11.0 Radioactive Waste Management

11.1 Source Terms

The information provided in this section defines the radioactive source terms in the reactor water and steam which serve as design bases for the gaseous, liquid and solid radioactive waste management systems.

Radioactive source term data for boiling water reactors has been incorporated in American National Standard ANSI/ANS-18.1 (Reference 11.1-1). The Standard provides bases for estimating typical concentrations of the principal radionuclides which may be anticipated over the lifetime of a BWR plant. The source term data is based on the cumulative industry experience at operating BWR plants, including measurements at several stations through 1981. It therefore reflects the influence of a number of observations made during the transition period from operation with fuel of older designs to operation with fuel of current improved designs. The source terms specified in this section were obtained by applying the procedures of Reference 11.1-1 for estimation of typical source terms and adjusting the results upward as appropriate to assure conservative bases for design.

The various radionuclides included in the design basis term have been categorized as fission products or activation products and tabulated in the subsections which follow. The lists do not necessarily include all radionuclides which may be detectable or theoretically predicated to be present. Those which have been included are considered to be potentially significant with respect to one or more of the following criteria:

(1) Plant equipment design

(2) Shielding design

(3) Understanding system operation and performance

(4) Measurement practicability

(5) Evaluation of radioactivity in effluents to the environment

11.1.1 Fission Products

11.1.1.1 Noble Radiogas Fission Products

Typical concentrations of the 13 principal noble gas fission products as observed in steam flowing from the reactor vessel are provided in the Source Term Standard ANSI/ANS-18.1 (Reference 11.1-1). Concentrations in the reactor water are considered negligible because all of the gases released to the coolant are assumed to be rapidly transported out of the vessel with the steam and removed from the system with the other non-condensables in the main condenser. As

a consequence of the immediate removal of all the gases, the expected relative mix of gases does not depend on the reactor design.

The design basis noble gas source term for ABWR is selected such that the mix is that of Reference 11.1-1 and the total of the release rates of the 13 noble gases from the vessel is 3700 MBq/s as evaluated at 30-minute decay. The noble radiogas source term rate after 30-minute decay has been used as a conventional measure of the fuel leakage rate, since it is conveniently measurable and was consistent with the nominal 30-minute offgas holdup system used on a number of early plants. A design basis noble gas release rate of 3700 MBq/s at 30-minute decay has historically been used for the design of the gaseous waste treatment systems in BWR plants (Reference 11.1-2) with satisfactory results. It was selected on the basis of operating experience with consideration given to several judgmental factors, including the implications to environmental releases, system contamination, and building air contamination. The design basis value is considered to represent a long-term average value. Operation at higher release rates can be tolerated for reasonable periods of time. Normal operational noble gas release rates for the ABWR are expected to be approximately 555 MBq/s as evaluated at 30-minute decay. This may be compared with normal release rates on the order of 1850 MBq/s based on fuel experience through the mid 1970’s (Reference 11.1-3). Consequently, continued application of the same design basis of 3700 MBq/s provides increased margin relative to expected release rates when operating with fuel of modern design. The design basis noble radiogas source terms are presented in Table 11.1-1.

11.1.1.2 Radioiodine Fission Products

For many years, design basis radioiodine source terms for BWRs have been specified to be consistent with an I-131 leak rate of 25.9 MBq/s from the fuel (Reference 11.1-2). Experience indicated that I-131 leakage rates this high would be approached only during operation with substantial fuel cladding defects. It would not be anticipated that full power operation would continue for any significant period of time with fuel cladding defects as severe as might be indicated by I-131 leakage in excess of 25.9 MBq/s.

