Total Effective Dose from Radiologic Emissions from INL Facilities for Calculation of Population Dose for the INL 2021 CY Annual Site Environmental Report

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INTRODUCTION

Total effective radiation dose from airborne releases was calculated using air dispersion modeling performed by the National Oceanic and Atmospheric Administration (NOAA) Idaho Falls Office using their HYSPLIT computer model (Stein et al. 2015; Draxler et al. 2013), and the Dose Multi-Media (DOSEMM) dose assessment model version 190926 (Rood 2019)[1]. The objective of these calculations was to provide a grid of total effective dose across a model domain that encompasses a 50-mile (80-km) radius from any Idaho National Laboratory (INL) Site source. In addition to INL Site sources, releases from the Radiological and Environmental Sciences Laboratory (RESL) (Bldg IF-683), Bldg IF-611, and Bldg IF-603 located at the INL Research Center (IRC) within the Idaho Falls city limits were also included. The dose results will be combined with GIS software to compute a total population dose for the CY 2021 INL Annual Site Environmental Report (ASER). This report does not cover the population dose calculation and only documents generation of the gridded dose file.

MODEL DOMAIN AND HYSPLIT PROCESSING

The HYSPLIT model was used to calculate dispersion and deposition factors. Dispersion factors are defined as the monthly-average air concentration (g m^{-3}) divided by the release rate (g s^{-1}) and have units of s m^{-3}. Deposition factors are defined as the monthly-average deposition rate (g m^{-2} s^{-1}) divided by the release rate (g s^{-1}) and have units of m^{-2}. HYSPLIT model results were received from Bai Yang of the NOAA Idaho Falls office in NetCDF format. The modeling domain parameters are presented in

[1] The DOSEMM documentation (Rood 2019) is for version 190429. The difference is version 190926 has the option to use age-specific external dose coefficients from Federal Guidance Report 15 (EPA 2019). This option was used for the calculations in this report however, the receptor was an adult so results between the two versions would be identical provided the non-age-specific dose coefficients represented an adult.

Table 1. The 0.02-degree grid spacing equates to approximately 2 km. The files were first processed through the utility ncdump via the Perl script *runncdumpl.pl* that produced ASCII files of the gridded concentrations and deposition data (Appendix A) for each facility modeled.

Table 1. HYSPLIT modeling domain parameters

Parameter	Value
Model domain SW corner latitude (degrees)	42.6
Model domain SW corner longitude (degrees)	-114.76
Number of East-West nodes	177
Number of North-South nodes	101
Grid spacing (degrees)	0.02
Datum	WGS84
Grid center latitude (degrees)	43.6
Grid center longitude (degrees)	-113.0
Top of ground-level cell	50 m above ground level

Separate NetCDF files were produced for each INL Site facility (e.g., INTEC, INTEC-MS, CFA, etc.) and IRC facilities (Table 2). Within each file, concentration data for three species were provided. Average monthly ground-level concentration output (in units of g m^{-3}) was provided in the variables con1, con2, and con3. The variable con1 was for concentration of a tracer (i.e., non-decaying non-depositing) gas. The variable con2 was for the concentration of a particulate with a dry deposition velocity of 0.0018 m s^{-1}, and the variable con3 was for the concentration of a reactive gas with a deposition velocity of 0.035 m s^{-1}. Monthly deposition output (in units of g m^2) was provided in the variable dep2 and dep3 corresponding to species 2 and 3. There was no deposition output for species 1. All concentration and deposition values were based on a constant source release rate of 1 g s^{-1}.

Table 2. Facilities modeled with HYSPLIT and release parameters. Only those facilities that had an appreciable dose were considered.

