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Predictive Analysis of Radionuclide Source Term from Hypothetical Severe Nuclear Accident involving APR1400: Machine Learning Based Approach

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Abstract: Nuclear accident results to significant released of discharged radionuclides to the environment, which endangers the public, and the environment. Decision-makers are always faced with challenges in such situation especially in determining the contributing variables associated with radionuclides source term released. In these situations, machine learning can be a crucial tool in helping decision-makers in determining the contribution of each variables associated with released radionuclides, which aids in early warning and helps to protect people and the environment. In this study, Source Term to Dose (STDose) model of Radiological Assessment System for Consequence Analysis computer Code (RASCAL) was used to generate radionuclides source term from Advanced Power Reactor (APR1400) by using two (2) hypothetical severe accident scenario for Long Term Station Blackout (LTSBO) and Loss of Coolant Accident (LOCA). Supervised Machine learning based approach-using Classification and Regression Tree (CART) Analysis was used to determine the most important predictors' variable associated with radionuclides source term release for Cs-137, Cs-134, I-131, Te-132 and Xe-133 as well as their relative importance. The result of the prediction shows that containment leakage rate contribute 100% to source term released to the environment during nuclear accident with coolant duration contribute 0.1% of source term released. The containment leakage rate accounts for the wide spread and dispersion of radionuclide source terms to the environment. The LTSBO and LOCA scenarios are categorized as accident with wider consequences with significance released of radioactive materials to the environment by International Nuclear and Radiological Event Scale (INES).

Keywords: Nuclear Accident, INES, APR1400, LTSBO, LOCA, RASCAL, Machine Learning, CART.

1 Introduction

Due to its low greenhouse gas emissions, nuclear energy is regarded as one of the cleanest energy sources. In contrast to other renewable energies like solar and wind energy, it is a baseload power with a steady and enormous production. The construction and operation of nuclear power plants place a strong focus on public safety [1]. During normal operation, nuclear power plants emit very low amounts of radioactive materials into the air and are usually less than recommended limits for radioactive air emissions [2].

Severe accident in nuclear reactors is one whose severity exceeds the design basis accidents with consequences resulting in core damage, fission product releases, and fuel meltdown, among others, which could result to substantial release of radionuclides to the environment. Such releases might be in gaseous or liquid effluents. Thus, assessing the amount of the released radionuclides to the environment as well as the contributing variables associated with such released is of outmost importance in emergency management [3].

Radionuclides source term refers to the assessment of risk due to accidental releases and discharge of radionuclides to the environment [3, 4]. There is quite concerned about the possible risks associated with nuclear power plants accident because of the massive quantities of radioactive materials released during nuclear disasters. Such have a considerable negative impact on both humans and the environment as recorded in Chernobyl in Ukraine (1986), Three Mile Island (TMI) in Middletown, USA (1979), and Fukushima Daiichi nuclear accident in Japan (2011). Therefore, estimation of source term following nuclear accident is vital in accessing

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the extent of radionuclides release to the environment and the risk of exposure associated thereof [5]. The release of source term from nuclear or research reactor accident to the environment depends on the inventory of fission products and other radionuclides in the core; the progression of core damage; the fraction of radionuclides released from the fuel and its characteristics among others [6].

Advanced Power Reactor with electrical output of 1400MWe (APR1400) is an evolutionary advanced light water reactor (ALWR) developed by the Korean Electric Power Company (KEPCO) in 2002 with plant life time of 60 years and 18 months refueling period. The APR1400 uses advanced design characteristics with significantly improved plant safety, economical efficiency, and convenience of operation and maintenance. The design was based on experienced from development, construction, operation and maintenance of Optimum Power Reactor 1000Mwe (OPR1000), the first standard pressurized water reactor (PWR) plant in Korea [7].

In this study, Machine Learning was employed to performed predictive analysis of radionuclide source term released from hypothetical severe nuclear power plant accident. Radiological Assessment System for Consequence Analysis (RASCAL) computer Code developed by the United State Nuclear Regulatory Commission (US-NRC) was used to generate radionuclides source term using source term to dose model (STDose) from APR1400 hypothetical severe accident using two (2) scenarios involving Long Term Station Blackout (LTSBO) and Loss of Coolant Accident (LOCA) respectively. LTSBO is an accident involving total loss of electric power while LOCA involves loss of core cooling system where the safety injection system actuation signal is automatically actuated to cool and submerged the reactor core.

