

**Ecological Risk Assessment Software for Radioactive Waste Management Facilities
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ABSTRACT

Environmental Risk Assessment (ERA) is a systematic process which can be used to identify, quantify and characterize the risk posed by contaminants and physical stressors in the environment on biological receptors, including human and non-human biota. Human receptors can be addressed through a Human Health Risk Assessment and non-human biota can be addressed through an Ecological Risk Assessment (EcoRA). In 2012 the Canadian Standards Association (CSA) issued a CSA standard N288.6 Environmental Risk Assessment at Class I Nuclear Facilities and Uranium Mines and Mills. The standard applies to radioactive waste management facilities, as well as nuclear power plants. The ERA can also be used retrospectively, to estimate the effect that a contaminant or stressor has already had on the environment; and can be used to assist in determining possible remedial or risk management options to return the quality of the affected environment to a predetermined state.

While industry-standard tools for estimating radiological doses to humans are readily available, there is a need for a tool to implement the CSA N288.6 standard for Ecological Risk Assessment. To address this need, AMEC developed a computer code called “Assessment of Impact of Contaminants on Ecological Receptors (AICER)”. The code was developed to be consistent with the CSA standard N288.6, by assessing the impact of radiological contamination on non-human biota for normal operations. The code can also be used to screen for the potential effects of conventional contamination on the environment. In addition, the code is also applicable for abnormal events and accidents with the appropriate modification of some parameters used in the code.

The AICER code was qualified in accordance with the requirements of the Canadian quality standard CSA N286.7 “Quality Assurance of Analytical, Scientific, and Design Computer Programs for Nuclear Power Plants”. The functionality of the code is illustrated with screen shots in the paper, following the introduction of the theoretical model for the dose calculation. An inter-comparison with RESRAD-BIOTA and ERICA Assessment tool at the conceptual level was conducted. In addition, the practical application of the code for the assessment of the impacts related to an existing radioactive waste management facility is provided. In particular, analysis was conducted to evaluate radiological doses to non-human biota resulting from a fire accident scenario involving an existing waste storage and processing facility. Analysis included all feasible waterborne and airborne exposure pathways. Doses were evaluated for a range of species representing valued ecological components at various trophic levels and compared with benchmark values for indicator species.

INTRODUCTION

Environmental Risk Assessment (ERA) is a systematic process which can be used to identify, quantify and characterize the risk posed by contaminants and physical stressors in the environment on biological receptors, including human and non-human biota. Human receptors can be addressed through a Human Health Risk Assessment and non-human biota can be addressed through an Ecological Risk Assessment (EcoRA). In 2012 the Canadian Standards Association (CSA) issued a CSA standard N288.6 Environmental Risk Assessment at Class I Nuclear Facilities and Uranium Mines and Mills [1]. The standard applies to radioactive waste management facilities, as well as nuclear power plants. The ERA

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While industry-standard tools for estimating radiological doses to humans are readily available, there is a need for a tool to implement the CSA N288.6 standard for Ecological Risk Assessment. To address this need, AMEC developed a computer code called “Assessment of Impact of Contaminants on Ecological Receptors (AICER)”. The code was developed to be consistent with the CSA standard N288.6, by assessing the impact of radiological contamination on non-human biota for normal operations. The code can also be used to screen for the potential effects of conventional contamination on the environment. In addition, the code is also applicable for abnormal events and accidents with the appropriate modification of some parameters used in the code such as transfer factors, bioaccumulation factors, etc.

