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UK ABWR

Document ID	:	GA91-9101-0101-20002
Document Number	:	HE-GD-5052
Revision Number	:	A

UK ABWR Generic Design Assessment

Generic PCSR Sub-chapter 20.2 : Definition of Radioactive Sources

Hitachi-GE Nuclear Energy, Ltd.

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20.2.1 General Description

During Operation Condition I as well as transport/storage of radioactive/contaminated items, radiation arises from activity within the systems and components and/or from surface contamination, which leads to measurable dose rate in the surrounding areas. This must be taken into account for radiation protection purposes. The radioactive sources, which mean the radioactive nuclide inventory composition, vary depending on plant operational phases and vary between different systems and components. Consequently, the radiological impact is also different and so shielding provision must be adapted to local radiation levels within the plant.

The radiological impact of nuclides with a short half-life such as nitrogen-16 (N-16) and nitrogen-17 (N-17), 7 seconds and 4 seconds respectively, becomes totally negligible after a few minutes due to radioactive decay after shut-down and therefore during outages. Their contribution is not negligible during operation and this contribution must be taken into account.

The alpha and beta particles emitted by radionuclides such as tritium or carbon-14 have sufficiently low energy hence they can be sufficiently attenuated by the containment structures of piping and equipment etc. As a result, their contributions are negligible for shielding design.

Systems and components which are connected to the primary circuit and contain or transport primary fluid (reactor water and main steam) are identified as the main radioactive sources in the plant. Also radioactive waste systems and the off-gas system are understood as radioactive sources in this sense.

During the reactor’s operating life, activated materials transported by the primary coolant will be deposited on the inner surfaces of the piping and equipment in contact with the primary coolant. This accumulation of contamination, especially corrosion products, is a continuous process that depends mainly on the physical and chemical conditions of the primary system in the different reactor states.

During outages the largest contribution to whole body radiation dose is cobalt-60 (Co-60) which is an activated corrosion product that has accumulated on inner surfaces of containment piping and equipment.

The radioactive sources are used as a design parameter for UK ABWR shielding design. The radioactive sources are conservative compared with operating experiences. Radioactive sources for shielding design do not necessarily include all radionuclides which may be detectable or theoretically predicated to be present. It is sufficient to use reference (or key nuclides) for shielding calculations. Overall, these radioactive sources can be regarded as included in the shielding design since fundamental radioactive sources of the reactor coolant are conservative and bounding.

Radioactive source data for boiling water reactors has been incorporated in “Source Term and Radiation Zoning for Shielding Design of BWR” The Federation of Electric Power Companies of Japan [Ref-1], “Review for Scope of ALAP Provision” Tokyo Electric Power Company Inc., Toshiba Corporation and Hitachi, Ltd. [Ref-2] and “Technical Derivation of BWR 1971 Design Basis Radioactive Material Source Term” NEDO-10871 [Ref-3]. These guidelines provide the bases for estimating typical radioactive concentrations of the principal radionuclides which may be anticipated over the lifetime of a BWR plant.

The radioactive source data is based on the cumulative industry experience at operating BWR plants, including measurements at several stations through the 1970’s. 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.

In addition, Hitachi-GE has reviewed and developed source terms based on Resolution Plan for RO-ABWR-0006 Source Terms. Therefore, source terms for shielding design provided in this sub-chapter will be developed and the description will be updated in Step 3.

20.2.2 Scope

The aim of this section is to define the radioactive source terms in the reactor water and steam which serve as shielding design bases for the gaseous, liquid and solid radioactive waste management systems during Operation Condition I as well as the transport and storage of radioactive and/or contaminated items including spent fuel.

For shielding design, the radioactive sources during each operating condition are the result of three general processes shown in Figure 20.2-1. The emissions of gamma rays and neutrons are considered because these are much more relevant for external radiation than alpha or beta particles.

Operation Condition I excluding outages includes start-up conditions, power operation and shut-down conditions. The radioactive source terms and radiation dose vary depending on the operational phases as mentioned above.

