to provide early venting of containment after core damage also is classified as early containment failures.
Late Containment Failure	Involves structural failure of the containment several hours after reactor vessel failure. A variety of mechanisms can cause late structure failure, including gradual pressure and temperature increase, hydrogen combustion, and basemat melt-through by core debris. Venting containment late in the accident also is classified as a late containment failure.

2. Representative Severe Reactor Accident Scenarios

Plant damage states that lead to containment failure (failure mode defined as bypass, early, and late) and release of radioactive materials to the environment are considered in this section. The representative accident scenarios are limited to the dominant sequence or sequences within a plant damage state that are major contributors to the release level categories associated with each of the containment failure modes defined above. The information is based on TVA's most recent analysis of severe accidents performed under the individual plant examination program, which covers both the level 1 and level 2 probabilistic risk assessments in detail. TVA's analyses of the Watts Bar and Sequoyah individual plant examinations were submitted to NRC in September 1992 (TVA 1992a, TVA 1992b). Both of these analyses have been revised since (TVA 1995, TVA 1994).

The selected release categories and examples of various accident scenarios leading to containment failure and/or bypass are presented below. Release Category I results from a reactor vessel breach with early containment failure. Release Category II results from a reactor vessel breach with containment bypass. Release Category III results from a reactor vessel breach with late containment failure. **Table 2** shows the equilibrium reactor core nuclide inventory at the time of a reactor trip (TVA 2007). **Table 3** provides important information on time to core damage, containment failure, release duration, and the isotope release fractions associated with each of the release categories (TVA 2007). **Table 4** provides a representation of the dominant accident scenarios that lead to each release category and the likelihood of their occurrence (TVA 2007).

Table 2 Watts Bar Unit 1 Core Inventory

Nuclide	*Isotope*	*Group* [a]	*Curies* [b]
Cobalt	Co-58	6	1.11E+06
	Co-60	6	8.67E+05
Krypton	Kr-83m	1	1.15E+07
	Kr-85m	1	2.39E+07
	Kr-85	1	1.03E+06
	Kr-87	1	4.81E+07
	Kr-88	1	6.66E+07
Xenon	Xe-131m	1	1.05E+06
	Xe-133m	1	6.16E+06
	Xe-133	1	1.91E+08
	Xe-135m	1	4.05E+07
	Xe-135	1	6.43E+07
	Xe-138	1	1.67E+08
Iodine	I-130	2	1.93E+06
	I-131	2	9.46E+07
	I-132	2	1.39E+08
	I-133	2	1.95E+08
	I-134	2	2.16E+08
	I-135	2	1.86E+08
Bromine	Br-83	2	1.15E+07
	Br-84	2	2.14E+07
Cesium	Cs-134	3	1.66E+07
	Cs-135	3	0.00E+00
	Cs-136	3	5.89E+06
	Cs-137	3	1.17E+07
	Cs-138	3	1.81E+08
Rubidium	Rb-86	3	1.87E+05
	Rb-88	3	6.83E+07
	Rb-89	3	8.92E+07
Strontium	Sr-89	4	9.34E+07
	Sr-90	5	8.94E+06
	Sr-91	5	1.16E+08
	Sr-92	5	1.24E+08
Yttrium	Y-90	7	9.48E+06
	Y-91m	7	6.76E+07
	Y-91	7	1.21E+08
	Y-92	7	1.25E+08
	Y-93	7	9.48E+07
	Y-94	7	1.51E+08
	Y-95	7	1.57E+08
Zirconium	Zr-95	7	1.67E+08
	Zr-97	7	1.61E+08
Niobium	Nb-95	7	1.69E+08
	Nb-97m	7	1.53E+08
	Nb-97	7	1.62E+08
Molybdenum	Mo-99	6	1.78E+08
Technetium	Tc-99m	6	1.57E+08
	Tc-99	6	0.00E+00
	Tc-101	6	1.61E+08

Nuclide	Isotope	Group [a]	Curies [b]
Ruthenium	Ru-103	6	1.48E+08
	Ru-105	6	1.00E+08
	Ru-106	6	5.00E+07
Rhodium	Rh-103m	6	1.48E+08
	Rh-105	6	9.55E+07
	Rh-106	6	5.33E+07
	Rh-107	6	5.77E+07
Antimony	Sb-127	4	8.05E+06
	Sb-129	4	3.03E+07
	Sb-130	4	1.00E+07
Tellurium	Te-125m	4	1.93E+04
	Te-127m	4	1.33E+06
	Te-127	4	7.93E+06
	Te-129m	4	5.81E+06
	Te-129	4	2.88E+07
	Te-131m	4	1.86E+07
	Te-131	4	7.99E+07
	Te-132	4	1.36E+08
	Te-133	4	1.06E+08
	Te-134	4	1.73E+08
Barium	Ba-137m	5	1.11E+07
	Ba-139	5	1.73E+08
	Ba-140	5	1.73E+08
	Ba-141	5	1.56E+08
	Ba-142	5	1.49E+08
Lanthanum	La-140	7	1.79E+08
	La-141	7	1.58E+08
	La-142	7	1.54E+08
	La-143	7	1.46E+08
Cerium	Ce-141	8	1.59E+08
	Ce-143	8	1.48E+08
	Ce-144	8	1.29E+08
Praseodymium	Pr-143	7	1.44E+08
	Pr-144	7	1.30E+08
	Pr-145	7	1.01E+08
Neodymium	Nd-147	7	6.39E+07
Neptunium	Np-239	8	1.87E+09
Plutonium	Pu-238	8	3.15E+05
	Pu-239	8	3.48E+04
	Pu-240	8	4.38E+04
	Pu-241	8	1.49E+07
	Pu-243	8	2.86E+07
Americium	Am-241	7	9.80E+03
	Am-242	7	7.93E+06
Curium	Cm-242	7	3.98E+06
	Cm-244	7	1.61E+05

[a] The grouping is based on NUREG-1465.
[b] Source: TVA 2007.

