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An Investigation of Technical Issues on VHTR Off-site Dose Analysis

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1. Introduction

Off-site dose analysis is a crucial step for designing a nuclear power plant including an advanced reactor such as the Very High Temperature Reactor (VHTR). Compared to Light Water Reactors (LWRs), studies on the off-site dose analysis for VHTR are not abundant. Due to mature technologies, computer codes developed for LWRs could be applied to VHTR. For example, Lee et al. [1] applied MACCS2 to a 600 MWth VHTR. However, off-site dose analysis codes developed for LWRs have to be carefully applied to VHTR due to different features of radiological source terms.

In this paper, some technical issues on VHTR off-site dose analysis were examined and discussed using a well-known off-site dose analysis code for LWRs. The RADTRAD code [2] was selected as a representative code. It was developed by Sandia National Laboratories (SNL) for the U.S. NRC. Currently, the RADTRAD code is popularly used as a licensing analysis code to show compliance with nuclear plant siting criteria for the site boundary radiation doses for various design basis accidents of LWRs. In this work, the applicability of the RADTRAD code to VHTR was assessed qualitatively. And then an example calculation was carried out to confirm the usefulness and limitation of the RADTRAD code.

2. RADTRAD Models

The RADTRAD code can be used to estimate the containment release using either the NRC TID-14844 or NUREG-1465 source terms and assumptions, or a user-specified table. In addition, the code can account for a reduction in the quantity of radioactive material due to natural deposition, filters, and other natural and engineered safety features. The RADTRAD code uses a combination of tables and/or numerical models of source term reduction phenomena to determine the time-dependent dose at the Exclusion Area Boundary (EAB) and the Low Population Zone (LPZ) and the Control Room (CR) for a given accident scenario. The code system also provides the inventory, decay chain, and dose conversion factor tables needed for the dose calculation.

2.1 Governing Equations

RADTRAD solves the time and space dependent nuclide balance equation as follows:

$$\frac{d}{dt} N^m_{n,i} = \sum_{v=1}^{n-1} \beta_{n,v} N^m_{v,i} \lambda_v + S^m_{n,i}$$
$$- \left[\sum_{\substack{j=1 \\ j\neq i}}^{L} \left| F^m_{i,j(conv)} + \frac{Q^m_{i,j(p)}}{Vol_i} \right| + \lambda_n + \lambda^m_{dep,n}(t) + \frac{\eta^m_{n:i,j}}{100} F^m_{i,j(forced)} \right] N^m_{n,i}$$
$$+ \sum_{\substack{j=1 \\ j\neq i}}^{L} \left[\left(1 - \frac{\eta^m_{n:i,j}}{100} \right) F^m_{i,j(forced)} + F^m_{i,j(conv)} + \frac{Q^m_{i,j(p)}}{Vol_j\, DF^m_{n(p)}} \right] N^m_{n,j} \tag{1}$$

Where $N^m_{n,i}$ = number of atoms of nuclide n in compartment i during time step m. $F^m_{i,j}$ = volume-normalized leakage air flow rate from compartment j to i. Q = volumetric flow rate, DF = decontamination factor, S = source injection rate, η = filter efficiency. The terms for spray and suppression pool which are not applicable to VHTR are omitted in Eq. (1).

2.2 Models and Correlations

Compartment Model

Compartment model is used to describe the space dependency of radionuclides. It can be any space in a containment, control room, or environment. The features of compartment can have spray, recirculation filters, natural deposition, overlying pool. However, only natural deposition is applicable to VHTR.

Natural Deposition

Henry, Powers, and user-defined coefficients are available. Powers model is not applicable to VHTR. The user-defined coefficients are specified by time-dependent table format.

Piping

Brockmann-Bixler model and user-defined removal coefficients are available. The user-defined removal coefficients describe the decontamination factor depending on flowrate and chemical forms of iodine.

Air Leakage

Time-dependent leakage rate of air can be specified by table.

Filter

Time-dependent filter efficiency depends on flowrate and chemical forms of iodine. A table format is used.