The International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) developed the International Nuclear and Radiological Event Scale (INES) in 1990 as a tool for quickly communicating the safety significance of reported nuclear and radiological incidents and accidents [8]. LTSBO and LOCA accident scenarios were categorized as level seven (7) of the INES scale since both accident involves significant release of radionuclides source term to the environment with widespread consequences.

Machine Learning Technique using Classification and Regression Tree (CART) Analysis is a supervised machine learning technique algorithm that uses historical data for prediction by using 70% of the historical data as training data set and 30% as test data set. CART model embedded in Minitab software was also used to make prediction for radionuclides source term thereby determining the contribution of each predicting variables to source term. Figure 1 and Table 1 shows the layout and parameters of APR1400.

Fig. 1: Layout Design of APR1400 [9].

Table 1: APR1400 Reactor Parameters [8, 9].

Parameters Reactor	**Specifications**
Reactor Thermal Power	3983 MWt
Gross Electrical Output	1455 MWe
Net Electrical Output	1400 MWe
Plant Availability	>90%
Design Lifetime	60 years
Fuel Cycle Length	18 months
Fuel Assemblies in core:	241 (16 x 16)
Number of Control Element Assemblies	93
Active Core Diameter	143.6 in
Active Core Length	150 in
Average Linear Heat Rate	5.6 kW/ft
Seismic Design Basis	SSE 0.3g
Average burnup:	28914 MWd/MTU
Discharged Burnup- in spent fuel storage	50000 MWd/MTU
Containment volume:	3.13E+06 ft^3
Containment type:	PWR Dry Ambient
Core Damage Frequency	1.0E-5/RY
Containment Failure Frequency	1.0E-6/RY
Design leak rate:	0.10 %/d
Coolant mass:	2.92E+05 kg
Number of Coolant Loops	2
Operating Pressure	2,250 psia
Coolant Inlet/Outlet Temperature	555 ºF /615 ºF
Steam generator type:	U-Tube
Steam Generator water mass:	218000 kg
Occupational radiation exposure:	< 1 manSv/RY

2 Methodologies

2.1 Hypothetical Accident Scenarios

RASCAL is a set of tools for emergency response applications developed by United State Nuclear Regulatory Commission (US-NRC) Emergency Operations Centre (EOC) to estimate the projected doses to the public in the case of radiological emergencies [10]. The source term to dose (STDose) model of RASCAL was used to generate data of radionuclides source term released during LTSBO and LOCA accident scenarios. The activity balance file are very helpful for comprehending the RASCAL source term model which are based on reactor condition and released pathways such as containment leakage, steam generator tube rapture and containment bypass for LTSBO and LOCA. RASCAL source term model for LTSBO and LOCA scenarios can be represented by reactor, containment, and atmosphere as shown in Figure 2.

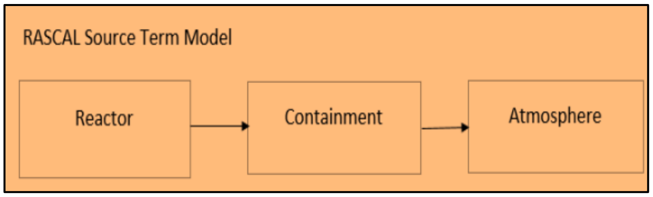

Fig. 2: RASCAL Source Term Model for PWR [10].

In the reactor, calculations are made about the initial reactor fuel inventory, radionuclide decay, and radionuclide discharge. With the containment building, which is distinguished by a single volume for all PWRs, the containment case consists of a portion of the reactor vessel as well as different pipelines and ducts. Radionuclides released from the fuel are presumed to instantly mix uniformly inside the container.

Two hypothetical severe nuclear accidents scenarios involving LTSBO and LOCA were used to generate radionuclides source term using different parameters of RASCAL including reactor power, average burnup, cooling duration, core recovery, percentage of cladding failure and core meltdown, release pathways, containment leakage rates and sprays open or close. The LTSBO implementation in RASCAL is based on the LTSBO accident progression as described in NUREG-1935, Part 1 and Part 2, "State-of-the-Art Reactor Consequence Analyses (SOARCA)" while LOCA is based on NUREG-1465 Report [10,11, 12, & 13] . The summary of the two scenarios are presented in Table 2.

Table 2: Summary scenarios for LTSBO and LOCA.