Table 3 Release Category Timing and Source Terms

Release Times, Heights, Energies, and Source Terms for Selected Release Categories					
Release Category	*Release Height (meters)*	*Warning Time (hours)*	*Release Time (hours)*	*Release Duration (hours)*	*Release Energy* [a] *(megawatts)*
I	10.00	8	10	2	28
II	10.00	20	24	4	1
III	10.00	20	30	10	3.5

Fission Product Source Terms (fraction of total inventory)										
Release Category	*NG*	*I*	*Cs*	*Te*	*Sr*	*Ru*	*La*	*Ce*	*Ba*	*Mo*
I	0.90	0.042	0.043	0.044	0.0027	0.0065	0.00048	0.004	0.0046	0.0065
II	0.91	0.21	0.19	0.0004	0.0023	0.07	0.00028	0.00055	0.025	0.07
III	0.94	0.0071	0.011	0.0052	0.00036	0.00051	4.2×10^{-6}	4.0×10^{-6}	0.0013	0.00051

NG = Noble gases.
[a] These values were taken from similar accident scenarios given in NUREG/CR-4551.
Sources: TVA 1992a, TVA 1992b, TVA 2007.

Table 4 Release Category Frequencies and Related Accident Sequences for the Watts Bar Nuclear Plant

Release Category	*Frequency*	*Remarks (Example Scenario)*
I	3.4×10^{-7}	The major accident contributors to this release event are initiated by loss of offsite power and the essential raw cooling water system; failure of the emergency diesels to start and/or failures in the 125-volt direct current distribution system, together with loss of secondary cooling; and no recovery before core melt.
II	1.4×10^{-6}	The main contributor to this release event is initiated by a steam generator tube rupture in conjunction with either an operator error or a random failure of electrical distribution systems, leading to failure of the coolant system and failure to control the affected steam generator before core melt occurs.
III	3.0×10^{-6}	The major accident contributors to this release event are initiated by loss of offsite power and various failures in the alternating current distribution systems; no recovery of power before core melts; a reactor coolant system loss-of-coolant accident (large- and medium-sized loss-of-coolant accident); and failure to establish long-term core cooling.

Source: TVA 2007.

3. Methodology for Estimating Radiological Impacts

3.1 Introduction

The MACCS2 computer code (Version 1.13.1) was used to perform probabilistic analyses of radiological impacts. A detailed description of the MACCS model is provided in NUREG/CR-4691 (NRC 1990). The enhancements incorporated in MACCS2 are described in the MACCS2 User's Guide (NRC 1998).

The input parameters given with the MACCS2 Sample Problem A, which include the data used in NUREG 1150 (NRC 1998), formed the basis for the analysis. These generic data values were supplemented with parameters specific to the WBN Plant and the surrounding area. Site-specific data included population distribution, economic parameters, and agricultural product. Plant-specific release data included nuclide release, release duration, release energy (thermal content), release frequency, and release category (i.e., early release, late release). The behavior of the population during a release (evacuation parameters) was based on declaration of a general emergency and the emergency planning zone (EPZ) evacuation time. These data, in combination with site-specific meteorology, were used to simulate the probability distribution of impact risks (exposure and fatalities) to the surrounding 80-kilometer (within 50 miles) population.

3.2 Site-Specific Parameters

This section describes the method and assumptions used to develop site-specific parameters.

Population

The population surrounding the WBN Plant site was estimated for the year 2040. The distribution is given in terms of the population at 10 distances, ranging from 0 miles to 50 miles from the plant, the direction of each of the 16 compass points (north, north-northeast, northeast, etc.), a total of 160 segments. The population projections were determined using 2000 census population data. A map was prepared displaying county and census tract boundaries for all counties partly or totally within the 50 mile boundary. County population data for 2000 were allocated to the appropriate sectors, using census tracts to the extent feasible. For segments near the plant site, especially within 5 miles, aerial photos and TVA staff knowledge of the area were also used. The segments populations were projected for the year 2040 using growth rates from county population projections (Eblen 2007). The total projected population within 50 miles of the site was estimated to be 1,523,390, (see **Table 5**).

Agriculture and Economy

Agriculture production information was generated using SECPOP 2000. SECPOP provides the MACCS2 model with required information on the crops season and shares (fraction of land devoted to the crop). The SECPOP-generated data were compared with those used in the CLWR EIS, which was based on data for neighboring counties. The SECPOP data were considered more representative (more recent) and, except for the pasture, use larger land fractions for specific crops.

