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Selective Application of Revised Source Terms to Operating Nuclear Power Plants

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Abstract

More than 30 years later since 1962 when TID-14844 was promulgated, there has been a big change of the US NRC's regulatory position in using accident source terms for radiological assessment following a design basis accident (DBA). To replace the instantaneous source terms of TID-14844, the time-dependent source terms of NUREG-1465 was published in 1995. In the meantime, the radiological acceptance criteria for reactor site evaluation in 10 CFR Part 100 were also revised. In particular, the concept of total effective dose equivalent has been incorporated in accordance with the radiation protection standards set forth in revised 10 CFR Part 20. Subsequently, the publication of Regulatory Guide 1.183 and the revision of Standard Review Plan 15.0.1 followed in 2000, which provided the licensee of operating nuclear power reactor with the acceptable guidance of applying the revised source term. The guidance allowed the holder of an operating license issued prior to January 10, 1997 to voluntarily revise the accident source terms used in the radiological consequence analyses of DBA. Regarding to its type of application, there suggested full and selective applications. Whether it is full or selective, based upon the scope and nature of associated plant modifications being proposed, the actual application of the revised source terms to an operating plant is expected to give a large impact on its facility design basis. Considering scope and cost of the analyses required for licensing, selective application is seemed to be more appealing to an licensee of the operating plant rather than full application. In this paper, hence, the selective application methodology is reviewed and is actually applied to the assessment of offsite radiological consequence following a LOCA at Ulchin Unit 3&4, in order to identify and analyze the potential impacts due to application of revised source terms and to assess the considerations taken in each application prior to its actual implementation of design modifications.

1. Introduction

In compliance with the requirements set forth in 10 CFR Part 100 and 50, the radiological consequences of design basis accidents (DBA) should be evaluated. The traditional regulatory framework for calculating the radiological consequence of a design basis accident was described in a series of Regulatory Guides and Standard Review Plan (SRP) chapters. The previous framework, however, was developed to be consistent with the instantaneous source terms presented in TID-14844 [1] published in 1962 and with the specific off-site dose criteria of whole body and thyroid dose set forth in 10 CFR Part 100.

In 1995, the revised source terms, in lieu of TID-14844, were published as NUREG-1465 [2] for

regulatory purpose, which assumes the time-dependent rather than instantaneous releases of fission products, and envelops all light water reactor plants with the representative accident source terms. In the meantime, the radiological acceptance criteria for reactor site evaluation in 10CFR Part 100 were also revised. In particular, to incorporate the concept of total effective dose equivalent (TEDE) introduced in revised 10 CFR Part 20 of 1991, the off-site dose criteria have changed from "dose of 25 cSv whole body or 300 cSv thyroid" to "dose of 25 cSv TEDE." In conjunction with subsequent implementation of the revised source terms, the time-period of computing the dose at exclusion area boundary (EAB) has changed from "for 2 hours immediately following onset of the postulated fission product release" to "for any 2 hour period following onset of the postulated fission product release." In the revised criteria, the term of "any 2-hour period" can be interpreted as "the sliding 2-hour period during which the resultant radiological offsite consequence becomes the greatest." The comparison of two regulatory frameworks is summarized in Table 1.

Table 1. The differences between two regulatory frameworks

		Traditional	Updated
Source terms		TID-14844	NUREG-1465
	■ Release time (entire)	Instantaneous	Continuous (5 release phases)
	■ Radionuclide composition	Noble gases Iodine Solids	8 groups of fission products
	■ Release fraction[1)] - Noble gases - Iodine	 100% 50%	 100% 40%
	■ Iodine chemical form - Elemental - Particulate: - Organic	 91% 5% 4%	 4.85% 95% 0.15%
	■ Solids	Ignored in offsite and control room dose assessment	Treated as an aerosol
Offsite dose limit at EAB		300 cSv thyroid, 25 cSv whole body, first 2 hours	25 cSv TEDE, worst 2 hours

1) The values in the column of "updated" are the total release fractions till the end of early in-vessel phase.