Facility	File Designation	Latitude and Longitude (degrees)	Release parameters
Advanced Test Reactor (ATR) Complex ATR stack[a]	ATR_stack	43.589, -112.9671	Ht: 76.2 m, Stack dia: 1.524 m, Exit vel: 10.03 m/s, Temp: 293 K
ATR Complex, surface release	ATR_surface	43.5878, -112.9643	Ht: 0 m
Central Facilities Area (CFA)	CFA_surface	43.529, -112.9441	Ht: 0 m
Critical Infrastructure Test Range Complex (CITRC)[a]	CITRC_surface	43.5504, -112.8593	Ht: 0 m
Idaho Nuclear Technology and Engineering Center (INTEC), main stack[b] (MS)	INTEC_stack	43.572, -112.9336	Ht: 76.2 m, Stack dia: 1.83 m, Exit vel: 10.65 m/s, Temp: 293 K
Idaho Nuclear Technology and Engineering Center surface release	INTEC_surface	43.572, -112.9336	Ht: 0 m
Materials and Fuels Complex (MFC) surface release	MFC_surface	43.5951, -112.6567	Ht: 0 m
MFC, main stack and Transient Reactor Test Facility (TREAT) stack[c]	MFC_stack	43.5951, -112.6567	Ht: 60 m, Stack dia: 1.52 m, Exit vel: 9.081 m/s, Temp: 293 K
Naval Reactors Facility	NRF_surface	43.6489, -112.9162	Ht: 0 m
Radioactive Waste Management Complex (RWMC)	RWMC_surface	43.4999, -113.0407	Ht: 0 m
Radioactive Release Test Range (RRTR), Test Area North Technical Support Facility (TAN-TSF), and Specific Manufacturing Capability	RRTR_surface	43.8734, -112.725	Ht: 0 m

(SMC)			
Radiological and Environmental Sciences Laboratory (RESL), Buildings IF-683, IF-611, and IF-603[d]	RESL_surface	43.5159, -112.0348	Ht: 10 m, Exit Vel 0 m/s (no plume rise)

a. Releases from CITRC resulted in CAP88 doses that were about 5 orders of magnitude less than all the other facilities at the MEI. For this reason, CITRC was not included in the dose calculations.
b. The stack exit velocity is based on 2013-2015 records. Estimated velocity for 2021 was 6.32 m/s.
c. Releases from the TREAT stack were modeled using the dispersion and deposition values from the MFC main stack. The TREAT stack diameter is 0.61 m resulting in higher stack velocity, greater plume rise, and greater dispersion. Thus, concentrations assuming the main stack for TREAT releases are overestimated and conservative.
d. All three sources are located at the INL Research Center and were assumed to be released from the RESL stack location.

SOURCE TERM

The radionuclide source term for facilities that contributed significantly to the annual dose was determined using CAP88 Version 4.1 (EPA 2019) modeling performed for the annual INL NESHAP[2] report for radionuclides (INL 2022). These sources and radionuclides were included in the HYSPLIT/DOSEMM modeling. Radionuclides that yielded greater than 0.01% of the total dose at the location of the maximally exposed individual (MEI) for the INL Site were selected (Table 3, Table 4, and Table 5). No radionuclide emissions from CITRC were includes because all emissions from this source were less than 0.01% of the total. The INL Site MEI for 2021 was Receptor 54 near the INL east entrance. For the IRC sources in Idaho Falls, radionuclides that result in a dose greater than 0.1% of the total dose at the MEI location in Idaho Falls were included (Table 6) plus Xe-135 and I-129 which were included because prior years showed these to be important radionuclides. Output from the CAP88 processing databases was used for this task. Details are presented in Appendix B.

[2] The National Emission Standards for Hazardous Air Pollutants (NESHAPs) report for radionuclides is produced annually for all U.S. Department of Energy facilities that emit any radionuclides other than radon-222 and radon-220 into the air according to 40 CFR part 61, Subpart H.

Table 3. Particulate radionuclide source term (Ci yr^{-1}) for radionuclide-facility combinations that contributed greater than 0.01% of the total dose for INL Site facilities at the MEI location.