The design basis reactor water radioiodine concentrations for the ABWR have been based on the relative mix of radioiodines in reactor water predicted by the data of Reference 11.1-1 with magnitudes increased such that the I-131 concentration is consistent with a release rate of 25.9 MBq/s from the fuel. This provides a substantial margin relative to the expected I-131 release rate of approximately 3.7 MBq/s. Reference 11.1-1 specifies expected concentrations of the five principal radioiodines in reactor water for a reference BWR design and provides the bases for adjusting the concentrations for plants with relevant plant parameters which do not match those of the reference plant. The concentration adjustment factors were calculated as described in Subsection 11.1.3 using the plant parameters in Table 11.1-6 and removal parameters from Table 11.1-7. The scale factor required to increase the I-131 concentration from that calculated using Reference 11.1-1 to the design basis value was approximately 6.7. The design basis concentrations are presented in Table 11.1-2.

The ratio of concentration in reactor steam to concentration in reactor water (carryover ratio) is taken to be 0.015 for radioiodines (Reference 11.1-1). Consequently, the design basis concentrations of radioiodines in steam are defined by multiplying the values of Table 11.1-2 by the factor 0.015.

11.1.1.3 Other Fission Products

This category includes all fission products other than noble gases and iodines and also includes transuranic nuclides. Some of the fission products are noble gas daughter products which are produced in the steam and condensate system. The only transuranic nuclide which is detectable in significant concentrations is Np-239. Concentrations of those radionuclides which are typically observable in the coolant are provided in Reference 11.1-1 for a Reference BWR plant. The Reference Plant concentrations were adjusted to obtain estimates for the ABWR plant by using the procedure described in Subsection 11.1.3 and appropriate data from Tables 11.1-6 and 11.1-7. In order to assure conservative design basis concentrations for the ABWR the results were increased by the same factor used to obtain design basis radioiodine concentrations (6.7). The design basis reactor water concentrations are presented in Table 11.1-3. The ratio of concentration in steam to concentration in water (carryover) for these nuclides is expected to be less than 0.001. The design basis concentrations in steam are obtained by multiplying the values in Table 11.1-3 by 0.001.

11.1.2 Activation Products

11.1.2.1 Coolant Activation Products

The coolant activation product of primary importance in BWRs is N-16. ANSI-18.1 (Reference 11.1-1) specifies a concentration of 1.85 MBq/g in steam leaving the reactor vessel. This is treated as essentially independent of reactor design because both the production rate of N-16 and the steam flow rate from the vessel are assumed to vary in direct proportion to reactor thermal power. The design basis N-16 concentration in steam for the ABWR is designated to be 1.85/g. This value has, in fact, been used as the design basis concentration for BWRs since the early 1970’s, and operating experience indicates that it is adequately conservative. It should be noted that a portion of the source term traditionally identified as “N-16” actually represents C-15, which is present to the extent of no more than about 0.555MBq/g. Historically, gross gamma dose rate measurements made to confirm the magnitude of the N-16 concentration have included responses to gamma-rays from C-15. Use of the combined “N-16” source term in the shielding design introduces additional conservatism because the C-15 component has a 2.45-s half-life and therefore decays more rapidly with transport time through the system than does N-16, which has a 7.1-s half-life.

The design basis N-16 concentrations in steam and reactor water are shown in Table 11.1-4. Reference 11.1-1 gives the reactor water concentration at the recirculation system nozzle as 2.2 MBq/g. Since the ABWR does not have an external recirculation loop, the reactor water

concentration has been decay-corrected to the reactor core exit to obtain an estimated value of 7.03 MBq/g.

It has been observed that during operation with intentional introduction of hydrogen to the feedwater for the purpose of controlling feedwater oxygen concentrations (i.e., with hydrogen water chemistry), the N-16 concentration in the steam is significantly elevated. Under these circumstances, conditions for production of volatile nitrogen chemical species are more favorable so that a greater portion of the N-16 produced is carried with the steam. The C-15 concentration remains approximately the same. For operation with hydrogen water chemistry, the recommended design basis N-16 concentration in steam is six times (11.1 MBq/g) the value for natural water chemistry.