THEORETICAL MODEL FOR CALCULATION OF DOSE TO NON-HUMAN BIOTA

Graded Approach to Ecological Risk Assessment (EcoRA)

Due to the nature and complexity of EcoRAs, a graded or tiered assessment approach is recommended in the CSA N288.6-12 [1]. The tiered approach starts from a broad evaluation using protective generic parameters and a high level of conservatism and then advances toward more precise analysis, taking into account site-specific, realistic parameters and less conservatism. Specifically, CSA N288.6 recommends the following three tiers of risk assessment for nuclear facilities:

- Screening level risk assessment (SLRA): Equivalent to a Tier 1 risk assessment, SLRA represents the less detailed assessment and serves as the most conservative and broadest form of risk assessment.
- Preliminary quantitative risk assessment (PQRA): Equivalent to a Tier 2 risk assessment, PQRA is carried out based on available site concentration data to produce a preliminary estimation of exposure and risk for each receptor at relevant locations for each selected contaminant or physical stressor. Generic parameter values are often used in the exposure estimation.
- Detailed quantitative risk assessment (DQRA): Equivalent to a Tier 3 risk assessment, DQRA focuses on the risk issues identified through PQRA which require further assessment. A DQRA can involve a refined exposure assessment and risk characterization, or can consider other lines of evidence. At this level of assessment, additional site-specific monitoring data or more sophisticated modelling to estimate more realistic exposure concentrations can be used to reduce uncertainty about exposure, dose and risk.

For nuclear power plants, the emissions of conventional contaminants (e.g. chemicals) are normally relatively low, as are the typical emissions of the radiological contaminants when placed in the context of the legal dose limit for human receptors. However, given public concern with respect to the potential impact of radiological emissions on the environment, it has been the accepted practice to implement quantitative assessment of radiological impact (PQRA or DQRA) on non-human biota. AICER provides this capability. With regards to conventional emissions, AICER provides SLRA capability with the screening based on the current Canadian standards or guidelines for environmental quality. If a screening criterion is exceeded then a quantitative risk assessment for that contaminant or stressor is required..

Generic Steps for Quantitative Risk Assessment

For quantitative risk assessment of radiological emissions for non-human biota, the following generic steps are involved:

- Selection of receptors and characterization
- Selection of radionuclides of concern
- Selection of exposure pathways
- Development of conceptual assessment model
- Calculation of dose to non-human biota
- Comparison with the appropriate benchmark values

The methods of calculating doses to non-human biota, which represent the theoretical basis of AICER software, are discussed below.

Equations for Calculation of Internal Dose

Non-human biota could be exposed to radiation through different pathways. The total dose to non-human biota is the sum of internal dose and external dose. Internal dose (D_{int}) can be calculated as follows [1]:

$$D_{int} = DC_{int} \times C_t \quad (\text{Eq.1})$$

Where

DC_{int} = internal dose coefficient for aquatic or terrestrial organism

C_t = radionuclide concentration in tissue of the aquatic or terrestrial organism

The key to calculate internal dose to any organism is to obtain the concentrations of radionuclides in the tissue of the organism. The tissue concentration can be determined based on the measurement of field biota samples. If it is not available, the tissue concentration can be derived based on environmental media concentrations and transfer factors. Specifically, for plants, invertebrates and fish, the tissue concentration can be calculated with the following equation:

$$C_t = C_m \times BAF \quad (\text{Eq.2})$$

Where

C_t = tissue concentration

C_m =environmental media concentration

BAF=Indicator-specific, media-dependent bioaccumulation factors

For birds and mammals, the tissue concentration, C_t can be calculated with the following equation:

$$C_t = \sum(C_x \times I_x \times TF) \quad (\text{Eq.3})$$

Where for a given radionuclide,

C_x = concentration in the food chain item, x, of the bird or mammal

I_x = ingestion rate of the food item, x

TF= Indicator-specific transfer factor

In this assessment, the BAF and TF used to estimate radionuclide concentrations in indicator species are as follows:

- Transfer from water to: fish, aquatic plants, amphibians and benthic invertebrates
- Transfer from soil to invertebrates
- Transfer from air and soil to plants
- Transfer from air (inhalation), soil (intake), water (intake), and foodstuff to mammals and birds