Source	Am-241	Br-82	Cl-36	Co-60	Cs-137	Pu-239	Pu-240
CFA	7.50E-12	8.29E-07		2.11E-11	3.75E-08	1.28E-11	1.25E-12
INTEC	3.14E-04		5.02E-06	1.64E-05	2.17E-04	1.16E-04	1.15E-04
INTEC-MS	2.66E-13				5.99E-10	9.81E-14	8.83E-14
MFC	2.77E-11		7.19E-03	1.97E-12	2.60E-01	2.29E-07	3.58E-11
MFC-MS						1.74E-08	
MFC-TREAT						8.20E-09	
NRF					6.30E-05	3.80E-06	
RTC[a]	2.19E-05			7.07E-03	5.48E-03	8.46E-06	1.28E-14
RTC-ATR[a]	5.79E-07			4.93E-06	4.38E-05		
RWMC	1.05E-04			4.43E-17	4.43E-18	4.14E-05	1.13E-05
SMC		1.03E+01	2.71E-09				
TAN-TSF							
Total	4.41E-04	1.03E+01	7.19E-03	7.09E-03	2.66E-01	1.70E-04	1.26E-04

Source	Sr-90	Te-129m	U-234	U-235	U-238	Zn-65
CFA	2.10E-12	7.17E-14	6.57E-12	2.41E-13	3.57E-13	9.45E-14
INTEC	5.28E-05		1.76E-07	1.02E-08	1.29E-07	6.53E-17
INTEC-MS	5.49E-10					
MFC	2.23E-06	4.32E-02	6.52E-02	2.19E-02	1.10E-01	3.32E-01
MFC-MS	9.05E-08					
MFC-TREAT						
NRF	6.90E-05					
RTC[a]	2.65E-02		1.41E-10	3.09E-10	1.57E-09	9.52E-06
RTC-ATR[a]						
RWMC	4.29E-08			2.48E-10	1.40E-08	
SMC			1.65E-08	1.15E-09	9.16E-08	4.27E-08
TAN-TSF	1.02E-06					
Total	2.66E-02	4.32E-02	6.52E-02	2.19E-02	1.10E-01	3.32E-01

a. The Advanced Test Reactor (ATR) Complex was formerly known as the Test Reactor Area (TRA) and Reactor Technology Complex (RTC). Acronyms based on former names may still be used to describe facility buildings, meteorological stations, etc.

Table 4. Noble gases source term (Ci yr^{-1}) for radionuclide-facility combinations that contributed greater than 0.01% of the total dose for INL Site facilities at the MEI location.

Source	Ar-41	Kr-87	Kr-88	Kr-89	Xe-138
CFA	4.70E-05	7.08E-05	3.75E-03		5.90E-05
INTEC					
INTEC-MS					
MFC					
MFC-MS					
MFC-TREAT	8.09E+01	1.05E+01	9.51E+00	3.42E+01	1.62E+01
NRF					
RTC[a]	5.40E-05	3.40E-05	5.21E-03		1.18E-04
RTC-ATR[a]	3.47E+02	3.11E+00			1.13E+01
RWMC					
SMC	8.69E-11	1.74E-20			
TAN-TSF					
Total	4.28E+02	1.36E+01	9.52E+00	3.42E+01	2.75E+01

a. The Advanced Test Reactor (ATR) Complex was formerly known as the Test Reactor Area (TRA) and Reactor Technology Complex (RTC). Acronyms based on former names may still be used to describe facility buildings, meteorological stations, etc.

Table 5. Iodine, C-14, and H-3 source term (Ci yr^{-1}) for radionuclide-facility combinations that contributed greater than 0.1% of the total dose for INL Site facilities at the MEI location.