11.1.2.2 Noncoolant Activation Products

Radionuclides are produced in the coolant by neutron activation of circulating impurities and by corrosion of irradiated system materials. Typical reactor water concentrations for the principal activation products are contained in Reference 11.1-1. The values of Reference 11.1-1 were adjusted to ABWR conditions by using the procedure described in Subsection 11.1-3 and appropriate data from Tables 11.1-6 and 11.1-7. These results were arbitrarily increased by the same factor used for the design basis radioiodine concentrations (6.7) to obtain the conservative design basis reactor water concentrations shown in Table 11.1-5. The steam carryover ratio for these isotopes is estimated to be less than 0.001. A factor of 0.001 is applied to the Table 11.1-5 values to obtain the design basis concentrations in steam.

11.1.2.3 Tritium

Tritium is produced by activation of naturally occurring deuterium in the primary coolant and, to a lesser extent, as a fission product in the fuel (Reference 11.1-2). The tritium is primarily present as tritiated oxide (HTO). Since tritium has a long half-life (12 years) and will not be affected by cleanup processes in the system, the concentration will be controlled by the rate of loss of water from the system by evaporation or leakage. All plant process water and steam will have a common tritium concentration. The concentration reached will depend on the actual water loss rate; however, References 11.1-1 and 11.1-3 both specify a typical concentration of3.7E-04 MBq/g, which is stated in Reference 11.1-3 to be based on BWR experience adjusted to account for liquid recycle. This value is taken to be applicable for the ABWR.

11.1.2.4 Argon-41

Argon-41 is produced in the reactor coolant as a consequence of neutron activation of naturally occurring Argon-40 in air which is entrained in the feedwater. The Argon-41 gas is carried out of the vessel with the steam and stripped from the system with the non-condensables in the main condenser. Observed Argon-41 levels are highly variable due to the variability in air in-leakage rates into the system.

Reference 11.1-3 specifies an Argon-41 release rate from the vessel of 1.48 MBq/s for a 3400 MW Reference BWR. This value bounded the available experimental database. Based on adjusting to the ABWR thermal power, a design basis Argon-41 release rate of 1.70 MBq/s is specified for the ABWR.

11.1.3 Radionuclide Concentration Adjustment

In order to determine the estimated concentrations of radionuclides in the groups classified as iodines, other non-volatile fission products, and non-coolant activation products using the ANSI/ANS-18.1 Source Term Standard (Reference 11.1-1), it is necessary to apply appropriate adjustment factors to the Reference Plant concentrations provided in the Standard.

Equilibrium concentrations in reactor water are assumed to satisfy the relationship:

$$C = \frac{s}{M(\lambda + R)} \tag{11.1-1}$$

where:

C = Radionuclide concentration

s = Radionuclide input rate to coolant

M = Reactor water mass

λ = Radionuclide decay constant

R = Sum of removal rates of the radionuclide from the system.

Consequently, if the radionuclide input rate is taken to depend primarily on the reactor thermal power, the adjustment factors to be applied to the Reference Plant reactor water concentrations are given by:

$$\text{AdjustmentFactor} = \frac{P \cdot M_r \cdot (\lambda + R_r)}{P_r \cdot M \cdot (\lambda + R)} \tag{11.1-2}$$

where the subscript "r" refers to the Reference Plant, P is the reactor thermal power and M, λ, and R are as defined above. The removal rate from the system is the sum of the removal rates due to the Reactor Water Cleanup (CUW) System and the condensate demineralizer and is given by:

$$R = \frac{F_c \cdot E_c + (F_s \cdot A \cdot B \cdot E_s)}{M} \tag{11.1-3}$$

where:

F_c = Cleanup system flow rate

E_c = Fraction of radionuclide removed in cleanup demineralizer

F_s = Steam flow rate

A = Ratio of radionuclide concentration in steam to concentration in water (carryover ratio)

B = Fraction of radionuclide in steam which is circulated through the condensate demineralizer