Equations for Calculation of External Dose

The equations to calculate external dose (D_{ext}) to aquatic organisms are as follows:

$$D_{ext} = DC_{ext} \times \{[OF_s + 0.5 \times OF_{ws} + 0.5 \times OF_{seds}] \times C_w + [OF_{sed} + 0.5 \times OF_{seds}] \times C_s\} \quad (\text{Eq.4})$$

Where

DC_{ext} = External dose coefficient

C_s = radionuclide concentration in sediment

C_w = radionuclide concentration in water

OF_w = Fraction of time in water

OF_{ws} = Fraction of time on water surface

OF_{sed} = Fraction of time in sediment

OF_{seds} = Fraction of time on sediment surface

External dose to terrestrial organisms can be calculated with the equation below

$$D_{ext} = DC_{ext,s} \times OF_s \times C_s + DC_{ext,ss} \times OF_{ss} \times C_{ss} \quad (\text{Eq.5})$$

Where

$DC_{ext,s}$ = External dose coefficient for exposure in soil

$DC_{ext,ss}$ = External dose coefficient for exposure on soil surface

C_s = radionuclide concentration in soil

C_{ss} = radionuclide concentration in soil surface

OF_s = Fraction of time in soil

OF_{ss} = Fraction of time on soil surface

Parameters Used for Dose Calculation

As shown in the equations discussed above, the calculation of dose to non-human biota requires the data of a series of parameters. The parameters include internal and external dose coefficients, biological information of the species such as food intakes and the exposure fraction for different environmental media, and transfer factors or bioaccumulation factors which will be used to derive the tissue concentrations in species of concern. The key references for these parameters used in the code are listed below:

- Internal and external dose coefficients (DC): ICRP 108, Environmental Protection - the Concept and Use of Reference Animals and Plants [2].
- Biological information for various species: US EPA Wildlife Exposure Factors Handbook [3 and 4]
- Transfer factors: CSA N288.1-14, Guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operation of nuclear facilities [5], and ICRP 114, Environmental Protection: Transfer Parameters for Reference Animals and Plants [6]

The parameter values used in the code are stored in a built-in database which is accessible to the user.

FUNCTIONALITY AND USE OF THE CODE

Inputs and Outputs of the Code

The code, with the start menu being shown in Figure 1, is a wizard type program. It takes users through input of data step-by-step. The inputs to the code include species of concern and the concentrations of



Figure 1: Starting Menu of the Code

the radionuclides in environmental media. The concentrations could be measured values or modelled results, which are obtained outside the code. If the concentrations of radionuclides in the tissue of the indicator species, referred to as tissue concentrations, are available, they can also be used as the input data. The outputs of the code are doses to each species of concern, with a dose breakdown by applicable pathway for each radionuclide of concern. The code also has the capability of comparing the calculated doses against the benchmark values. Any exceedance will be marked with a special color of the font.

Use of the Code

As the assessment of conventional contaminants at the screening level is relatively straightforward, the use of the code is only illustrated here for the assessment of radiological contaminant exposure of different aquatic and terrestrial species.

The screen shots presented below display the three major steps for the calculation of dose to species of interest:

- Step 1: Select the species of concern to user, as illustrated in Figure 2.

- Step 2: Provide the concentrations of radionuclides in different environmental media including air, water, sediment and soil, as illustrated in Figure 3. Note that if the concentrations of radionuclide in the tissue of the species are available, they can be input into the code as well, as illustrated in Figure 4.
- Step 3: Display the results of dose calculation for different radionuclides through different pathways, if applicable, for each species selected by the user. This is illustrated in Figure 5.