MACCS2 also requires spatial distribution of certain economic data (fraction of land devoted to farming, annual farm sales, fraction of farm sales resulting from diary production, property values of farm and nonfarm land). SECPOP also produces this data for each site. Although these data were generated and added to the site data, they were not used in the analysis.

Table 5 Projected 2040 Population Distribution within 80 Kilometers (50 miles) of Watts Bar Nuclear Plant

Direc-tion	*Miles*										
	0-1	*1-2*	*2-3*	*3-4*	*4-5*	*5-10*	*10-20*	*20-30*	*30-40*	*40-50*	*0-50*
N	0	18	0	0	135	2,465	1,885	2,778	4,768	6,172	18,222
NNE	0	0	18	411	185	1,536	11,762	18,766	14,502	2,547	49,727
NE	0	0	18	308	287	827	3,783	16,734	29,838	78,334	130,130
ENE	0	0	18	308	287	497	3,553	29,539	63,798	25,3831	351,832
E	0	8	431	308	616	552	11,352	18,647	30,063	44,013	105,990
ESE	0	0	0	27	41	68	6,230	20,120	5,068	3,280	34,833
SE	8	0	0	29	39	135	19,852	15,185	3,950	4,822	44,020
SSE	21	0	0	246	413	103	8,951	12,907	2,918	48,593	74,151
S	16	0	0	0	1,983	3,824	4,586	42,883	56,430	17985	127,707
SSW	0	0	21	0	0	546	5,725	42,517	46,281	106,392	201,482
SW	0	0	0	0	0	1,051	12,978	14,499	62,307	111,795	202,630
WSW	0	6	36	59	126	711	12,791	2,837	2,840	3,372	22,778
W	0	14	22	101	90	710	3,406	5,555	2,944	5,474	18,316
WNW	0	0	22	126	79	490	2,091	4,372	5,654	20,511	33,345
NW	0	108	332	376	526	2,655	2,889	18,634	10,462	15,956	51,940
NNW	0	0	0	173	123	3,116	1,536	33,843	11,609	5,890	56,290
Total	45	154	918	2,472	4,930	19,286	11,3370	299,816	353,432	728,967	1,523,390

Note: To convert from mile to kilometer multiply the value by 1.609.
Source: Eblen 2007

Evacuation

Evacuation data, including delay time before evacuation, area evacuated, average evacuation speed, and travel distance, was obtained from the *Tennessee Multi-Jurisdictional Radiological Emergency Response Plan for the Watts Bar Nuclear Plant,* Annex H (TVA 2006). For this analysis, the evacuation and sheltering region was defined as a 10-mile radial distance (the EPZ) centered on the plant. A sheltering period was defined as the phase occurring before initiation of evacuation procedures. During the sheltering period, shielding factors appropriate for sheltered activity were used to calculate doses to individuals in contaminated areas.

At the end of the sheltering period, residents would begin traveling out of the region. Travel speeds and delay times were based on the evacuation data also found in the *Tennessee Multi-Jurisdictional Radiological Emergency Response Plan for the Watts Bar Nuclear Plant,* Annex H (TVA 2006). General population evacuation times for the various areas within the 10-mile radius were averaged to determine an overall evacuation delay time and evacuation speed. Average evacuation speeds based on the most conservative general population evacuation times in an adverse weather condition were considered (see **Table 6**).

Table 6 Evacuation Times 0-to-16-kilometer (0-to-10-mile) Area

Evacuation Paths	*Permanent Population, Adverse Condition (hrs-min)*	*Special Population, Adverse Condition (hrs-min)*	*General Population, Adverse Condition (hrs-min)*
1	6 - 40	3 - 40	5 - 12
2	4 - 23	2 - 41	3 - 47
3	4 - 21	2 - 43	5 - 0
4	4 - 10	2 - 36	3 - 41
5	4 - 37	2 - 53	4 - 05
6	4 - 25	2 - 45	3 - 54
7	4 - 21	2 - 43	3 - 51
8	4 - 25	2 - 45	3 - 54
9	3 - 26	2 - 15	3 - 30
10	3 - 26	2 - 15	3 - 30
11	3 - 26	2 - 30	3 - 50
12	3 - 26	2 - 30	3 - 54
13	3 - 26	2 - 0	3 - 30
14	3 - 26	1 - 35	3 - 30
15	3 - 20	1 - 30	3 - 25
Total	61 - 20	37 - 21	58 - 33
Average hours	4 - 5	2 - 29	3 - 54
Average speed over 10 miles (miles per hour)	2.45	4.02	2.56
(meters per second)	1.1	1.8	1.15

Source: WBN 2006.

Based on the data cited above, an average evacuation speed of 1 meter per second following a sheltering and evacuation delay time of 45 minutes and 2.50 hours were used. These delay values are provided in the *Tennessee Multi-Jurisdictional Radiological Emergency Response Plan for the Watts Bar Nuclear Plant,* Annex H, (TVA 2006) and NUREG/CR-4551, Vol. 2 (NRC 1990). In addition, consistent with the analysis in the CLWR EIS and the NUREG-1150 evaluation of the Sequoyah Nuclear Plant, it was assumed that 99.5 percent of the population in the 10-mile EPZ would be evacuated.