E_s = Fraction of radionuclide removed in condensate demineralizer

The Reference Plant and ABWR plant parameters are shown in Table 11.1-6 and the nuclide-dependent removal rate parameters used for the ABWR are shown in Table 11.1-7. The nuclide-dependent parameters are the same as those used for the Reference Plant except for the fraction circulated through the condensate demineralizer. The Reference Plant data is given for a plant without pumped-forward heater drains so that the fraction of condensate treated by the demineralizer is 1.0. In the ABWR, which has pumped-forward drains, the radionuclides are assumed to preferentially go with the pumped-forward flow (Reference 11.1-3). The effective treatment fractions are 0.18 for iodines and 0.01 for other fission products and non-coolant activation products (Reference 11.1-3).

11.1.4 Fuel Fission Production Inventory

Fuel fission product inventory information is used in establishing fission product source terms for accident analysis and is discussed in Chapter 15.

11.1.5 Process Leakage Sources

Process leakage results in potential release of noble gases and other volatile fission products via ventilation systems. Liquid from process leaks is collected and routed to the liquid-solid radwaste system. With the effective process offgas treatment systems now in use, the ventilation releases are relatively significant contributions to total plant releases.

Leakage of fluids from the process system results in the release of radionuclides into plant buildings. In general, the noble radiogases will remain airborne and will be released to the atmosphere with little delay via the building ventilation exhaust ducts. Other radionuclides will partition between air and water and may plate-out on metal surfaces, concrete, and paint. Radioiodines are found in ventilation air as methyl iodide and as inorganic iodine (particulate, elemental, and hypoiodous acid forms).

As a consequence of normal steam and water leakage in to the drywell, equilibrium drywell concentrations will exist during normal operation. Purging of this activity from the drywell to the environment will occur via the Standby Gas Treatment System and will make minor contributions to total plant releases.

Airborne release data from BWR building ventilation systems and the main condenser mechanical vacuum pump have been compiled and evaluated in Reference 11.1-4, which contains data obtained by utility personnel and from special in-plant studies of operating BWR plants. Releases due to process leakage are reflected in the airborne release estimates discussed in Section 11.3.

11.1.6 References

11.1-1 American National Standard Radioactive Source Term for Normal Operation of Light Water Reactors, ANSI/ANS-18.1.

11.1-2 Skarpelos, J.M. and R.S. Gilbert, “Technical Derivation of BWR 1971 Design Basis Radioactive Material Source Terms”, March 1973 (NEDO-10871).

11.1-3 Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Boiling Water Reactors, NUREG-0016, Revision 1, January 1979.

11.1-4 Marrero, T.R., “Airborne Releases From BWRs for Environmental Impact Evaluations”, March 1976 (NEDO-21159).

Table 11.1-1 Noble Radiogas Source Terms in Steam

Isotope	Decay Constant 1/hours	Source Term t = 30 min (MBq/s)
Kr-83m	3.73 E-01	1.1E+02
Kr-85m	1.55 E-01	2.0E+02
Kr-85	7.37 E-06	8.9E-01
Kr-87	5.47 E-01	5.6E+02
Kr-88	2.48 E-01	6.3E+02
Kr-89	1.32 E+01	6.3E+00
Xe-131m	2.41 E-03	7.4E-01
Xe-133m	1.30 E-02	1.1E+01
Xe-133	5.46 E-03	3.1E+02
Xe-135m	2.72 E+00	2.5E+02
Xe-135	7.56 E-02	8.1E+02
Xe-137	1.08 E+01	2.6E+01
Xe-138	2.93 E+00	7.8E+02
TOTAL		3.7E+03

Table 11.1-2 Iodine Radioisotopes in Reactor Water

Isotope	Decay Constant 1/hours	Concentration (MBq/g)
I-131	3.59 E-03	5.9E-04
I-132	3.03 E-01	5.2E-03
I-133	3.33 E-02	4.1E-03
I-134	7.91 E-01	8.9E-03
I-135	1.05 E-01	5.6E-03