Source	I-129	I-131	C-14	H-3
CFA	1.29E-18	2.51E-12	2.00E-09	5.19E-01
INTEC	6.91E-05		3.15E-02	1.59E-01
INTEC-MS	3.92E-06			1.28E-03
MFC	4.91E-05	9.40E-02		3.65E-01
MFC-MS				
MFC-TREAT				
NRF	1.20E-05	5.20E-06	5.50E-01	1.10E-02
RTC[a]	1.31E-10	1.75E-06	4.32E-10	7.48E+01
RTC-ATR[a]		5.10E-07		3.80E+02
RWMC			2.22E-02	4.81E+01
SMC				
TAN-TSF				3.26E-02
Total	1.34E-04	9.40E-02	6.04E-01	5.04E+02

a. The Advanced Test Reactor (ATR) Complex was formerly known as the Test Reactor Area (TRA) and Reactor Technology Complex (RTC). Acronyms based on former names may still be used to describe facility buildings, meteorological stations, etc.

Table 6. Radionuclide source term (Ci yr^{-1}) for radionuclides that contributed greater than 0.1% of the total dose for INL facilities in Idaho Falls plus Xe-135 and I-129.

Radionuclide	IF-603	IF-611	IF-683 (RESL)	Total
Ac-227			5.39E-09	5.39E-09
Am-241			1.02E-07	1.02E-07
Am-243			1.04E-09	1.04E-09
Ba-133			3.59E-07	3.59E-07
Co-60	2.00E-17		1.16E-08	1.16E-08
Cs-134	9.37E-07		2.57E-08	9.63E-07
Cs-137	9.40E-08		7.18E-08	1.66E-07
Eu-152			4.49E-08	4.49E-08
Eu-154	1.50E-13		7.69E-08	7.69E-08
I-125			4.88E-08	4.88E-08
I-129			1.10E-10	1.10E-10
Np-237			6.48E-09	6.48E-09
Pa-231			1.15E-09	1.15E-09
Pu-238			7.83E-08	7.83E-08
Pu-239			1.32E-07	1.32E-07
Ra-226			7.53E-08	7.53E-08
Sr-90			7.04E-08	7.04E-08
U-232			3.18E-08	3.18E-08
U-233			1.64E-07	1.64E-07
Xe-133		4.63E-01		4.63E-01
Xe-135		1.24E-04		1.24E-04
Zn-65	4.70E-08		8.41E-08	1.31E-07

DOSEMM MODELING AND MODEL PARAMETERS

The DOSEMM model version 190926 (Rood 2019) was used to calculate total effective dose across the model domain for a fixed receptor scenario. DOSEMM reads the dispersion and deposition factors produced by HYSPLIT and the source term summarized in Table 3,

Table 5. Iodine, C-14, and H-3 source term (Ci yr^{-1}) for radionuclide-facility combinations that contributed greater than 0.1% of the total dose for INL Site facilities at the MEI location.

Source	I-129	I-131	C-14	H-3
CFA	1.29E-18	2.51E-12	2.00E-09	5.19E-01
INTEC	6.91E-05		3.15E-02	1.59E-01
INTEC-MS	3.92E-06			1.28E-03
MFC	4.91E-05	9.40E-02		3.65E-01
MFC-MS				
MFC-TREAT				
NRF	1.20E-05	5.20E-06	5.50E-01	1.10E-02
RTC[a]	1.31E-10	1.75E-06	4.32E-10	7.48E+01
RTC-ATR[a]		5.10E-07		3.80E+02
RWMC			2.22E-02	4.81E+01
SMC				

Source	I-129	I-131	C-14	H-3
TAN-TSF				3.26E-02
Total	1.34E-04	9.40E-02	6.04E-01	5.04E+02

b. The Advanced Test Reactor (ATR) Complex was formerly known as the Test Reactor Area (TRA) and Reactor Technology Complex (RTC). Acronyms based on former names may still be used to describe facility buildings, meteorological stations, etc.

Table 6,

Table 5. Iodine, C-14, and H-3 source term (Ci yr^{-1}) for radionuclide-facility combinations that contributed greater than 0.1% of the total dose for INL Site facilities at the MEI location.