For this analysis, it was conservatively assumed that persons residing farther than 10 miles away from the plant would continue their normal activities unless the following predicted radiation dose levels were exceeded. At locations where a 50-rem whole body effective dose equivalent in 1 week was predicted, it was assumed that relocation would take place after half a day. If a 25-rem whole body dose equivalent in 1 week were predicted, relocation of individuals in those sectors was assumed to take place after 1 day.

Meteorology

Annual onsite meteorology data sets from 2001 through 2005 were used to prepare the sequential hourly data (8760 hours) required for use in MACCS2 (TVA 2007). The 2002 sequential hourly meteorology data was found to result in the largest risk and was used for all of the analyses presented below. The conditional dose from each of the other years was found to be within 20 percent of the chosen year. The 2003 weather data set was found to result in the lowest population doses. Two sampling methods, bin sampling and stratified random sampling, were used. In bin sampling, the representative subset is selected by sampling the weather sequences after sorting them into weather bins defined by windspeed, atmospheric stability, and intensity and distance of the occurrence of rain. In stratified sampling, the representative subset is selected by randomly sampling hourly weather data from each day. The analysis is based four samples per day. This selection was based on a test by the developer of the MACCS code that indicated that random samples from each 6-hour interval of the year would yield results closer to those obtained from sampling all 8760 hours of the year.

4. Analysis Results

Table 7 summarizes the consequences of the beyond-design-basis accident, with mean meteorological conditions, to the maximally exposed offsite individual and an average individual in the public within an 80-kilometer (50-mile) radius of the reactor site. The analysis assumes that a site emergency would have been declared early in the beyond-design-basis accident sequence and that all nonessential site personnel would have evacuated the site in accordance with site emergency procedures before any radiological releases to the environment occurred. In addition, emergency action guidelines would be implemented to initiate evacuation of the public within 16.1 kilometers (10 miles) of the plant. The location of the maximally exposed offsite individual may or may not be at the site boundary for these accident sequences because emergency action guidelines would have been implemented and the population would be evacuating from the path of the radiological plume released by the accident. The MACCS2 computer code models the evacuation sequence to estimate the dose to the maximally exposed individual and the general population within 80 kilometers (50 miles) of the accident. **Table 8** summarizes the risks associated with the beyond-design-basis accident to the same receptors in terms of latent cancer fatalities (considering the likelihood of occurrence for each release category). The frequency of each release category is given in Table 4. **Table 9** shows the population dose risks (accident consequence multiplied by the release frequency) for each accident release category.

Table 7 Severe Reactor Accident Consequences

Release Category	*Maximally Exposed Offsite Individual*		*Average Individual Population within 80 Kilometers (50 miles)*	
	Dose (rem)	*Cancer Fatality* [a]	*Dose (rem)*	*Cancer Fatality* [a]
Weather Bin Sampling				
I - Early Containment Failure	64.8	0.078	0.53	0.00032
II - Containment Bypass	15.62	0.0094	0.59	0.00035
III - Late Containment Failure	0.131	0.000079	0.042	0.000025
Weather Stratified Sampling				
I - Early Containment Failure	42.6	0.051	0.43	0.00026
II - Containment Bypass	12.0	0.0072	0.50	0.00030
III - Late Containment Failure	0.153	0.000092	0.037	0.000022

[a] Increased likelihood of cancer fatality based on the health risk factor of 0.0006 cancers per rem for exposures below 20 rem. For exposures greater than or equal to 20 rem, the health risk factor is doubled.

Table 8 Severe Reactor Accident Annual Risks

Release Category	*Maximally Exposed Offsite Individual*		*Average Individual Population within 80 Kilometers (50 miles)*	
	Dose [a] (rem/year)	*Cancer Fatality [b]*	*Dose [a] (rem/year)*	*Cancer Fatality [b]*
Weather Bin Sampling				
I - Early Containment Failure	2.2×10^{-5}	2.6×10^{-8}	1.8×10^{-7}	1.1×10^{-10}
II - Containment Bypass	2.2×10^{-5}	1.3×10^{-8}	8.2×10^{-7}	4.9×10^{-10}
III - Late Containment Failure	3.9×10^{-7}	2.4×10^{-10}	1.3×10^{-7}	7.8×10^{-11}
Weather Stratified Sampling				
I - Early Containment Failure	1.4×10^{-5}	1.7×10^{-8}	1.5×10^{-7}	9.0×10^{-11}
II - Containment Bypass	1.7×10^{-5}	1.0×10^{-8}	7.0×10^{-7}	4.2×10^{-10}
III - Late Containment Failure	4.6×10^{-7}	2.8×10^{-10}	1.1×10^{-7}	6.6×10^{-11}

[a] Includes the likelihood of occurrence of each release category.
[b] Increased likelihood of cancer fatality per year.

Table 9 Annual 80-Kilometer (50-mile) Population Dose Risk

Release Category	*Weather Bin Sampling*	*Weather Stratified Sampling*
	Dose [a] (person-rem/year)	*Dose [a] (person-rem/year)*
I - Early Containment Failure	0.28	0.23
II - Containment Bypass	1.25	1.07
III - Late Containment Failure	0.19	0.17

[a] Includes the likelihood of occurrence of each release category. The population within 80 kilometers (50 miles) is projected to be 2,104,700.