During shut-down, there is a transient phenomenon, which is called activity spike, in which radioactive crud concentration in the reactor coolant increases temporarily during the decreasing pressure and temperature phases of shut-down. However, this is not considered for shielding design because it is identified as a temporary fluctuation and it can be mitigated by operational control. This is discussed in reactor water chemistry in PCSR Chapter 23. Therefore, it is defined that Operation Condition I excluding outages can be represented as power operation for shielding design.

Radioactive sources are defined conservatively in shielding design. Fission products and activation products (including corrosion products) are considered in shielding design for the reactor core, the reactor, turbine and radioactive waste management systems. Neutron and gamma ray’s caused by nuclear fission and fission products are considered for the reactor core in shielding design. The radioactive sources during Operation Condition I excluding outages are discussed in sub-section 20.2.3.1.

During outages, the radioactive sources consist of activation products including corrosion products. However, activation products, N-16 and N-17, are nuclides with a short radioactive half-life. These nuclides become totally negligible after a few minutes. As a result, the radioactive sources during outages consist of only corrosion products, which are discussed in sub-section 20.2.3.2.

During transport and storage of radioactive and/or contaminated items, the radioactive sources of the spent fuel assemblies consist of fission products, actinides and activation products which originate from reaction of the neutrons with the structural materials of the fuel. Source terms of spent fuel interim storage will be discussed in PCSR Chapter 32.

The radioactive sources of the other radioactive and/or contaminated items consist of activation products such as the control rods and corrosion products from reactor water. These are described in sub-section 20.2.3.2.

The radioactive sources during design basis accidents and severe accidents will be discussed in PCSR Chapter 24 and 26, respectively. In addition, source terms to be taken into account for decommissioning associated with activation and contamination will be provided in PCSR Chapter 31 and in Topic Report associated with RO-ABWR-0006 Source Terms, respectively.