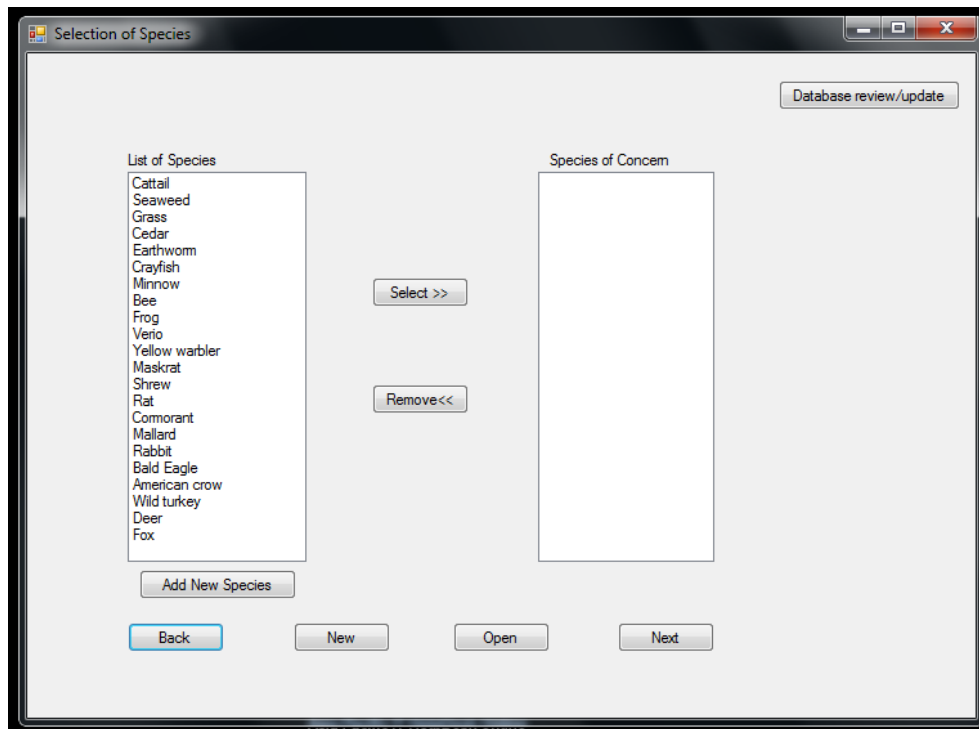


Figure 2: Selection of Species of Concern

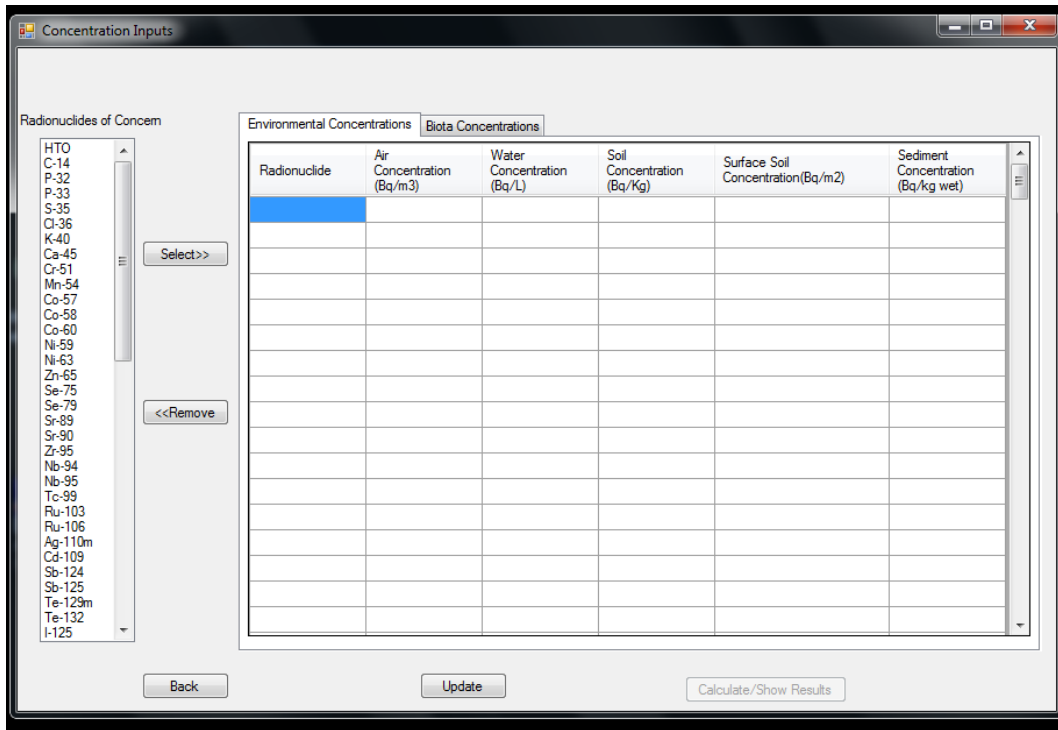


Figure 3: Concentration Inputs

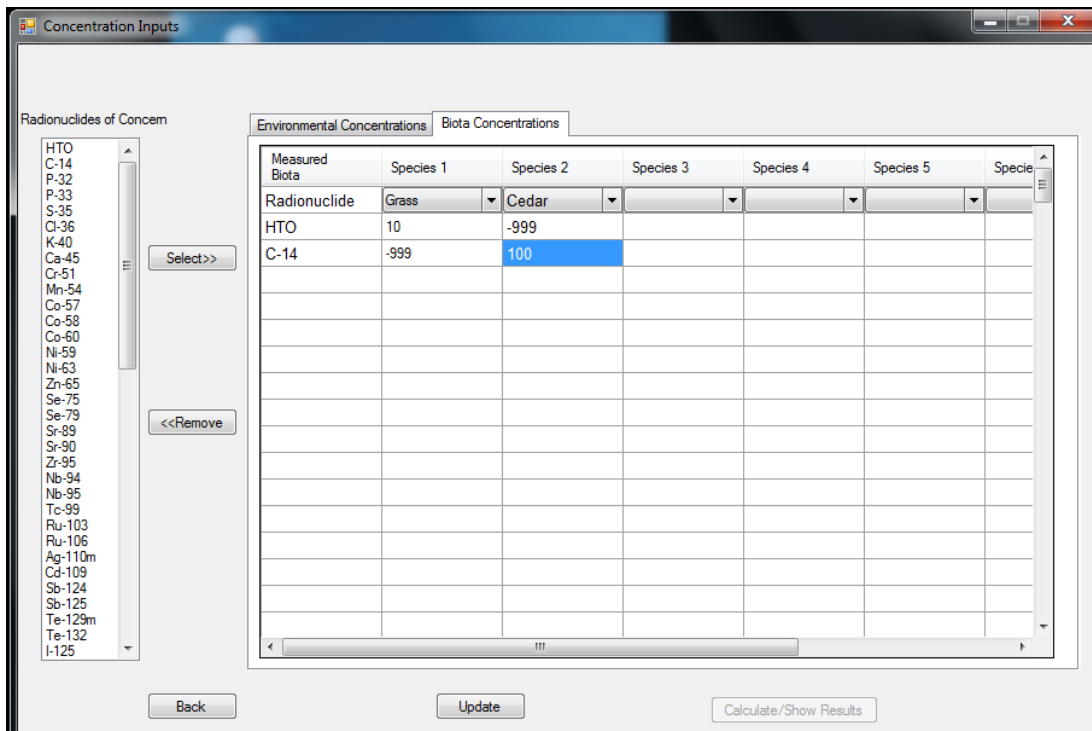


Figure 4: Biota Concentration

Species	Radionuclide	Direct Internal dose (μGy/d)	Inhalation dose (μGy/d)	Drinking water dose (μGy/d)	Soil consumption dose (μGy/d)	Sediment consumption dose (μGy/d)	Food consumption dose (μGy/d)	Water/Sediment external dose (μGy/d)	Soil external dose (μGy/d)	Sub Total (μGy/d)	Total Dose (μGy/day)	Criterion (μGy/d)
Grass	HTO	7.92E-003	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	7.92E-003	5.57E+000	2.40E+000
	C-14	5.56E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	0.00E+000	5.56E+000		

Figure 5: Calculation Results

The code provides the user the option to add any new species and its characteristics, as shown in Figure 6. The built in database, which is shown in Figure 7, can be reviewed and updated if needed to meet the user’s special requirement on the datasets.