Subsequently, the publication of Regulatory Guide 1.183 [3] and the revision of SRP 15.0.1 [4] followed in the year of 2000, which provided the licensee of an operating nuclear power reactor with the acceptable guidance of applying the revised source term. The revised regulatory guidance allowed the holder of an operating license issued prior to January 10, 1997 to voluntarily revise the accident source terms used in the radiological consequence analyses of DBA. Regarding to its type of application, two types are suggested: full and selective applications.

Whether it is full or selective, based upon the scope and nature of associated plant modifications being proposed, the actual application of the revised source terms to an operating plant is expected to give a large impact on its facility design basis. Considering scope and cost of the analysis required for licensing, selective application is seemed to be more appealing to an licensee of the operating plant rather than full application. In this paper, hence, the selective application methodology is reviewed and is actually applied to the assessment of offsite radiological consequence following a LOCA at Ulchin

Unit 3&4, in order to identify and analyze the potential impacts due to application of revised source terms and to assess the considerations taken in each application prior to its actual implementation of design modifications.

2. Review of Selective Application Methodology

In Reference [3], selective application is defined as "a modification of the facility design basis that (1) is based on one or more of the characteristics of the revised source terms or (2) entails re-evaluation of a limited subset of the design basis radiological analyses," while full application is defined as "a modification of the facility design basis that addresses all characteristics of the revised source term, that is, composition and magnitude of the radioactive material, its chemical and physical form, and the timing of its release." Regarding to selective application, two representative types of selective application from the revised source terms could be considered: release timing-only and chemical form-only selective applications. In applying the revised source terms, it should be noted that the aspects of the revised source terms that are applied should avoid physical inconsistencies and be appropriately conservative [5].

While a complete DBA LOCA analysis should be performed as a minimum for full implementation, for selective application, there is no minimum requirement that a DBA LOCA analysis be performed. However, the analyses performed need to address all impacts of the proposed modification, the selected characteristics of the revised source term, and the TEDE criteria, if dose calculations are performed. If affected design basis analyses are to be re-calculated, all affected assumptions and inputs should be updated and all selected characteristics of the revised source terms and the TEDE criteria should be addressed. The main features of the methodology to calculate offsite doses following a DBA, different from the traditional regulatory framework, are summarized as follows:

(1) The release into the containment is assumed to terminate at the end of the early in-vessel phase that is described in NUREG-1465 for DBA analysis. The activity released from the core during each release phase is modeled as increasing in a linear fashion over the duration of the phase. Also, in lieu of treating the release in a linear ramp manner, the activity for each phase can be modeled as being released instantaneously at the start of that release phase, i.e., in step increases.

(2) The dose calculations should determine the TEDE. And use of the updated dose conversion factors (DCFs) [6, 7], instead of those based on ICRP-2 [8], for the computation of internal and external exposures is recommended.

(3) As described in Table 1, the maximum EAB TEDE for any two-hour period following the start of the radioactivity release should be determined and used in determining compliance with the dose criteria in 25 cSv TEDE as shown in Table 1.

(4) If the sump or suppression pool pH is controlled at values of 7 or greater, the chemical form of radioiodine released to the containment should be assumed to be 95% cesium iodide (CsI), 4.85% elemental iodine, and 0.15% organic iodide. Regarding to this application, it should be noted that it is inconsistent to credit the chemical form as being cesium iodide (CsI) and ignore the increased cesium (Cs) release fraction. With the exception of elemental and organic iodine and noble gases, fission products should be assumed to be in particulate form.

(5) It is allowed that the time-dependent removal rate could be used if the removal rate is based on the calculated time-dependent airborne aerosol mass. And the prior practice of deterministically assuming that a 50% plateout of iodine is released from the fuel is no longer acceptable as it is inconsistent with the characteristics of the revised source terms.

3. Application of the Revised Source Term

This section covers the selective application of the revised source terms of NUREG-1465, and the potential impacts of each type of application and the considerations taken for each type of application. It should be noted that any modification of the facility design of UCN 3&4 is not considered in this application and all the results are only the illustrative purpose to show the potential impacts by the application type of the revised source terms themselves. While this paper only focuses on these two types of selective application, there may still exist variations that could emerge as individual licensee actually begins to apply the revised source term.