Source	I-129	I-131	C-14	H-3
CFA	1.29E-18	2.51E-12	2.00E-09	5.19E-01
INTEC	6.91E-05		3.15E-02	1.59E-01
INTEC-MS	3.92E-06			1.28E-03
MFC	4.91E-05	9.40E-02		3.65E-01
MFC-MS				
MFC-TREAT				
NRF	1.20E-05	5.20E-06	5.50E-01	1.10E-02
RTC[a]	1.31E-10	1.75E-06	4.32E-10	7.48E+01
RTC-ATR[a]		5.10E-07		3.80E+02
RWMC			2.22E-02	4.81E+01
SMC				
TAN-TSF				3.26E-02
Total	1.34E-04	9.40E-02	6.04E-01	5.04E+02

c. The Advanced Test Reactor (ATR) Complex was formerly known as the Test Reactor Area (TRA) and Reactor Technology Complex (RTC). Acronyms based on former names may still be used to describe facility buildings, meteorological stations, etc.

Table 6, and Table 6. The dispersion and deposition factors and source term are used in combination with a food-chain and exposure model in DOSEMM to calculate radionuclide concentrations in air, soil, vegetables, meat, and milk, and calculate the associated doses from inhalation, ingestion, and external exposure. Nuclide independent parameters were taken from previous ASER spreadsheet calculations for assessment years 2015 and earlier (Table 7). DOSEMM uses a food-chain model similar to the ASER spreadsheet which is based on the CAP88 model (EPA 2013). Appendix B in Rood (2019) contains a benchmark comparison of the

DOSEMM output and the ASER spreadsheet. Nuclide-independent parameters included the media intake rates and agriculture parameters.

Element-specific parameters include the linear sorption coefficient (K_d), plant and forage concentration ratios, and milk and meat transfer coefficients (Table 8). Carbon-14 and tritium are modeled using a specific-activity model and model parameters for these nuclides are presented in Table 9. Radionuclide-specific parameters (Table 10) include half-lives and dose coefficients for ingestion, inhalation, ground surface and volume external exposure, and submersion in air. Exposure scenario parameters were taken from CAP88 version 4.1 and include inhalation and ingestion rates (Table 11). The NESHAP dose was computed using CAP88 version 4.1. The half-lives (not reported) were taken from the ICRP-107 (ICRP 2008) tabulation.

Table 7. Radionuclide independent parameters for DOSEMM modeling.

Variable	Value	Units	Description
V_d	0.0018	m s^{-1}	Deposition velocity for particulates
V_d	0.035	m s^{-1}	Deposition velocity for molecular iodine
DD1	0.50	---	Fraction of radioactivity retained on leafy vegetables and produce after washing.
FSUBG	1.00	---	Fraction of produce grown in garden of interest
FSUBL	1.00	---	Fraction of leafy vegetables grown in garden of interest
FSUBP	0.40	---	Fraction of year animals graze on pasture
FSUBS	0.43	---	Fraction of daily feed that is pasture grass when animal grazes on pasture
LAMW	0.0029	hr^{-1}	Removal rate for weathering from plants
P	215.00	kg m^{-2}	Effective surface density of soil. This value assumes a 15-cm soil depth with a bulk density of 1.43 g/cm^3
QSUBF	15.60	kg day^{-1}	Consumption rate of contaminated feed or forage by an animal (dry wt)
R_1	0.57		Fallout interception fraction (pasture)
R_2	0.2		Fallout interception fraction (vegetables)
TH_1	0.00	hr	Time delay-ingestion of pasture grass by animals
TH_2	2,160	hr	Time delay-ingestion of stored feed by animals
TH_3	336	hr	Time delay-ingestion of leafy vegetables by man
TH_4	336	hr	Time delay-ingestion of produce by man
TSUBB	876,000	hr	Buildup time in soil (hr) for food chain (100 yrs)
$TSUBE_1$	720	hr	Period of exposure (grassy pasture)
$TSUBE_2$	1,440	hr	Period of exposure (crops/leafy vegetables)
TSUBF	2.0	day	Transport time: animal feed-milk-man
TSUBS	20	day	Average time from slaughter of meat animal to consumption
VSUBM	11.0	liter day^{-1}	Milk production of cow
$YSUBV_1$	0.28	kg m^{-2}	Productivity: agriculture (grass-cow-milk-man pathway)
$YSUBV_2$	0.716	kg m^{-2}	Productivity: produce and vegetables (wet)