Type	LTSBO (SOARCA)	LOCA (NUREG-1465)
Shutdown:	2017/04/28 01:00	2017/04/28 03:30
Core uncovered	2017/04/28 13:00	2017/04/28 16:30
Core recovered	2017/04/29 01:00	2017/04/28 19:00
Number of Scenarios	12 scenarios	12 scenarios

2.2 Determination of Source Term

A total of 8156 big data for Cs-137, Cs-134, I-131, Xe-133 and Te-132, radionuclides source term were generated from 24 different scenarios involving LTSBO and LOCA using RASCAL computer code. The choice for the above radionuclides was due to the fact that Cs-137 and Cs-134 constitutes major fission products in nuclear process and also an important sources of contamination to the environment with half-lives of 30 years and 2.1 years respectively; I-131 when ingested primarily affects the thyroid gland that plays a fundamental role in childhood development, Xe-133, an inert gas, excessive inhalation could results to severe consequences including death. Te-132 has been assessed as the radionuclides with third largest releases from Fukushima Daiichi Nuclear Accident [14]. Radionuclides source term can be estimated using equation 1 expressed as:-

$$\mathbf{ST} = \sum(\boldsymbol{FPI_i} \times \boldsymbol{CRF_i} \times \boldsymbol{RDF_i} \times \boldsymbol{EF_i}) \qquad (1)$$

Where:

ST = Source Term
$\boldsymbol{FPI_i}$ = Fraction of the fission products released from the core to the coolant;
$\boldsymbol{CRI_i}$ = Element released from the core;
$\boldsymbol{RDF_i}$ = Reduction factor (element available for release before and after reduction mechanism); and
$\boldsymbol{EF_i}$ = Escape factor, (element released to the environment).

2.3 Activity Released to the Atmosphere in the PWR Events

The activity releases to the atmosphere in the PWR events of LTSBO and LOCA are summarized and compared in Table 3. LTSBO scenarios have lesser noble gas discharges and more releases of iodine and other particles than the LOCA scenarios. The reduction in noble gas releases for LTSBOs is directly associated to the interval between the time of reactor shutdown and the beginning of core damage. The discharges of iodine and other particles in PWR LTSBO accidents scenarios are greater than the releases in LOCAs because the LTSBO core release portions for the iodine and cesium groups are larger than the resultant LOCA core release fractions [15].

Table 3: Activity Released to the Atmosphere in the Event LTSBO and LOCA [15].

Radionuclides Category	**LTSBO**		**LOCA**		**LTSBO /LOCA Ratio**
	Activity (Ci)	% Released	Activity (Ci)	% Released	
Noble Gas	6.2E+04	44.9	9.4E+04	60.3	0.66
Iodine	4.1E+04	29.7	3.6E+04	23.1	1.14
Others	3.5E+04	25.4	2.6E+04	16.6	1.36
Total	1.4E+05	100	1.6E+05	100	0.88

2.4 Machine Learning Technique

Machine learning technique was employed in conducting predictive analysis of source term from hypothetical severe accident scenarios involving LTSBO and LOCA for APR1400 PWR by using 70% (5709) of the radionuclides as training data for the model and 30% (2447) as test data for prediction. A total of 15 predictors variable were used for predicting the most important variables associated with the release of radionuclide source term to the environment. The method of node splitting is least square error using maximum R-squared as criteria for selecting optimal tree with standard K-fold cross-validation.

2.4.1 Classification and Regression Tree (CART)

The radionuclides source term generated from LTSBO and LOCA scenarios of RASCAL were used as input data for CART model embedded in Minitab tool alongside prediction variables which includes accident type, reactor power, average burnup, containment sprays, release path percentage of core meltdown, cladding failure and leakage rate, core recovered, cooling duration, as well as emergency core cooling system. The summary of the data used in CART model are presented in Table 4.

Table 4: Summary of data used in CART Model.

Parameters	**Specifications**
Node splitting	Least Squared Error
Optimal tree	Maximum R-squared
Model validation	10-folds cross validation
Row used	8156
Training data set	5709 (70%)
Test data set	2447 (30%)
Total predictors	15
Important predictors	11

3 Results and Discussion

3.1 R-Squared and Mean Absolute Percentage Error

The result of optimal R-squared for Cs-137 , Cs-134, Te-132, I-131 and Xe-133 with their respective terminal nodes as well Mean Absolute Percentage Error (MAPE) for both training and test data set are presented in Table 5 and Figure 3.

Table 5: R-Squared and Mean Absolute Percentage Error for training and test data set.