3.1 Base Case

This case is the re-analysis using the same inputs as those given in FSAR of UCN 3&4 [9]. A large break LOCA is the DBA and the accident source terms are based on Regulatory Guide 1.4[10]. To convert radioiodine activities transported to the point of interest to dose, the dose conversion factors (DCFs), based on ICRP-2 are used. The release pathways of radioactivity from containment to environment are through: 1) low-volume purge; 2) containment leakage; and 3) re-circulation leakage. The main parameters used in the re-analysis are summarized in Table 2. According to Reference [3], the updated DCFs, instead of those based on ICRP-2, is also applied for the computation of internal and external exposures, in order to analyze the impact to off-site doses due to change of DCFs. Using STARDOSE [11], 0-2 hour off-site doses at EAB are computed, and the results are summarized in Table 3. Comparing two results, the update of DCFs results in a decrease in of TEDE by about 10%.

Table 2. Main parameters used for the base case

System	Design Parameters	Values
Containment	• Free volume, ft^3	2.273×10^6
	• Design leak rate, %/day	
	– 0~24 hours	0.2
	– 1~30 days	0.1
	• Sprayed region, %	75
	• Unsprayed region, %	25
	• Spray removal rate, hr^{-1}	
	– Elemental	20.0
	– Particulate	0.55
	• Mixing rate	
	– Turnovers of unsprayed region, hr^{-1}	2
	• Containment low volume purge rate, cfm	2.335×10^4
ESF	• Iodine Partitioning, %	10
	• Re-circulation loop leakage, gpm	4.25×10^{-2}
	• ECCS equipment room HVAC system	
	– Flow rate (cfm)	6,000
	– Volume covered by HVAC system, ft^3	1.35×10^6
Atmospheric Dispersion Factor	• EAB (700m)	
	– 0~4 hours, sec/m^3	1.96×10^{-4}

Table 3. 0-2 hour doses at EAB – base case

(unit: cSv)

With DCFs of ICRP-2				With updated DCFs			
Thyroid	Whole Body	Skin	TEDE	Thyroid	Whole Body	Skin	TEDE
222	2.43	1.12	6.50	129	1.75	2.99	5.82

3.2 Release Timing-Only Selective Application

As described in Section 2, there are two types that could be considered: step and linear ramp release. First, it is assumed that the radioactivity is released in the form of puff at the beginning of each phase of the gap and early in-vessel releases which are described in NUREG-1465. That is, the gap release is taken as a "puff" at the start of the phase, which equals to 5% of the core inventory of radioiodines and noble gases. The remainder of release fraction, that is, 95% of noble gases and 20% of radioiodines, is then released as one additional puff beginning at the start of the early in-vessel release phase. The chemical form of radioiodines is assumed to be principally elemental. The one area in which the potential exists for the elemental form assumption to be non-conservative would be the selection of spray removal rates for radioiodines during the phase of gap release since particle sizes may be small because concentrations are low, and this means that the spray removal could potentially be less effective than would be the case for the period of in-vessel release. According to SRP 6.5.2 [12], therefore, the spray removal rate for elemental iodines during the gap release phase is conservatively assumed to be lower. That is, the removal rate during the gap release phase is assumed to be 2 per hour, which is one tenth of the value used in the previous cases. From the beginning of the in-vessel release phase till the end of spray injection period, the removal rate is assumed to be 20 per hour. After that time, then the lower value should once again be used. And the mixing rate attributed to natural convection between sprayed and unsprayed regions of the containment building is conservatively assumed to be two turnovers of the unsprayed regions per hour during the whole period of the accident. In order to estimate the offsite dose at EAB for any (worst) 2-hour period, the cumulative function of off-site dose is first generated starting from the initiation of the accident to the time of interest by using the time-dependent release of fission products into the environment, and then the cumulative function is differentiated to find the worst resultant 2-hour offsite dose.

Second, the case of linear ramp release is only different from the case of step release in that the release pattern is assumed to be a uniform release over each release phase instead of puff release. The other parameters used for and the method of offsite dose calculation are the same as those in the case of step release.