Parameter	Note	Unit	Value
Name of new species	NA	NA	
Category	Specified category	NA	
Occup	fraction fo time in area of concern	%	
Inh rate	Inhalation rate	m3/day	
Water Intake	Water ingestion rate	L/day	
Soil Intake	Soil intake	kilogram/Day	
Sed Intake	Sediment intake	kilogram/Day	
Food Intake	Total food intake rate	kilogram/Day	
Food1Name	Food component 1	NA	
Food1	Fraction of Food1	%	
Food2Name	Food component 2	NA	
Food2	Fraction of Food2	%	
Food3Name	Food component 3	NA	
Food3	Fraction of Food3	%	
Food4Name	Food component 4	NA	
Food4	Fraction of Food4	%	
Ofa	Exposure to air	%	
OFw	Fraction of time in water	%	
OFws	Fraction of time on water surface	%	

Figure 6: Add New Species

Radionuclide	Large Mammal	Small Mammal	Bird	Amphibian	Fish	Marine Fish	Benthic Invertebrate	Ins
HTO	1.58E-004	1.58E-004	1.58E-004	1.58E-004	1.58E-004	1.58E-004	1.58E-004	1.58E-004
C-14	6.80E-004	6.80E-004	6.80E-004	6.80E-004	6.80E-004	6.80E-004	6.80E-004	6.80E-004
P-32	9.60E-003	9.20E-003	9.40E-003	8.90E-003	9.40E-003	9.10E-003	9.30E-003	7.0E-003
P-33	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.0E-003
S-35	6.80E-004	6.80E-004	6.80E-004	6.70E-004	6.80E-004	6.80E-004	6.80E-004	6.7E-004
Cl-36	3.80E-003	3.70E-003	3.80E-003	3.70E-003	3.80E-003	3.70E-003	3.70E-003	3.4E-003
K-40	8.40E-003	7.20E-003	7.30E-003	6.80E-003	7.30E-003	7.10E-003	7.30E-003	5.6E-003
Ca-45	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.10E-003	1.1E-003
Cr-51	3.50E-004	1.10E-004	1.40E-004	8.80E-005	1.30E-004	1.10E-004	1.20E-004	7.2E-005
Mn-54	6.90E-003	1.10E-003	1.70E-003	5.50E-004	1.50E-003	1.00E-003	1.40E-003	1.9E-003
Co-57	1.50E-003	4.70E-004	5.80E-004	3.80E-004	5.50E-004	4.90E-004	5.40E-004	3.2E-004
Co-58	8.50E-003	1.70E-003	2.40E-003	1.00E-003	2.20E-003	1.60E-003	2.10E-003	6.1E-003
Co-60	2.00E-002	4.00E-003	5.70E-003	2.60E-003	5.10E-003	4.00E-003	5.00E-003	1.6E-003
Ni-59	9.60E-005	9.50E-005	9.60E-005	9.40E-005	9.60E-005	9.60E-005	9.60E-005	8.9E-005
Ni-63	2.40E-004	2.40E-004	2.40E-004	2.40E-004	2.40E-004	2.40E-004	2.40E-004	2.4E-004
Zn-65	4.70E-003	7.90E-004	1.20E-003	4.40E-004	1.10E-003	7.70E-004	1.00E-003	1.9E-003
Se-75	3.80E-003	7.80E-004	1.10E-003	5.00E-004	1.00E-003	7.90E-004	9.70E-004	3.1E-003

Figure 7: Database Review and Update

In addition, the code can save and open the files set up by the user through the standard save and open file dialogue windows, respectively. For example, the save file dialogue window is illustrated in Figure 8. The code also provides the capability to export the dataset files in spreadsheet format.