Source Terms	Terminal Nodes	R^2 Training	R^2 Test	MAPE Training	MAPE Test
Cs-137	20	0.8386	0.8358	6.9045	6.9193
Cs-134	40	0.8401	0.8375	6.1426	6.1451
Te-132	35	0.8194	0.8161	10.3342	10.3868
I-131	28	0.8250	0.8223	12.2885	12.2825
Xe-133	31	0.9516	0.9493	0.4229	0.4269

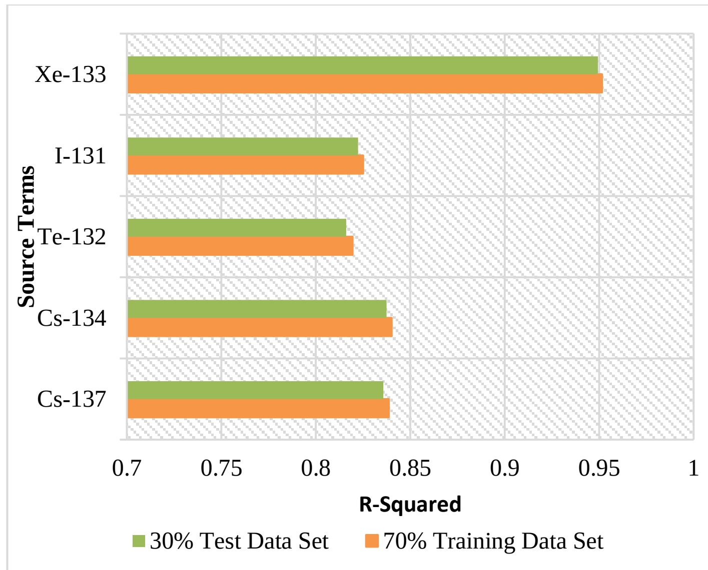

Fig.3: R-squared values for training and test data set.

The R-squared values for Cs-137 , Cs-134, Te-132, I-131 and Xe-134 training and test data set presented in Table 5 and Figure 3 signifies a strong positive linear relationship between the predicted (test) data set and real (training) data set. The Mean Absolute Percentage Error (MAPE) measures the goodness of error value. The lower the MAPE value, the more accurate the prediction. MAPE values for Cs-137, Cs-134, and Xe-134 training/test data are 6.9045/6.9193, 6.1426 / 6.1451, and 0.4229/0.4269 were found to be all less than 10 %. The result signifies very good MAPE while values for Te-132 and I-131 for training and test data are more than 10% but less than 20% that shows the MAPE for training and test data are good. Conversely, if MAPE values are greater than 50%, the MAPE is bad and hence the prediction is not accurate.

3.2 Source Term Predictors Variables and Relative Importance

Table 6 and Figure 4 illustrate the relative importance and contribution of each variables to source terms prediction. Containment leakage rate is of top most relative importance for the discharge of Cs-137, Cs-134, Te-132, I-131 and Xe-133 with 100% relative importance towards source term release. Accident type account for the second most important source term predictive variables for Cs-137 , Cs-

134, Te-132 and I-131 with 40.2%, 40.2%, 45.8% and 23.5% relative importance while average burnup has 13% relative importance for Xe-133 radionuclides source terms. RASCAL source term are based on reactor condition and released pathways from containment leakage, steam generator tube rapture and containment bypass for LTSBO and LOCA.

Table 6: Relative Importance of predictive variables to source term.

Variables	Cs-137 %	Cs-134%	Te-132%	I-131%	Xe-133%
Leak Rate %/d	100	100	100	100	100
Accident type	40.2	40.2	45.8	23.5	1.3
Release path	4.4	4.5	4.8	3.7	1.7
Core recovered	3.2	3.2	3.5	2.7	1.4
sprays	2.6	2.6	2.8	2.2	1.2
% cladding failure	1.9	1.9	1.7	1.8	0.1
% core melt	1.6	1.6	1.7	1.6	0.7
Reactor Power	1.5	1.6	1.3	1.4	1.5
Average Burnup	1.5	1.5	1.2	1.5	13.0
ECCS	0.3	0.3	0.3	0.2	0.2
Cool duration (hrs)	0.1	0.1	0.1	0.1	0.1