The results of two cases are presented in Figure 1, and summarized in Table 4. In Figure 1, the solid lines represent the cumulative offsite and the dashed lines are the doses for sliding 2-hour period. Figure 1 shows that, while, due to the early large release of radioactivity relatively to the case of linear ramp release and the small spray removal of radioiodines generated during the gap release phase, the offsite dose for the case of step release rapidly increases and is larger than that for the case of linear ramp release till about the middle of the accident progression, the tendency is vice versa after that time, due to the continuous release of radioactivity and the small spray removal of radioiodines generated during the late phase of early in-vessel release. The worst resultant 2-hour dose for the case of linear ramp release is the larger by about 20% than that for the case of step release, shown in Table 4.

Table 4. 2-hour doses at EAB -release timing-only selective application

(unit: cSv)

With step release				With linear ramp release			
Thyroid	Whole Body	Skin	TEDE	Thyroid	Whole Body	Skin	TEDE
70.80	1.25	2.13	3.48	103.8	0.99	1.65	4.24

Note) Each value in the table is the greatest offsite dose for sliding 2-hour period.

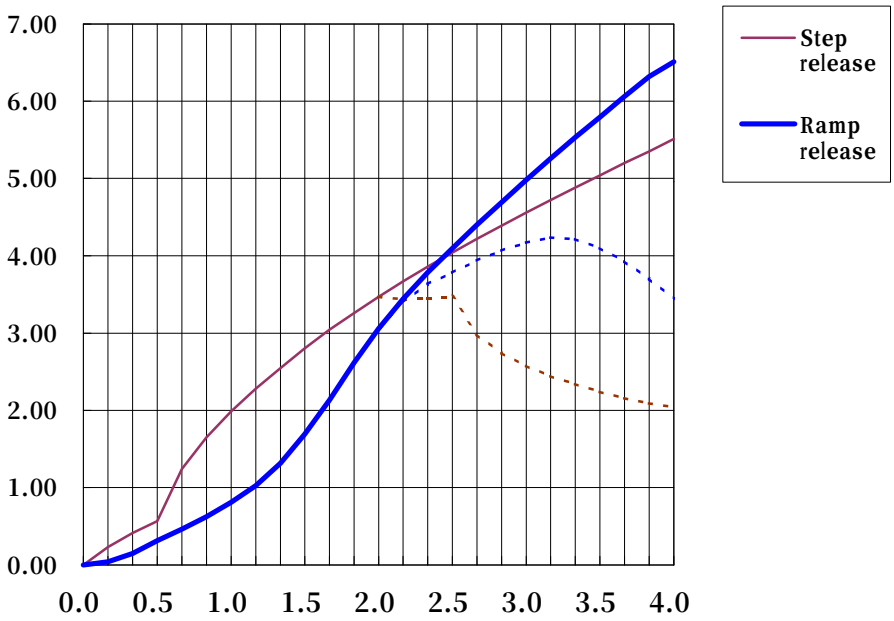

Figure 1. The results for two timing-only selective applications

3.3 Chemical Form-Only Selective Application

The scope presented here is for the selective application of the revised accident source terms involving only a change in the chemical form of radioiodines. According to the assumed spray removal rates for radioiodines, two cases are considered.

First, the chemical form of radioiodines is assumed to be 95% particulate, 4.85% elemental, and 0.15% organic, according to NUREG-1465. Considering the fact that it is inconsistent to credit the chemical form as being cesium iodide (CsI) and ignore the increased cesium (Cs) release fraction, the release fraction of Cs from core to containment is assumed to be 25% of the core inventory. The spray removal rates for radioiodines are assumed to be the same as those of the first case in Section 3.2. For this application, it is very important to confirm that pH of the containment water pool is maintained at 7 or above over the 30 days. For simplicity of calculation, it is assumed that pH of the containment water pool is maintained at 7 or above, based on the previous analysis results of UCN 3&4, in this application.

As shown in Figure 2, it is known that the spray removal rate for particulate iodine assumed in the previous case is very underestimated. As the second case, hence, the spray removal rate for particulate iodine is increased to 5, which is the typical PWR spray removal rate described in NUREG-1465.