Table 8. Element-specific parameters for DOSEMM modeling (default values for RESRAD v7.2 Kamboj et al., 2018 except as noted).

Element	K_d (mL g^{-1})	Concentration Ratio vegetables	Concentration Ratio forage	Transfer Coefficient milk (L d^{-1})	Transfer Coefficient meat (kg d^{-1})
Ac	2.00E+01	2.50E-03	1.00E-01	2.00E-05	2.00E-05
Am	2.00E+01	1.00E-03	1.00E-03	2.00E-06	5.00E-05
Ar	(a)	(a)	(a)	(a)	(a)
Ba	0.00E+00	5.00E-03	5.00E-03	5.00E-04	2.00E-04
Bi	0.00E+00	1.00E-01	1.00E-01	5.00E-04	2.00E-03
Br	1.00E-01	2.00E-02	2.00E-02	1.00E-02	7.00E-03
C	(b)	(b)	(b)	(b)	(b)
Cd	0.00E+00	3.00E-01	3.00E-01	1.00E-03	4.00E-04
Cl	0.00E+00	2.00E+01	2.00E+01	8.00E-02	6.00E-02
Co	1.00E+03	8.00E-02	8.00E-02	2.00E-03	2.00E-02
Cs	4.60E+03	4.00E-02	4.00E-02	8.00E-03	3.00E-02
Eu	3.40E+02	2.50E-03	2.50E-03	2.00E-05	2.00E-03
H	(b)	(b)	(b)	(b)	(b)
I	1.00E-01	2.00E-02	2.00E-02	1.00E-02	7.00E-03
Kr	(a)	(a)	(a)	(a)	(a)
Np	8.00E+00[c]	2.00E-02	2.00E-02	5.00E-06	1.00E-03
Pa	5.00E+01	2.50E-03	1.00E-01	5.00E-06	5.00E-03
Pb	1.00E+02	1.00E-02	1.00E-02	3.00E-04	8.00E-04
Po	1.00E+01	9.00E-03	1.00E-01	3.00E-04	5.00E-03
Pu	2.00E+03	1.00E-03	1.00E-03	1.00E-06	1.00E-04
Ra	7.00E+01	4.00E-02	4.00E-02	1.00E-03	1.00E-03
Rn	(a)	(a)	(a)	(a)	(a)
Sr	3.00E+01	3.00E-01	3.00E-01	2.00E-03	8.00E-03
Te	0.00E+00	6.00E-01	6.00E-01	5.00E-04	7.00E-03
Th	6.00E+04	1.00E-03	1.00E-03	5.00E-04	7.00E-03
U	5.00E+01	2.50E-03	2.50E-03	5.00E-04	7.00E-03
Y	0.00E+00	2.50E-03	2.50E-03	2.00E-05	2.00E-03
Xe	(a)	(a)	(a)	(a)	(a)
Zn	0.00E+00	4.00E-01	4.00E-01	1.00E-02	1.00E-01

a. Noble gases do not deposit and are not incorporated into food products
b. C-14 and H-3 are modeled using a specific activity model.
c. The K_d value for Np was the INL default value for INTEC modeling (Jenkins 2001) because RESRAD does not have a default value.

Table 9. Tritium and carbon-14 model parameters used for DOSEMM modeling.