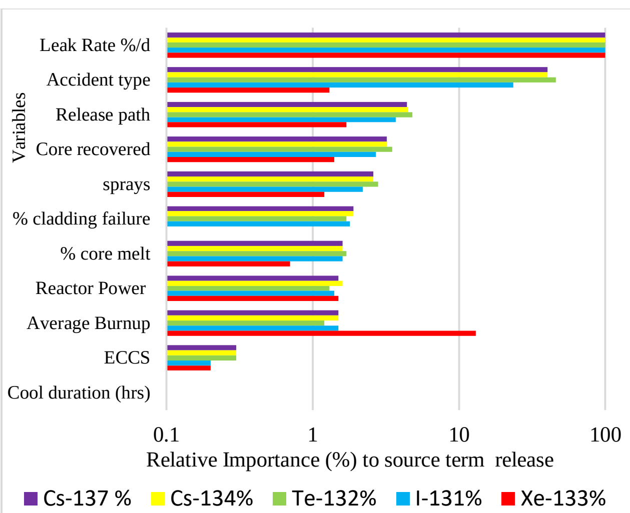

Fig.4: Variable of relative Importance to Source Term Release.

3.3 Activity Released to Atmosphere by Nuclide every Time Step

Figure 5 shows the radionuclide activity released to the atmosphere following discharge of Cs-137, Xe-133, I-131 and Te-132 radionuclides source terms for LTSBO and LOCA every 15 minutes time step. Noble gas group (Xe-133) exhibit higher activity release for both LTSBO and LOCA than tellurium group (Te-132), halogen group (I-131), and alkali metal (Cs-137). LTSBO accidents have a much longer period than LOCAs because loss of coolant occurs over a period of hours rather than seconds or minutes.

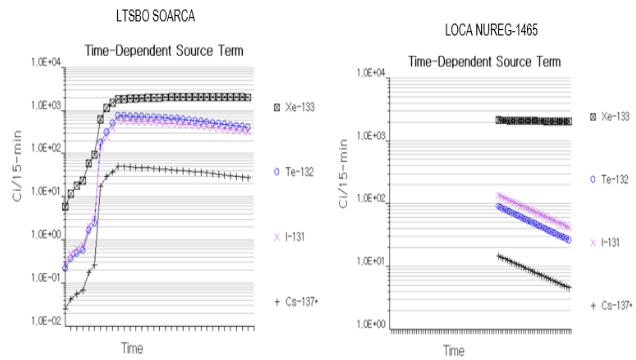

Fig.5: Activity released to Atmosphere by nuclide every 15 minutes Time Step.

The duration between reactor shutdown and the onset of core damage is directly correlated with the decrease in noble gas leaks for LTSBOs. Because the LTSBO core release portions for the iodine and cesium groups are larger than the resulting LOCA core release fractions, the discharges of iodine and other particles for LTSBO incidents scenarios are greater than the releases in LOCAs.

4 Conclusions

Machine learning is an effective tool in predicting the important variable associated with the released of radionuclides source term during nuclear accident. Such technique is of outmost important during nuclear emergency situation which help in making suitable and timely decisions for protection of people and the environment from the discharge of radionuclides during nuclear emergencies. In this study, a machine learning based approached was employed in predicting the variable of relative importance associated with discharge of Cs-137, Cs-134, Xe-133, I-131 and Te-132 radionuclide source terms to the environment resulting from LTSBO and LOCA hypothetical accident involving APR1400. The R-squared values for radionuclides training and test data set shows strong positive linear relationship between the training data and test data set. The MAPE values also shows the accuracy of the model prediction for training and test data. Therefore, the result of R-squared and MAPE values obtained from this study shows that that machine learning is an accurate tool for prediction.

The study shows that leakage rate constitute the major source of radionuclide release with 100% relative importance while cooling time has the least probability of radionuclide release during accident. Containment leakage rate constitute the top relative variable of importance for the discharge of radionuclides source term release. Reactor state, released pathways from containment leakage, steam generator tube rapture, and containment bypass for LTSBO and LOCA are the basis for RASCAL source terms.

The result implies that the relative variable of importance associated with leakage rate is more informative and should be contained to minimize discharge of radionuclides to the environment. The activity released to the atmosphere following discharged of radionuclides source terms for LTSBO and LOCA with time step of 15 minutes shows that, noble gas group exhibit higher activity release for both LTSBO and LOCA than tellurium group. Halogen group and alkali metal because loss of coolant occurs over hours rather than just a few seconds or minutes, LTSBO mishaps last significantly longer than LOCAs. This study highlighted the contribution of some variables associated with released of radionuclides source term to the environment resulting from LTSBO and LOCA events associated with APR1400. However, further studies is recommended for similar events with wider consequences such as SGTR.

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