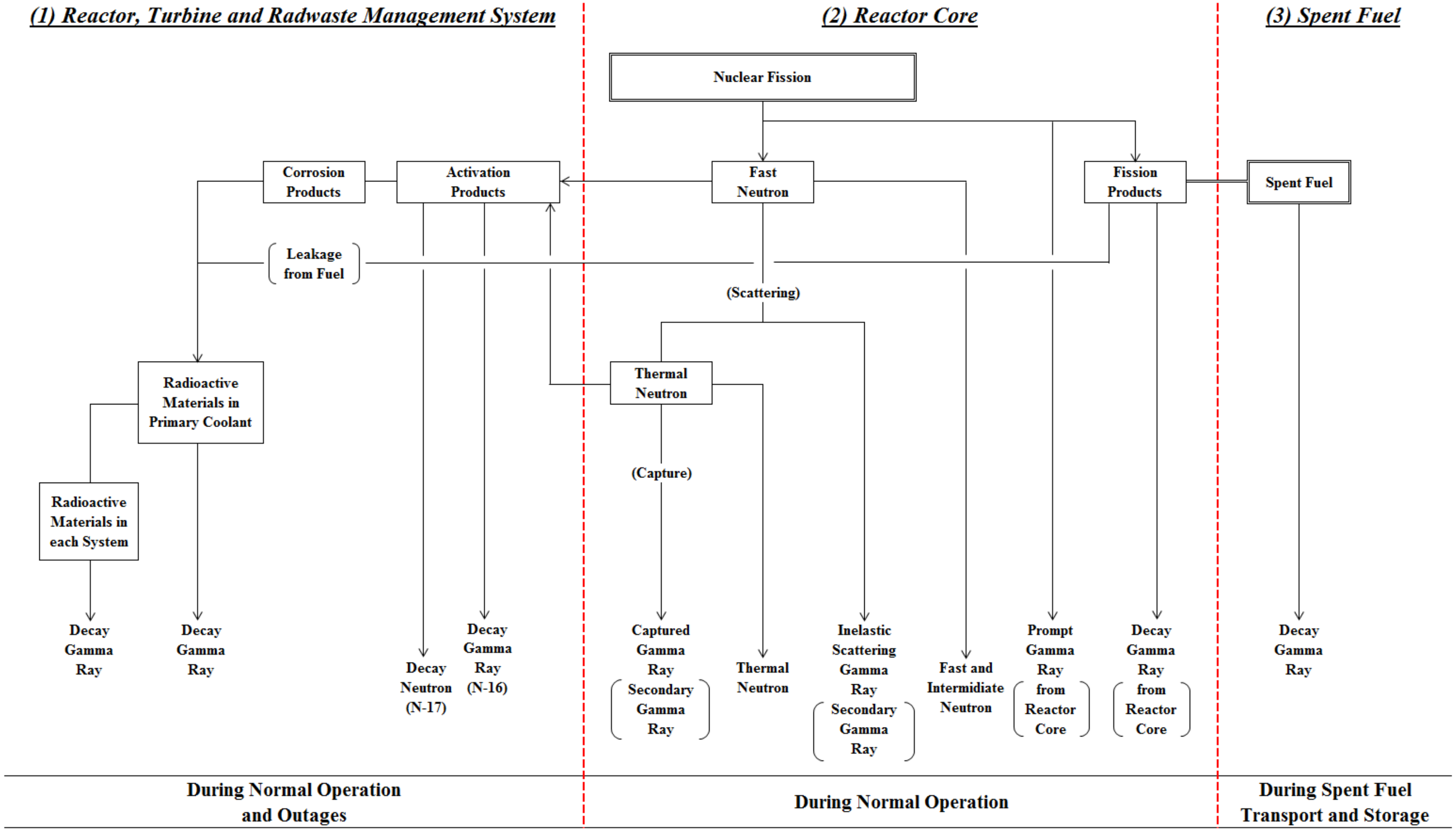

Figure 20.2-1: Emission Process of Neutrons and Gamma Rays

20.2.3 Radioactive Sources

20.2.3.1 Radioactive Sources during Operation Condition I excluding Outages

In this sub-section, three radioactive sources during Operation Condition I excluding outages are discussed. These radioactive sources are:

(1) Reactor Water
(2) Reactor, Turbine and Radioactive Waste Management System
(3) Reactor Core

20.2.3.1.1 Reactor Water

(1) Primary Radioactive Sources

The primary radioactive sources in reactor water consist of fission products based on noble gas release rate, activation products and corrosion products.

(a) Fission Products based on Noble Gas Release Rate

The shielding design is based on the plant operating at maximum design power with the release of fission products resulting in a source of 3.7×10^9 Bq/s of noble gas after a 30-minute decay period, and the corresponding activation and corrosion product concentrations in the reactor water. Operation at higher release rates can be tolerated for reasonable periods of time with respect to shielding considerations.

The radioactive concentration of fission products in reactor water is 5.8×10^4 Bq/g calculated based on noble gas release rate by using the method described in NEDO-10871 [Ref-3].

(b) Activation Products (N-16 and N-17)

The most important activation products are N-16 and N-17. However, the dose contribution of N-17 is sufficiently small compared with N-16. Consequently the consideration of N-17 is negligible and so only N-16 is considered for the shielding design.

N-16, which is produced by an (n,p) reaction with oxygen-16 (O-16), is the primary radioactive source in the equipment containing reactor coolant and main steam under operation in BWRs.

The radiological impact of radionuclides with a short radioactive half-life such as N-16 becomes totally negligible after a few minutes simply due to radioactive decay during outages. However, it has an impact during Operation Condition I excluding outages. Therefore the influence of N-16 decay with the transport time to arrive at respective equipment from the reactor is considered in the shielding design.

The radioactive concentration of N-16 in reactor water moving to CUW at RHR nozzle of RPV is 1.8×10^6 Bq/g calculated by reactor thermal power, flow-rate, decay time and so on.