The risk results presented here are generally lower than those given in the CLWR EIS for the same accidents due to the use of different data inputs such as lower release frequency, higher core inventory, and slower evacuation speed. The release frequencies used in this analysis are lower by a factor 2 to 5 than those used in the CLWR EIS. These frequencies are based on Revision 3 of the WBN Plant probabilistic safety assessment model (TVA 2007). The ratio of isotopic core inventory is higher by a factor 1 to 3. The evacuation speed is slower by a factor of 2/3, and the population is almost 1.5 times that projected in the CLWR EIS. The latter increases resulted in higher average individual population doses as compared to those projected in the CLWR EIS.

The results presented in Tables 7 through 9 indicate that the highest risk to the maximally exposed offsite individual is one fatality every 38 million years (or 2.6×10^{-8} per year), and highest risk to an average individual member of the public is one fatality every 2 billion years (or 4.9×10^{-10} per year). Overall, the risk results presented above are small. Completion and operation of WBN Unit 2 would not change the risks evaluated here because the likelihood of an accident that could affect both units and lead to radioactive releases beyond those analyzed here is extremely low. This is consistent with the conclusions of NRC's *Generic Environmental Impact Statement for License Renewal of Nuclear Plants* (GEIS) (NRC 1996). Accidents that could affect multiunit sites are initiated by external events. Severe accidents initiated by external events as tornadoes, floods, earthquakes, and fires traditionally have not been discussed in quantitative terms in final environmental statements and were not considered in the GEIS (NRC 1996). In the GEIS, however, NRC staff did evaluate existing impact assessments performed by NRC and the industry at 44 nuclear plants in the United States and concluded that the risk from beyond-design-basis earthquakes at existing nuclear power plants is small. Additionally, the staff concluded that the risks from other external events are adequately addressed by a generic consideration of internally initiated severe accidents.

4.1 Sensitivity Analysis

This section discusses how changes in the analysis assumptions would affect the calculated consequences. The parameters evaluated in this section include release energy, evacuation speed, evacuation fraction with a 16-kilometer EPZ, and release frequency. The effect of the weather sampling method is provided in the baseline analysis above. For the sensitivity evaluations, the input parameters corresponding to Release Category I were used. For each evaluation, only the selected input parameter would be changed.

Release Energy

The release energy (heat content) would lift the plume to a higher elevation where it would spread over a large area downwind from the accident. This effect would reduce the plume contaminant concentration in the vicinity of the plant. Since the analysis used complete washout of the plume at the last ring, the effect of the release energy on the population beyond 50 miles would be negligible. For this analysis, the release energy was reduced from 28 MW to 1 MW. The results indicate that the new population dose risk would decrease by about 22 percent. The dose to nearby residents in the vicinity of the plant would increase, but because these individuals would be evacuated or sheltered, the health effects would be small.

Evacuation Speed

The evacuation speed used in the baseline analysis was 1.0 meter per second, or 2.34 miles per hour. The evacuation time analysis for the 0-to-10-kilometer (0-to-10-mile) area given in the *Tennessee Multi-Jurisdictional Radiological Emergency Response Plan for the Watts Bar Nuclear Plant,* Annex H, (TVA 2006) shows a range of evacuation times from 2 to more than 6 hours, with an average duration value of 4 hours. For the sensitivity analyses, average evacuation speeds of 1.5 and 0.7 meters per second (or 3.36 and 1.57 miles per hour) were used. The new population dose risks for these evacuation speeds were determined to be within 0.96 and 1.06 of the baseline consequences for the cases with the 1.5 and 0.7 meters per second evacuation speeds, respectively.

Evacuation Fraction

The baseline public evacuation fraction within the 16-kilometer (10-mile) EPZ was 99.5 percent. For this analysis, it was assumed that 95 percent of the public would be evacuating. The new population dose risk did not increase the baseline dose risk, the change was within the roundup of MACCS2 numerical output. Therefore, the impact of lower evacuation fraction would be negligible.

Release Frequency

The risks of accidents are proportional to their projected frequency of occurrence. The release frequency values provided in Table 4 are best estimate values. The 95^{th} percentile uncertainty on these estimates could range between 2 to 5 (TVA 2007). Therefore, the population dose risk could vary proportionally as well. The final risk results would be small (see Table 9).

5. MACCS2 Computer Code

The MACCS2 computer code, Version 1.13.1, was used to estimate the radiological doses and health effects that could result from postulated accidental releases of radioactive materials to the atmosphere.

The specification of the release characteristics, designated a "source term," can consist of up to four Gaussian plumes that are often referred to simply as "plumes."

The radioactive materials released are modeled as being dispersed in the atmosphere where they are transported by the prevailing wind. During transport, whether or not there is precipitation, particulate material can be modeled as being deposited on the ground. If contamination levels exceed a user-specified criterion, mitigative actions can be triggered to limit radiation exposures.

Two aspects of the code's structure are basic to understanding its calculations: (1) the calculations are divided into modules and phases, and (2) the region surrounding the facility is divided into a polar-coordinate grid. These concepts are described in the following sections.

MACCS2 is divided into three primary modules: ATMOS, EARLY, and CHRONC. Three phases are defined as the emergency, intermediate, and long-term phases. The relationship among the code's three modules and three phases of exposure are summarized below.