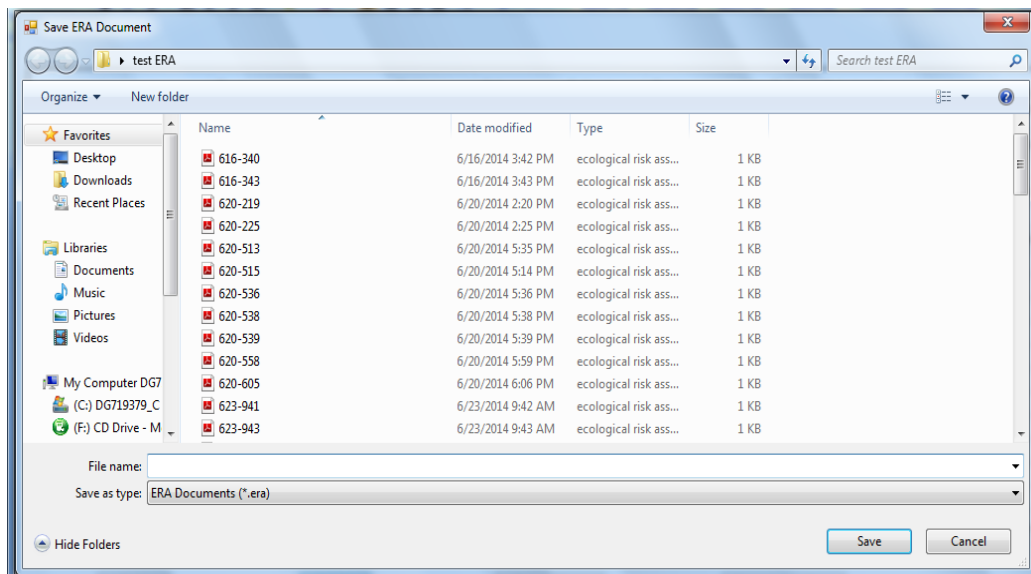


Figure 8: Save File Dialogue Box

QUALITY ASSURANCE

The AICER code was developed in accordance with AMEC NSS quality procedures including Software Development and Documentation and Software Verification, Validation and Qualification. The procedures are developed in compliance with ISO 9001 and CSA N286.7 standards for quality assurance [7]. Specifically, a theory manual and a user manual have been developed, along with the completion of the verification report.

COMPARISON WITH RESRAD-BIOTA AND ERICA

A brief comparison of the features of the AICER software with other similar computer codes developed for the calculation of dose to non-human biota was conducted. The comparison results are presented in Table 1.

Table 1: Comparison of features of AICER and other codes for calculation of dose to non-human biota

Computer codes	AICER	RESRAD BIOTA	ERICA
Standard or guidance	Canada, CSA N288.6 (2012) [1]	USA, DOE-STD-1153-2002 (2002) [8]	EU [9]
Approach	<ul style="list-style-type: none"> Screening level assessment for conventional contaminants Quantitative risk assessment for radiological contaminants 	Graded quantitative risk assessment	Graded quantitative risk assessment

Computer codes	AICER	RESRAD BIOTA	ERICA
Contaminants	<ul style="list-style-type: none"> Chemical contaminants Radiological contaminants 	Radiological contaminants	Radiological contaminants
Organisms	Actual indicator species	Reference organisms, option to configure user-defined organisms	Reference organisms
Result format	Provides dose breakdown by pathways and radionuclides	Provides dose breakdown by environmental media and radionuclides	Provides dose breakdown by environmental media and radionuclides

Furthermore, a comparison of the doses estimated by using AICER and ERICA was performed for different biota, using environmental concentrations as inputs. Assuming water and soil are contaminated by Cs-137 and the concentration in water and soil are 0.01 Bq/L and 10 Bq/kg, respectively, doses are calculated for pelagic fish, grass, tree, bird, large mammal and small mammal using the two codes. The results are presented in Table 2 and illustrated in Figure 9.