In addition, the radioactive concentration of N-16 in main steam at main steam nozzle of RPV was calculated by a similar approach as that in reactor coolant leaving the reactor vessel. However, it was reconsidered in comparison to actual measured data of BWRs.

The radioactive concentration of N-16 in main steam is based on actual measured data.

(c) Corrosion Products

The corrosion products are defined considering maximum values for each nuclides based on operating experience.

The radioactive concentration of corrosion products is determined based on actual measured data of the radioactive concentration in the reactor water in Japanese BWRs [Ref-2].

(2) Reactor Water Chemistry

The radioactive sources in reactor water vary depending on operational phases in reality, which means that radioactive sources have relationship to reactor water chemistry.

The detailed methods of reactor water chemistry control will be described in reactor water chemistry in PCSR Chapter 23 and provided in Topic Report associated with RO-ABWR-0006 Source Terms in Step 3.

20.2.3.1.2 Reactor, Turbine and Radioactive Waste Management System

20.2.3.1.2.1 Reactor Building

The considerations for each of these systems are described as follows:

(1) Main Steam System (MS)
The primary radioactive source is N-16. The transport time to arrive at respective equipment from the outlet nozzle of the Reactor Pressure Vessel (RPV) is considered when calculating radioactive concentration in this system.

(2) Reactor Water Clean-up System (CUW)

(a) Upstream from CUW Filter Demineraliser
The primary radioactive sources are fission products and N-16 at the piping and the CUW heat exchangers. For N-16, transport time to arrive at each equipment from the outlet nozzle of the Reactor Pressure Vessel (RPV) is considered.

(b) CUW Filter Demineraliser
Accumulation just before backwash is considered and Decontamination Factor (DF) of the CUW filter demineraliser to reduce radioactivity is considered.

(c) Downstream from CUW Filter Demineraliser
The primary radioactive sources are fission products passing through the CUW filter demineraliser and noble gas emitted by decay of halogens accumulated in the CUW filter demineraliser.

(3) Residual Heat Removal System (RHR) [Shut-down Cooling Mode]
The mode that radioactive concentration is the highest of all modes in this system (Shut-down Cooling Mode) is considered.

(4) Reactor Core Isolation Cooling System (RCIC)
The primary radioactive source is N-16 since main steam is used as the steam to drive the RCIC turbine. The decay time is considered when calculating the radioactive concentration of steam in the RCIC turbine.

(5) Fuel Pool Cooling and Clean-up System (FPC)
The radioactive concentrations of piping and the heat exchangers of the FPC are based on the actual measured data of BWR plants because the dose contribution by accumulation would be larger than expected in this area.

Decontamination Factor (DF) is considered when calculating the radioactive concentration of the FPC demineraliser to reduce radioactivity.

(6) Suppression Pool Clean-up System (SPCU) and High Pressure Core Flooder System (HPCF)
The radioactive concentration in the suppression pool described in (9) is used for these systems related to the suppression pool.

(7) Spent Fuel Pool (SFP)
The concentration of radioactivity in the SFP consists of reactor water, suppression pool and Condensate Storage Tank (CST) water is based on the following assumptions:

(a) The specific radioactivity in the SFP is based on the radioactive concentration of reactor water after four days from reactor-shut-down and CUW system shut-down because it takes about four days to start injection of water into the reactor well and the SFP after Reactor Pressure Vessel (RPV) head off.

(b) In addition, attenuation effect of dilution in the SFP is considered because suppression pool and CST water flows into the SFP.

(8) Spent Fuel
The radioactive sources of spent fuel considered are fission products, activation products and actinides.

(a) Spent Fuel Transport

For spent fuel transport from reactor core into the SFP, the considerations below for the shielding design are assumed.