Radiological Decay
Radiological decay can be considered.

Atmospheric Dispersion Factor (X/Q)
Time-dependent table is provided.

Breathing & Occupancy Factor
Time-dependent table is provided.

Nuclide Inventory
A separate file (with extension of NIF) is used for initial nuclide inventory. Default files are provided for LWRs. A user can make a NIF file for the inventory of any nuclide and define its daughter products.

Source Term Release Fraction and Timing
A separate file (with extension of RFT) is used for the source term release fraction and timing. Default files are provided for LWRs. A user can make a RFT file. Fig. 1 shows an example of input file for the source term release fraction and timing. Four timing locations and nine source term groups can be used in the current version of RADTRAD. These are based on the NUREG-1465 source term study. Four timing locations represent gap release, early in-vessel release, ex-vessel release, and late in-vessel release. Although a user can modify the captions and numerical values in Fig. 1, the source term groups cannot be changed and the number of timing locations cannot be increased.

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Release Fraction and Timing Name:
PWR, NUREG-1465, Tables 3.12 & 3.13, June 1992
Duration (h):
 0.5000E+00  0.1300E+01  0.2000E+01  0.1000E+02
Noble Gases:
 0.5000E-01  0.9500E+00  0.0000E+00  0.0000E+00
Iodine:
 0.5000E-01  0.3500E+00  0.2500E+00  0.1000E+00
Cesium:
 0.5000E-01  0.2500E+00  0.3500E+00  0.1000E+00
Tellurium:
 0.0000E+00  0.5000E-01  0.2500E+00  0.5000E-02
Strontium:
 0.0000E+00  0.2000E-01  0.1000E+00  0.0000E+00
Barium:
 0.0000E+00  0.2000E-01  0.1000E+00  0.0000E+00
Ruthenium:
 0.0000E+00  0.2500E-02  0.2500E-02  0.0000E+00
Cerium:
 0.0000E+00  0.5000E-03  0.5000E-02  0.0000E+00
Lanthanum:
 0.0000E+00  0.2000E-03  0.5000E-02  0.0000E+00
Non-Radioactive Aerosols (kg):
 0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
End of Release File
```

Fig. 1. Example input for source term release fraction and timing.

Dose Conversion Factor (DCF)
A separate file (with extension of INP) is used for the considered isotope list and the dose conversion factor. Default files are provided for LWRs. A user can make a DCF file. It should be noted that 60 nuclides considered in MACCS do not include several key nuclides which are very crucial in terms of the VHTR source term. For example, Rb-88, Ag-110m, and Ba-137m are missing [3]. Therefore, the DCF library of MACCS has to be modified for the VHTR application.

Chemical Form of Iodine
A user has to specify the iodine chemical fractions among aerosol, elemental, and organic options.

3. Applicability to VHTR

Intellectual Property
Currently, RADTRAD is commercialized. The distribution and maintenance are managed by a U.S. company named Alion Science & Technology [4]. RADTRAD was used for the licensing of SMART Design Certificate (DC) [5]. It means that there should be no intellectual property issue of RADTRAD code for the VHTR development. In addition, RADTRAD 3.0B version is registered in the OECD/NEA databank. Therefore this version can be used for the research purpose in OECD countries.

Governing Equation
Equation (1) is so general that it can be applied to VHTR. The terms for spray and suppression pool can be removed by inputs.

Physical Models
Table I summarizes the applicability of physical models of RADTRAD to VHTR.

Table I: Applicability of RADTRAD Physical Models to VHTR

Physical Models	Applicability
Compartment	applicable
Natural deposition	applicable
Piping	applicable
Air leakage	applicable
Filter	applicable
Radiological decay	applicable
Atmospheric dispersion factor	applicable