Table 2: Comparison of doses calculated with AICER and ERICA

Species	Results by ERICA (μGy/h)	Results by AICER (μGy/h)	Ratio: AICER dose/ ERICA dose
Pelagic fish	6.1E-03	6.4E-03	1.1
Grass	2.7E-03	6.2E-03	2.3
Tree	1.3E-03	2.1E-03	1.6
Bird	2.2E-03	4.5E-03	2.1
Large mammal	1.2E-02	6.0E-03	0.5
Small mammal	8.6E-03	4.6E-03	0.5

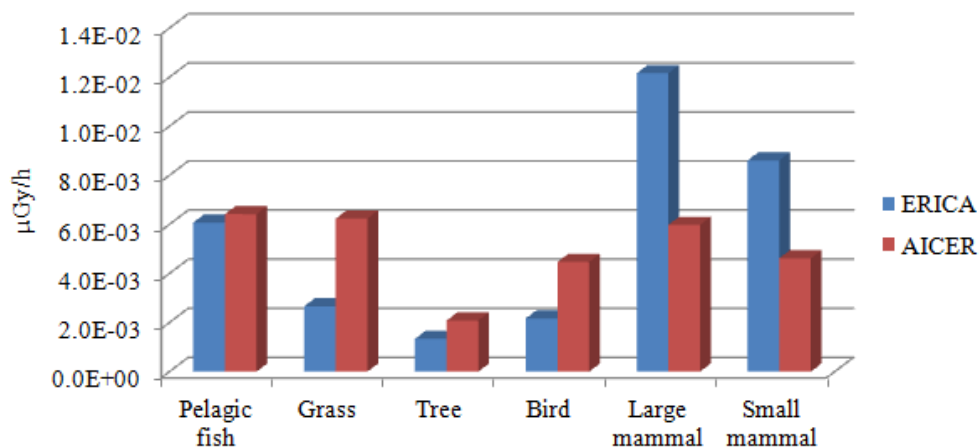


Figure 9: Comparison of the results by AICER and ERICA

As shown in Table 2, for the given contamination level, the ratio of the doses calculated by AICER and ERICA for different species is in the range of 0.5 to 2.3. While AICER's results are more conservative for fish, plant and bird, ERICA's values for mammal are higher than those calculated by AICER. In addition, the same comparison between AICER and RESRAD-BIOTA was carried out for a large mammal for the same contamination levels. The dose to a large mammal (deer) estimated by RESRAD-BIOTA is $2.4E-3$ $\mu\text{Gy/h}$, about 40% of the value estimated by AICER. The different calculation results are mainly due to the methods used by each code and the values of the parameters used in each code such as dose coefficients, transfer factors, bioaccumulation factors and relative biological effectiveness.

APPLICATION

The AICER code has been successfully used to assess the doses to terrestrial and aquatic species resulting from a postulated fire scenario at a radioactive waste management facility. The facility stores low and intermediate level radioactive waste. For the postulated fire scenario the contaminants are released to the environment through airborne emission and liquid discharge. The species of non-human biota considered in the assessment included fish, cedar, groundhog, deer, etc, representing different trophic level and exposure pathways. The doses to these species were calculated using AICER and then compared against the indicator-specific dose benchmarks.

SUMMARY

AICER is a computer code developed for the assessment of the impact of conventional and radiological contaminants on non-human biota associated with the operation of nuclear facilities. Developed in compliance with the requirements of the CSA N286.7 quality standard, the code provides the capabilities to efficiently assess ecological risks related to exposure to radiological and non-radiological contaminants in accordance with the current Canadian standard CSA N288.6-12. AICER is featured with a user-friendly interface and simplicity of operation. The code has been validated and successfully applied for projects supporting safety and environmental analysis for nuclear facilities in Canada. While the capabilities are generally similar to US and European analogues (RESRAD-BIOTA and ERICA, respectively), AICER is specifically designed to satisfy the needs of Canadian users, as it is designed to be consistent with the Canadian CSA N288.6 standard on environmental risk assessment.

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