- Irradiation time of fuel is 10^6 hours, which is selected as time leading to saturated source strength.
- Decay time of fuel is five days, because transporting into SFP from reactor core is expected to be started after five days have elapsed since reactor shut-down. It is expected to take about five days to open RPV head and reactor well and inject reactor water, suppression pool water and CST water into the SFP.

(b) Spent Fuel Storage

For spent fuel storage in the SFP, the considerations below for the shielding design are assumed.

- Irradiation time of fuel is 10^6 hours, similar to consideration of spent fuel transport.
- Decay time of fuel is 20 days, because refueling is expected to be completed and SFP gate is expected to be closed after 20 days have elapsed since reactor shut-down.

Source strength of fuel assembly per generating power is based on “REACTOR HANDBOOK, Second Edition, Vol.III Part.B, SHIELDING” [Ref-4].

(9) Suppression Pool
The suppression pool is used for the injection to the reactor well, dryer/separator pit or spent fuel pool depending on plant systems and operation.

Therefore the radioactive concentration in the suppression pool is based on actual measured data because the properties of the suppression pool water would be different for each operational phase and so it is difficult to assume the radioactive concentration in the suppression pool.

(10) Drywell
The radioactive concentration in the drywell is based on actual measured data because the radioactive concentration would be different for each operational phase and so it is difficult to assume the radioactive concentration in the drywell.

20.2.3.1.2.2 Turbine Building

The considerations for each of these systems are described as follows:

(1) Main Steam System (MS)
The primary radioactive source is the same as the MS System in < Reactor Building > (1) MS.

(2) Extraction Steam System (ES)
The primary radioactive source is N-16. The radioactive concentrations in the piping are assumed at their inlets.

(3) Condensate Water System (CW) and Feedwater System (FDW)

(a) Upstream from Condensate Filter and Demineraliser
The primary radioactive sources are fission products transferred to the turbine from reactor water with main steam and the daughter nuclides produced by the radioactive decay of noble gas.

(b) Condensate Filter and Demineraliser
Accumulation just before backwash or resin disposal is considered and the Decontamination Factor (DF) of the condensate filter and demineraliser to reduce the radioactivity are considered.

(c) Downstream from Condensate Demineraliser
The primary radioactive sources are fission products passing through the condensate demineraliser and noble gas produced by radioactive decay of halogens accumulated in the condensate demineraliser.

20.2.3.1.2.3 Liquid Radioactive Waste Management System

The primary radioactive sources in the liquid radioactive waste management system for shielding design are mainly fission products and corrosion products. The radioactive concentration in this system is calculated under the following assumptions:

(a) The nuclides in this system are based on those in the reactor water.

(b) The decay time in piping and equipment which does not have the function to accumulate activity is not considered.

(c) When there are more than two inlets, mixture is considered.

(d) When there are more than two inlets but no mixture, the system which has the highest radioactive concentration is considered.

(e) Decontamination Factor (DF) of filter, demineraliser and evaporator such as the Low Conductivity Waste System (LCW) filter and demineraliser, the High Conductivity Waste System (HCW) demineraliser and evaporator to reduce radioactivity are considered.

20.2.3.1.2.4 Off-Gas Radioactive Waste Management System

The radioactive concentration in this system is calculated under the following assumptions:

(a) The radioactive sources in this system are N-16 and noble gas from condenser and N-16 included in the Steam Jet Air Ejector (SJAE).

(b) For N-16 radioactive concentration of respective equipment, the transport time to arrive at this equipment from the outlet of the Reactor Pressure Vessel (RPV) is considered.

(c) Pressure and temperature of respective equipment are considered when calculating the radioactive concentration of off-gas up to the off-gas condenser.

(d) The period to hold up xenon (Xe), 30 days, and krypton (Kr), 40 hours, in the off-gas hold-up system is assumed to maximise accumulation.

(e) The daughter and granddaughter nuclides produced by radioactive decay of noble gas in respective equipment are considered from the outlet of the off-gas condenser up to the off-gas hold-up system (charcoal adsorber).