Table 11.1-3 Non-Volatile Fission Products in Reactor Water

Isotope	Decay Constant (1/hours)	Concentration (MBq/g)
Rb-89	2.74 E+00	7.8E-04
Sr-89	5.55 E-04	1.2E-05
Sr-90/Y-90	2.81 E-06	8.5E-07
Sr-91	7.31 E-02	5.2E-04
Sr-92	2.56 E-01	1.4E-03
Y-91	4.93 E-04	4.8E-06
Y-92	1.96 E-01	8.1E-04
Y-93	6.80 E-02	5.2E-04
Zr-95/Nb-95	4.41 E-04	9.6E-07
Mo-99/Tc-99m	1.05 E-02	2.4E-04
Ru-103/Rh-103m	7.29 E-04	2.4E-06
Ru-106/Rh-106	7.83 E-05	3.7E-07
Te-129m	8.65 E-04	4.8E-06
Te-131m	2.31 E-02	1.2E-05
Te-132	8.89 E-03	1.2E-06
Cs-134	3.84 E-05	3.3E-06
Cs-136	2.22 E-03	2.2E-06
Cs-137	2.63 E-06	8.9E-06
Cs-138	1.29 E+00	1.5E-03
Ba-140/La-140	2.26 E-03	4.8E-05
Ce-141	8.88 E-04	3.7E-06
Ce-144/Pr-144	1.02 E-04	3.7E-07
Np-239	1.24 E-02	1.0E-03

NOTE:

Nuclides shown as pairs are assumed to be in secular equilibrium. The parent decay constant and concentration are shown.

Table 11.1-4 Coolant Activation Products in Reactor Water and Steam

Isotope	Half-Life	Steam Concentration (MBq/g)	Reactor Water Concentration (MBq/g)
N-16	7.13 s	1.9E+00*	3.6E+00†

* Use 11.1 MBq/g for operation with hydrogen water chemistry.

† Valid at core exit.

Table 11.1-5 Non-coolant Activation Products in Reactor Water

Isotope	Decay Constant (1/hours)	Concentration (MBq/g)
Na-24	4.63 E-2	1.3E-03
P-32	2.02 E-3	2.4E-05
Cr-51	1.04 E-3	7.4E-04
Mn-54	9.53 E-5	8.5E-06
Mn-56	2.69 E-1	6.7E-03
Co-58	4.05 E-4	2.4E-05
Co-60	1.50 E-5	4.8E-05
Fe-55	3.04 E-5	1.2E-04
Fe-59	6.33 E-4	3.7E-06
Ni-63	7.90 E-7	1.2E-07
Cu-64	5.42 E-2	3.7E-03
Zn-65	1.18 E-4	2.4E-05
Ag-110m	1.16 E-4	1.2E-07
W-187	2.90 E-2	3.7E-05

Table 11.1-6 Plant Parameters for Source Term Adjustment

Parameter	Reference Plant	ABWR
Thermal Power, MW	3400	3926
Reactor Water Mass, kg	1.73 E+05	3.06 E+05
Cleanup System Flow Rate, kg/h	5.9 E+04	1.52 E+05
Steam Flow Rate kg/h	6.81 E+06	7.65 E+06
Ratio of Condensate Demineralizer Flow Rate to Steam Flow Rate	1.0	*
The above values are expressed in the units required by the procedure in ANSI/ANS-18.1.		

* See Table 11.1-7.

Table 11.1-7 Removal Parameters for Source Term Adjustment

Parameter	Iodines	Other Radionuclides*	Rb, Cs
Fraction removed by cleanup system	0.90	0.90	0.50
Fraction removed by condensate demineralizers	0.90	0.90	0.50
Ratio of concentrations in steam and reactor water	0.015	0.001	0.001
Fraction of radionuclides in steam treated by condensate demineralizer	0.18	0.01	0.01

* Including all non-coolant activation products and all non-volatile fission products except Rb and Cs.