Breathing and occupancy factor	applicable
Nuclide inventory	applicable
Release fraction and timing	modification required
Dose conversion factor	applicable (but several key nuclides are missing in MACCS library)
Chemical form of iodine	applicable

All models in RADTRAD are applicable without modification except the source term release fraction and timing. Table II compares the source term groups of LWR (NUREG-1465) and that of VHTR [6] (developed by the Idaho National Laboratories, INL). In the accident source term study, it is generally assumed that radionuclides in the same source term group have the same release and decontamination behavior. Therefore, the application of the LWR source term groups to VHTR may result in significant inaccuracy in the offsite dose calculation. In addition, four timing locations may not be sufficient to model mechanical source terms accurately.

Table II: Comparison of Source Term Groups of LWR and VHTR

LWR (NUREG-1465)	VHTR [6]
Noble gases (Xe, Kr)	Noble gases
Halogens (I, Br)	I, Br, Te, Se
Tellurium group (Te, Sb, Se)	Sb
Alkali Metals (Cs, Rb)	Cs, Rb
Strontium	Sr, Ba, Eu
Barium	
Noble metals (Ru, Rh, Pd, Mo, Tc, Co)	Ag, Pd
	Mo, Ru, Rh, Tc
Lanthanides (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am)	La, Ce
Cerium group (Ce, Pu, Np)	Pu, actinides

4. Example Calculation

In order to confirm the applicability of RATRAD to VHTR and illustrate the usefulness and limitation, an example calculation was performed. RADTRAD 3.03B was used in the calculation. Table III provides the major RADTRAD input values used for the example. A 350 MWth VHTR was selected and atmospheric dispersion factor (X/Q) of the Kori site was assumed.

Table III: Major RADTRAD Input for Example Calculation

Parameter	Value
Reactor power (MW)	350
Containment free volume (ft^3)	218,500
Containment leak rake (%vol./day)	100
Atmospheric dispersion factor (X/Q)	Kori data [5,7]

Table IV shows the key nuclides for VHTR reported in the INL study and their initial inventories [6]. As shown in Table IV, the DCFs of three nuclides (Ag-110m, Ag-111, Sb-125) are not available in the MACCS library. It means that off-site dose contributed by these nuclides cannot be considered without a user defined DCF file. Since the creation of a new DCF library is beyond the scope of this work, the default MACCS DCF library was applied for the present example. Table V provides the applied source term release fraction into the containment under Depressurized Conduction Cooldown (DCC) accident scenario. The values were obtained based on the INL study. For the timing locations, 1.0E-4 and 48 hrs were assumed for the short and long term releases, respectively.

Since RADTRAD only allows the same release fraction for the same source term group, the maximum release fraction of each source term group was applied except noble metals as shown in Table VI. Since Ag and Ru have significantly different release fractions, two cases (Cases A and B) were considered. Case A uses the release fraction of Ru-103 for noble metals whereas Case B uses the release fraction of Ag-110m for noble metals.

Table IV: Initial Inventory of Key Nuclides and Availability of DCF in MACCS Library

Nuclide	Inventory (Ci/MWth)	DCF in MACCS Library
Xe-133	5.94E+04	available
Kr-85	5.10E+02	available
Kr-88	4.54E+04	available
I-131	3.28E+04	Available
I-133	5.88E+04	Available
Te-132	4.43E+04	Available
Cs-137	2.59E+03	Available
Cs-134	2.97E+03	Available
Sr-90	2.71E+03	Available
Ag-110m	3.87E+01	not available
Ag-111	4.85E+03	not available
Sb-125	3.70E+02	not available
Ru-103	5.91E+04	Available
Ce-144	3.73E+04	Available
La-140	5.52E+04	Available
Pu-239	6.00E+00	Available