The ATMOS module performs calculations pertaining to atmospheric transport, dispersion, and deposition, as well as the radioactive decay that occurs before release and while the material is in the atmosphere. It utilizes a Gaussian plume model with Pasquill-Gifford dispersion parameters. The phenomena treated include building wake effects, buoyant plume rise, plume dispersion during transport, wet and dry deposition, and radioactive decay and in-growth. The results of the calculations are stored for use by EARLY and CHRONC. In addition to the air and ground concentrations, ATMOS stores information on wind direction, arrival and departure times, and plume dimensions.

The EARLY module models the time period immediately following a radioactive release. This period is commonly referred to as the emergency phase. The emergency phase begins at each successive downwind distance point where the first plume of the release arrives. The duration of the emergency phase is specified by the user and can range between 1 and 7 days. The exposure pathways considered during this period are direct external exposure to radioactive material in the plume (cloudshine), exposure from inhalation of radionuclides in the cloud (cloud inhalation), exposure to radioactive material deposited on the ground (groundshine), inhalation of resuspended material (resuspension inhalation), and skin dose from material deposited on the skin. Mitigative actions that can be specified for the emergency phase include evacuation, sheltering, and dose-dependent relocation.

The CHRONC module performs all of the calculations pertaining to the intermediate and long-term phases. CHRONC calculates the individual health effects that result from both direct exposure to contaminated ground and inhalation of resuspended materials, as well as indirect health effects caused by the consumption of contaminated food and water by individuals who could reside both on and off the computational grid.

The intermediate phase begins at each successive downwind distance point upon conclusion of the emergency phase. The user can configure the calculations with an intermediate phase that has a duration as short as zero or as long as 1 year. Essentially, there is no intermediate phase, and a long-term phase begins immediately upon conclusion of the emergency phase.

These models are implemented on the assumption that the radioactive plume has passed and the only exposure sources (groundshine and resuspension inhalation) are from ground-deposited material. For this reason, MACCS2 requires the total duration of a radioactive release to be limited to no more than 4 days. Potential doses from food and water ingestion during this period are not considered.

The mitigative action model for the intermediate phase is very simple. If the intermediate phase dose criterion is satisfied, the resident population is assumed to be present and subject to radiation exposure from groundshine and resuspension for the entire intermediate phase. If the intermediate phase exposure exceeds the dose criterion, then the population is assumed to be relocated to uncontaminated areas for the entire intermediate phase.

The long-term phase begins at each successive downwind distance point after conclusion of the intermediate phase. The exposure pathways considered during this period are groundshine, resuspension inhalation, and food and water ingestion.

The exposure pathways considered are those resulting from ground-deposited material. A number of protective measures can be modeled in the long-term phase to reduce doses to user-specified levels, including decontamination, temporary interdiction, and condemnation. The decisions on mitigative action in the long-term phase are based on two sets of independent actions: (1) decisions relating to whether land at a specific location and time is suitable for human habitation (habitability), and (2) decisions relating to whether land at a specific location and time is suitable for agricultural production (farmability).

All of the MACCS2 calculations are stored on the basis of a polar-coordinate spatial grid that treats calculations of the emergency phase and calculations of the intermediate and long-term phases somewhat differently. The region potentially affected by a release is represented with an (r,θ) grid system centered on the location of the release. The radius, r, represents downwind distance. The angle, θ, is the angular offset from north, going clockwise.

The user specifies the number of radial divisions and their endpoint distances. The angular divisions used to define the spatial grid are fixed in the code and correspond to the 16 points of the compass (each is 22.5 degrees wide). The 16 points of the compass are used in the U.S. to express wind direction. The compass sectors are referred to as the coarse grid.

Since emergency phase calculations use dose-response models for early fatalities and early injuries that can be highly nonlinear, these calculations are performed on a finer grid basis than the calculations of the intermediate and long-term phases. For this reason, emergency phase calculations are performed with the 16 compass sectors divided into three, five, or seven equal, angular subdivisions. The subdivided compass sectors are referred to as the fine grid.

The compass sectors are not subdivided into fine subdivisions for the intermediate and long-term phases because these calculations are limited to cancer and genetic effects and do not include estimates of the often highly nonlinear early fatality and early injury health effects. In contrast to the emergency phase, the calculations for these phases are performed using doses averaged over the full 22.5-degree compass sectors of the coarse grid.

Two types of doses, "acute" and "lifetime," may be calculated using the MACCS2 code. Acute doses are calculated to estimate deterministic health effects that can result from high doses delivered at high dose rates. Such conditions may occur in the immediate vicinity of a nuclear power plant following a hypothetical severe accident where containment failure has been assumed to occur. Examples of health effects based on acute doses are early fatality, prodromal vomiting, and hypothyroidism. Lifetime doses are the conventional measure of detriment used for radiological protection. These are 50-year dose commitments to either specific tissues (e.g., red marrow, lungs) or a weighted sum of tissue doses defined by the International Commission on Radiological Protection and referred to as an "effective dose." Lifetime doses may be used to calculate the stochastic health effect risk resulting from exposure to radiation. MACCS2 uses the calculated lifetime dose in cancer risk calculations.