The results for two cases are presented in Figure 2 and are summarized in Table 5. From Figure 2, although the results of the previous case comply with the new revised criteria, 25 cSv TEDE, it is known that the spray removal rate for particulate iodine should be re-evaluated for this application.

Table 5.2-hour doses at EAB - chemical form-only application

(unit: cSv)

With normal spray removal				With 5 times higher spray removal			
Thyroid	Whole Body	Skin	TEDE	Thyroid	Whole Body	Skin	TEDE
316	2.44	4.02	12.39	80.8	1.67	2.87	4.22

Note) Each value in the table is the greatest offsite dose for sliding 2-hour period.

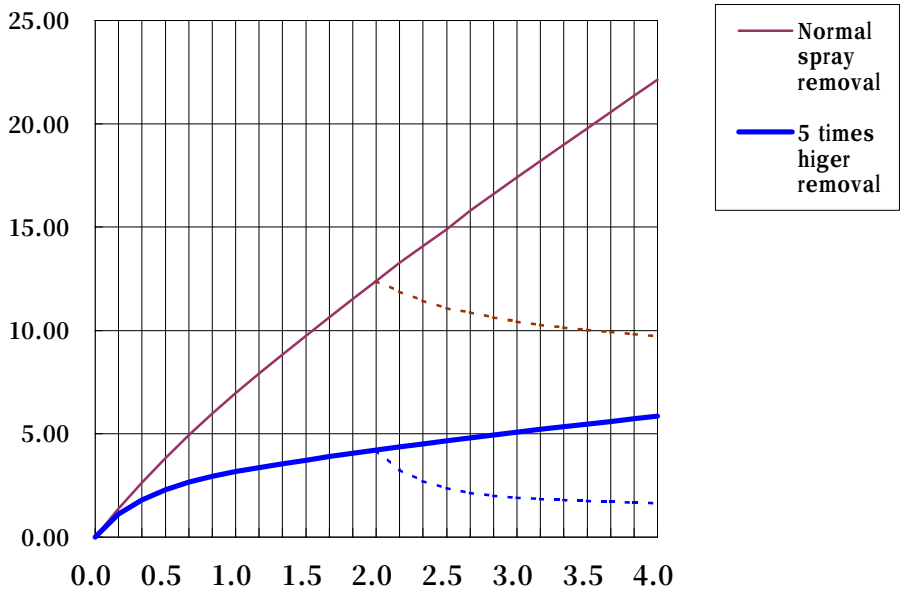

Figure 2. The results for two chemical form-only applications

3. DISCUSSION AND CONCLUSION

In recent, the revised accident source terms and radiological acceptance criteria were promulgated, which required the changes in reactor site evaluation and in designing some safety-related systems including engineered safety features. In particular, they provided the holder of an operating license issued prior to January 10, 1997 with the opportunity of revising the accident source terms used in the radiological consequence analyses of DBA, which implies the potential changes in plant design and/or operational procedure in the future. Hence, this paper, the off-site radiological consequences are closely scrutinized following various selective applications of the revised source terms of NUREG-1465. The results of investigation could be well used in improving the safety and performance of the plant.

Based upon the results of this study, the observations and conclusions apply as follows:

(1) In overall, the revised source terms and TEDE-based criteira allow us to take the increased margin of safety in the operating plants. For example, the results of Case 1 show that while the margin of safety is only about 26% against thyroid dose limit, 300 cSv that is the controlling limit in traditional acceptance criteria, the margin of safety is increased to about 74% against TEDE-based criteria, 25 cSv.

(2) The selective application should be a balanced use of the revised source terms such that the selective portions of NUREG-1465 are not biased toward low dose.

(3) Whatever the type of selective application is, it is recommended that spray removal rate for

radioiodines should be extensively examined for appropriateness or re-evaluated, if necessary.

(4) In chemical form-only selective application, it should be confirm that pH of the containment water pool is maintained at 7 or above over the period of 30 days following DBA.

In conclusion, a number of potential changes in plant operation when we used the revised accident source terms appear feasible from the standpoint of simplifying operations and improving safety. These could include the changes in allowable containment leak rate, isolation valve actuation timing, filtration unit, and accident-mitigation system actuation timing.

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