20.2.3.1.2.5 Solid Radioactive Waste Management System

The primary radioactive sources for the solid radioactive waste management system for shielding design are mainly fission products and corrosion products. The radioactive concentration in this system is calculated under the following assumptions:

(a) The nuclide composition in this system is based on that in the reactor water.

(b) The decay time in storage tanks for spent resins and sludges before further processing such as cementation is considered.

(c) The radioactive concentration of decant water in the waste sludge storage tanks and spent resin tanks is assumed from the amount of radioactivity flowing in. These ratios are based on measured data.

20.2.3.1.3 Reactor Core

The primary radioactive sources around the reactor core for shielding design are:

- Neutrons and gamma rays emitted by the fission in the reactor core
- Gamma rays emitted by the reaction between neutrons and the components in and out of the reactor core
- Gamma rays emitted by fission products

The emission process of these neutrons and gamma rays are shown in Figure 20.2-1.

(1) Neutrons

The neutron source strengths of fission per unit volume of reactor core are shown in the following:

$$S_{vi} = \frac{\nu \cdot N_f \cdot P}{\pi \cdot R^2 \cdot H} \cdot x_i$$

where S_{vi} is the source strength of fission neutrons for energy group i per unit volume of reactor core ($cm^{-3} \cdot s^{-1}$), ν is the average number of emissions of neutrons per nuclear fission ($fission^{-1}$), N_f is the amount of nuclear fission per watt and second ($fission \cdot W^{-1} \cdot s^{-1}$), P is core thermal power (W), R is core effective radius (cm), H is core effective height (cm), x_i is fission neutron spectra of energy group i for U-235.

(2) Gamma Rays

(a) Fission Product Gamma Rays
The source strength of the gamma rays emitted by decay of fission products is based on "REACTOR PHYSICS CONSTANTS" ANL-5800 Second Edition, Argonne National Laboratory [Ref-5].

(b) Other Gamma Rays
Capture gamma rays, inelastic scattering gamma rays and prompt gamma rays are evaluated in the process of transport calculation since these emission probabilities are incorporated in the appropriate cross section data in transport calculation code.

20.2.3.2 Radioactive Sources during Outages

During outages, the primary radioactive source is corrosion products attached to the internal surface of equipment or piping in the primary coolant and adjacent systems, especially Co-60. The radiation dose of Co-60 is dominant in the plant during outages, which accounts for the majority of the whole radiation dose according to actual measured data in BWRs in Japan and overseas.

The radioactive sources during outages are related to the reactor water chemistry which will be discussed in detail in reactor water chemistry, PCSR Chapter 23 and Topic Report of RO-ABWR-0006 Source Terms in Step 3.

- Radioactive Sources during Transport and Storage of Radioactive and/or Contaminated Items

With respect to transport and storage into the interim storage facilities outside the reactor building or the radwaste building, the spent fuel is considered as radioactive source which is transported in adequate transport or storage casks or containers. The radioactive source of the spent fuel consists of fission products and activation products and actinides. Radioactive sources of spent fuel interim storage will be discussed in PCSR Chapter 32 in Step 3.

In addition, the radioactive sources of the other radioactive and/or contaminated items consist of activation products including corrosion products.

20.2.4 References

[Ref-1] Source Term and Radiation Zoning for Shielding Design of BWR, The Federation of Electric Power Companies of Japan, March 1980
[Ref-2] Review for Scope of ALAP Provision, Tokyo Electric Power Company Inc., Toshiba Corporation and Hitachi, Ltd., March 1985
[Ref-3] Technical Derivation of BWR 1971 Design Basis Radioactive Material Source Term, NEDO-10871, March 1973
[Ref-4] REACTOR HANDBOOK, Second edition, Vol.III Part.B, SHIELDING, E.P.Blizard and L.S.Abbott ed, New York, London, January 1962
[Ref-5] REACTOR PHYSICS CONSTANTS, ANL-5800 Second Edition, Argonne National Laboratory, July 1963