5.1 Data and General Assumptions

To assess the consequences of beyond-design-basis accidents, the following data and assumptions were incorporated into the MACCS2 analysis.

- The **nuclide inventory** at accident initiation (e.g., reactor trip) of those radioactive nuclides that are important for the calculation of offsite consequences is given in Table 2.

- The **atmospheric source term** produced by the accident was described by the number of plume segments released; sensible heat content; timing; duration; height of release for each plume segment; time when offsite officials are warned that an emergency response should be initiated; and for each important radionuclide, the fraction of that radionuclide's inventory released with each plume segment. The release fractions for each accident scenario are provided in Table 3. MACCS2 calculates the atmospheric source terms based on the core nuclide inventory at the time of reactor trip, release time after the reactor trip, and the associated release fractions.

- **Meteorological data** characteristics of the site region were described by 1 year of hourly windspeed, atmospheric stability, and rainfall recorded at each site. Although 1 year of hourly readings contains 8,760 weather sequences, MACCS2 calculations examine only a representative subset of these sequences. As stated earlier in Section 3.1.2, two types of weather sampling were used: bin sampling and stratified sampling. These two methods are the most used methods selected by MACCS users. Bin sampling requires the user to provide rain intensity at downwind distances; stratified sampling is a purely random selection of hourly data from those occurring at the site. The analysis was based on 139 weather data in bin sampling and 1460 weather data in stratified sampling. Stratified random sampling resulted in less than 10 percent higher doses.

- **Population distribution information** regarding the Watts Bar site was based on data from the 2000 census as used in the SECPOP 2000 computer code (NRC 2003). The generated population data for the site was extrapolated to the year 2030 using the incremental increase in population during the decade recorded from census 1990 to 2000). This data is provided in Table 5 for a polar coordinate grid with 16 angular sectors aligned with the 16 compass directions and 10 radial intervals that extend outward to 80 kilometers (50 miles).

- **Habitable land fractions** for the region around each reactor site were determined in a manner similar to the population distribution. The census block group boundary files include polygons that are classified as water features. The percentage of each sector that is covered by water was determined by fitting this data to the polar coordinate grid.

- **Farmland fractions** are the percentage of land devoted to farming (DOE 1999).

- **Emergency response assumptions** for evacuation, including delay time before evacuation, area evacuated, average evacuation speed, and travel distance, are provided in the Tennessee Multi-Jurisdictional Plans, see Section 3.1.2. Average evacuation speeds are based on the most conservative general population evacuation times.

- **Shielding and exposure data** must be input into the MACCS2 code. The code requires shielding factors to be specified for people evacuating in vehicles (cars, buses); taking shelter in structures (houses, offices, schools); and continuing normal activities either outdoors, in vehicles, or indoors. Because inhalation doses depend on breathing rate, breathing rates must be specified for people who are continuing normal activities, taking shelter, and evacuating. Since indoor concentrations of gasborne radioactive materials are usually substantially less than outdoor concentrations, MACCS2 also requires that inhalation and skin protection shielding factors (indoor/outdoor concentration ratios) be provided.

The protection factors presented in **Table 10** were used in this analysis. The values in this table are for the Sequoyah Nuclear Plant, as stated in NUREG/CR-4551, and were used in the analysis for the WBN Plant.

Table 10 NUREG/CR–4551 Protection Factors

Protection Factor [a]	*Evacuees*	*Sheltering*	*Normal Activities*
Cloudshine Shielding Factor	1.0	0.65	0.75
Skin Protection Factor	1.0	0.33 [b]	0.41 [b]
Inhalation Protection Factor	1.0	0.33 [b]	0.41 [b]
Groundshine Shielding Factor	0.5	0.2	0.33 [c]

[a] A protection factor of 1.0 indicates no protection, while a protection factor of 0.0 indicates 100 percent protection.
[b] These values were based on the recommendation from S. Acharya of NRC as it appears in Appendix A-2 of NUREG/CR-4551, Vol. 2. The recommended values in the report are 0.2 and 0.5 for sheltering and normal activities, respectively (NUREG/CR-4551, Vol. 2, Table 3.12).
[c] This value was based on the recommendation from S. Acharya of NRC as it appears in Appendix A-2 of NUREG/CR-4551, Vol. 2. The recommended value in the report is 0.5 (NUREG/CR-4551, Vol. 2, Table 3.12).

For this analysis, the evacuation and sheltering region was defined as a 10-mile radial distance centered on the plant. A sheltering period was defined as the phase occurring before initiation of the evacuation. During the sheltering period, shielding factors appropriate for sheltered activity were used to calculate doses for individuals in contaminated areas.

At the end of the sheltering period, residents begin traveling out of the region. Travel speeds and delay times are based on the Tennessee Multi-Jurisdictional Plans. The general population evacuation times for the various areas within the 10-mile radius were averaged to determine an overall evacuation delay time and evacuation speed for the WBN Plant.