Table V: Source Term Release Fraction into Containment under DCC Accident

Nuclide	LWR Class	Short Term (1.0E-4 hr)	Long Term (48 hr)
Xe-133	Noble gases	2.87E-06	5.34E-06
Kr-85	Noble gases	2.81E-06	7.37E-06
Kr-88	Noble gases	2.88E-06	2.98E-11
I-131	Halogens	1.43E-07	2.93E-06
I-133	Halogens	1.38E-07	6.75E-07
Te-132	Te group	1.39E-07	2.25E-06
Cs-137	Alkali metals	5.00E-05	1.36E-05
Cs-134	Alkali metals	7.53E-06	1.50E-05
Sr-90	Strontium	4.50E-06	7.19E-06
Ag-110m	Noble metals	2.87E-04	7.90E-04
Ag-111	Noble metals	7.20E-05	6.44E-04
Sb-125	Te group	2.98E-06	1.58E-06
Ru-103	Noble metals	2.83E-09	7.11E-07
Ce-144	Ce group	5.15E-08	7.60E-08
La-140	Lanthanides	2.87E-09	3.18E-08
Pu-239	Ce group	1.92E-09	6.14E-09

Table VI: Source Term Release Fraction Used for RADTRAD Calculation

Source Term Group	1.0E-4 hr	48 hr
Noble gases	2.88E-06	7.37E-06
Halogens	1.43E-07	2.93E-06
Tellurium group	2.98E-06	2.25E-06
Alkali metals	5.00E-05	1.50E-05
Strontium	4.50E-06	7.19E-06
Barium	4.50E-06	7.19E-06
Noble metals (Case A)	2.83E-09	7.10E-07
Noble metals (Case B)	2.87E-04	7.90E-04
Lanthanides	2.87E-09	3.18E-08
Cerium group	5.15E-08	7.60E-08

Table VII shows the calculated offsite does at EAB and LPZ. It shows significantly different values for Cases A and B. It clearly indicates the importance of the release fraction of noble metals. In particular, the Total Effective Dose Equivalent (TEDE) is significantly increased for Case B. In the new source term guideline named Alternate Source Term (AST), TEDE has to be used accordance with 10 CFR Part 20 [7]. Therefore, it can be concluded that the source term group defined for LWRs should be avoided for VHTR and the modification of RADTRAD is necessary for the VHTR application.

Table VII: Offsite Dose Calculated by RADTRAD

Location	Case A	Case B
EAB at 2 hr		
Whole body dose (rem)	5.29E-03	9.56E-02
Thyroid dose (rem)	3.60E-01	9.76E-01
TEDE (rem)	3.01E-01	3.79E+01
LPZ at 720 hr		
Whole body dose (rem)	4.04E-03	1.06E-01
Thyroid dose (rem)	4.04E-01	1.17E+00
TEDE (rem)	2.82E-01	4.74E+01

5. Conclusions

In this work, in order to investigate technical issues on off-site dose analysis of VHTR, the applicability of RADTRAD to VHTR was assessed qualitatively and an example calculation was performed to confirm the usefulness and limitation. It was concluded that the governing equations and fundamental physical models of RADTRAD are applicable to VHTR. However, the source term group defined for LWRs has to be modified for VHTR applications. In addition, a study on new DCF library is also required to include several key nuclides such as Ag-110m, Ag-111, and Sb-125. The timing locations for the source term release may have to be augmented for accurate simulation of time-dependent behavior in terms of mechanical source term approach.

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REFERENCES

[1] J. Lee, J. Kim, and M. Jae, "Development of a Methodology for VHTR Accident Consequence Assessment," Transaction of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 12-13, 2016.
[2] S.L. Humphreys et al., RADTRAD: A Simplified Model for RADionuclide Transport and Removal And Dose Estimation, NUREG/CR-6604, Sandia National Laboratories, 1997.
[3] M. Richards, "HTGR Radionuclide Design Criteria and Fission Product Behavior," 2012. 12.
[4] www. radtrad.com
[5] Korea Atomic Energy Research Institute, SMART Standard Design Safety Analysis Report, Rev. 1, 2012.
[6] Idaho National Lab., Scoping Analysis of Source Term and Functional Containment Attenuation Factors, INL/EXT-11-24034, Rev. 1, 2012. 02.
[7] S. C. Lee, "Key Impact Parameters for Application of Alternate Source Term to Kori Unit 1," Nucl. Eng. Technol., Vol. 42, No. 4, pp. 394-413, 2010.