- Maximally Exposed Offsite Individual (MEI) dose is the total dose estimated to be incurred by a hypothetical individual assumed to reside at a particular location on the spatial grid. Population data, therefore, have no bearing on the generation of this consequence measure. Only direct exposure is considered in these results. Exposures from ingestion of contaminated food and water are not included. In addition, generation of these results takes full account of any mitigative action models activated by exceeding the dose thresholds. During evacuation, individuals have no protection from direct exposure. Therefore, in certain scenarios, it is possible that an evacuee may incur a larger direct exposure dose than an individual who does not evacuate.
- Long-term protective measures such as decontamination, temporary relocation, contaminated crops, milk condemnation, and farmland production prohibition are based on U.S. Environmental Protection Agency (EPA) Protective Action Guides.
- Mitigative actions (relocation, evacuation, interdiction, condemnation) are implemented for beyond-design-basis accidents (vessel breach with containment bypass, vessel breach with early containment failure, and vessel breach with late containment failure).
- Dose conversion factors required by MACCS2 for the calculation of committed effective dose equivalents are cloudshine dose-rate factor; groundshine dose-rate factor; "lifetime" 50-year committed inhalation dose (used for calculation of individual and societal doses and stochastic

health effects); and 50-year committed ingestion dose (used for calculation of individual and societal doses and stochastic health effects from food and water ingestion).

5.2 Health Effects Calculations

The health consequences from exposure to radionuclides due to accidental releases were calculated. Total effective dose equivalents were calculated and converted to estimates of cancer fatalities using dose conversion factors recommended by the International Commission on Radiological Protection. For individuals, the estimated probability of a latent cancer fatality occurring was reported for the maximally exposed individual, and an average individual in the population within 80 kilometers (50 miles).

The nominal values of lifetime cancer risk for low dose or low dose rate exposure (less than 20 rad) used in this EIS are 0.0006 per person-rem for a population of all ages, including workers (ISCORS 2002). These dose-to-risk conversion factors are about 20 percent more than those established by the National Council on Radiation Protection and Measurement and used in the CLWR EIS.

The MACCS2 code was applied in a probabilistic manner using a weather bin and a stratified sampling method. Each of the sampled meteorological sequences was applied to each of the 16 sectors (accounting for the frequency of occurrence of the wind blowing in that direction). Individual doses as a function of distance and direction were calculated for each of the meteorological sequence samples. The mean dose values of the sequences were generated for each of the 16 sectors. The highest of these dose values was used for the maximally exposed individual.

6. Conclusions

Table 11 summarizes the consequences of the beyond design-basis accident, with mean meteorological conditions, to the maximally exposed offsite individual, an average individual, and the population residing within an 80-kilometer (50-mile) radius of the reactor site. The analysis assumed that a site emergency would have been declared early in the accident sequence and that all nonessential site personnel would have evacuated the site in accordance with site emergency procedures before any radiological releases to the environment occurred. In addition, emergency action guidelines would have been implemented to initiate evacuation of 99.5 percent of the public within 16 kilometers (10 miles) of the plant. The location of the maximally exposed offsite individual may or may not be at the site boundary for these accident sequences because emergency action guidelines would have been implemented and the population would be evacuating from the path of the radiological plume released by the accident.

Table 11 Severe Reactor Accident Annual Risks

Release Category (frequency per reactor year)	*Maximally Exposed Offsite Individual*		*Population within 80 Kilometers (50 miles)*		
			Average Individual		*General public*
	Dose Risk [a] (rem/year)	*Cancer Fatality [b]*	*Dose Risk [a] (rem/year)*	*Cancer Fatality [b]*	*Dose Risk [a] (person-rem/year)*
Maximum dose and risk [c]					
I - Early Containment failure (3.4×10^{-7})	2.2×10^{-5}	2.6×10^{-8}	1.8×10^{-7}	1.1×10^{-10}	0.28
II - Containment Bypass (1.4×10^{-6})	2.2×10^{-5}	1.3×10^{-8}	8.2×10^{-7}	4.9×10^{-10}	1.25
III - Late Containment Failure (3.0×10^{-6})	4.6×10^{-7}	2.8×10^{-10}	1.3×10^{-7}	7.8×10^{-11}	0.19

[a] Includes the likelihood of occurrence of each release category.
[b] Increased likelihood of cancer fatality per year.
[c] These values are taken from Tables 8 and 9; the maximum dose to a maximally exposed offsite individual is from weather bin sampling and the maximum dose to an average individual and population is from weather stratified sampling.

The results presented in this table indicates that the highest risk to the maximally exposed offsite individual is one fatality every 38 million years (or 2.6×10^{-8} per year), and the highest risk to an average individual member of the public is one fatality every 2 billion years (or 4.9×10^{-10} per year). Overall, the risk results presented above are small. Completion and operation of WBN Unit 2 would not change the risks evaluated here because the likelihood of an accident that could affect both units and lead to radioactive releases beyond those analyzed here would be extremely low. This is consistent with the conclusions of NRC's GEIS (NRC 1996). Accidents that could affect multiple units are initiated by external events. Severe accidents initiated by external events as tornadoes, floods, earthquakes, and fires traditionally have not been discussed in quantitative terms in final environmental statements and were not considered in the GEIS (NRC 1996). In the GEIS, however, NRC staff evaluated existing impact assessments performed by NRC and the industry at 44 nuclear plants in the United States and concluded that the risk from beyond-design-basis earthquakes at existing nuclear power plants is small. Additionally, the staff concluded that the risks from other external events are adequately addressed by a generic consideration of internally initiated severe accidents.

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