Parameter	Value	Reference
Absolute humidity (g m^{-3})	4.90	Till (1983)
Atmospheric concentration of carbon (g m^{-3})	0.18	Till (1983)
Fraction of vegetation that is water	0.824	Moore et al. (1979)
Fraction of vegetation that is carbon	0.339	Moore et al. (1979)
Fraction of beef that is water	0.623	Moore et al. (1979)
Fraction of milk that is water	1.0	NCRP (1996)
Fraction of beef that is carbon	0.23	NCRP (1996)
Fraction of milk that is carbon	0.169	Moore et al. (1979)

Table 10. Radionuclide dose coefficients (DCs) used for DOSEMM modeling.

Nuclide	Solubility Class[a]	Inhalation (Sv/Bq)[c]	Ingestion (Sv/Bq)[c]	Submersion (Sv-m^3/Bq-s)[c]	Ground Plane (Sv-m^2/Bq-s)[d]	Ground Volume (Sv-m^3/Bq-s)[d]
Ac-227	M	4.60E-05	1.60E-10	4.22E-18	6.10E-20	2.17E-21
Ac-228	M	6.17E-09	1.73E-07	4.04E-14	5.80E-16	2.39E-17
Am-241	M	1.54E-05	5.91E-08	5.00E-16	9.90E-18	2.20E-19
Am-243	M	1.52E-05	5.84E-08	1.48E-15	2.81E-17	7.47E-19
Ar-41	n/a			6.20E-14	8.48E-16	3.62E-17
Ba-133	M	2.91E-09	1.00E-09	1.56E-14	2.26E-16	9.06E-18
Ba-137m	n/a			2.66E-14	3.90E-16	1.60E-17
Bi-210	M	5.05E-08	2.14E-09	1.03E-15	4.73E-17	5.90E-19
Bi-211	n/a			2.01E-15	2.89E-17	1.19E-18
Bi-214	M	1.09E-08	4.77E-11	7.21E-14	1.00E-15	4.19E-17
Br-82	F	2.09E-10	4.91E-10	1.21E-13	1.67E-15	7.18E-17
C-14	M	9.75E-10	1.59E-10	3.86E-17	6.12E-19	2.70E-20
Cd-115m	M	4.39E-09	9.95E-10	3.34E-15	1.13E-16	1.97E-18
Cl-36	F	4.32E-10	9.92E-10	6.44E-16	1.87E-17	3.62E-19
Co-60	M	1.13E-08	3.25E-09	1.18E-13	1.54E-15	6.93E-17
Cs-134	M	8.86E-09	1.39E-08	7.02E-14	9.98E-16	4.21E-17
Cs-137	M	8.38E-09	1.36E-08	3.89E-16	7.85E-18	2.20E-19
Cs-138	M	3.31E-11	1.29E-10	1.18E-13	1.62E-15	6.79E-17
Eu-152	M	3.73E-08	6.55E-10	5.33E-14	7.22E-16	3.12E-17
Eu-154	M	3.84E-08	7.16E-10	5.76E-14	7.88E-16	3.39E-17
H-3	W[b]	1.97E-11	1.95E-11	3.80E-20	6.65E-22	2.93E-23
I-125	F	5.35E-09	1.26E-08	2.78E-16	4.64E-18	5.35E-20
I-129	F	4.00E-08	9.39E-08	2.54E-16	4.41E-18	7.41E-20
I-131	F	6.87E-09	1.63E-08	1.69E-14	2.44E-16	1.01E-17

Table 10. Radionuclide dose coefficients (DCs) used for DOSEMM modeling.

Nuclide	Solubility Class[a]	Inhalation (Sv/Bq)[c]	Ingestion (Sv/Bq)[c]	Submersion (Sv-m^3/Bq-s)[c]	Ground Plane (Sv-m^2/Bq-s)[d]	Ground Volume (Sv-m^3/Bq-s)[d]
Kr-85	n/a			6.67E-16	1.67E-17	3.79E-19
Kr-85m	n/a			7.09E-15	1.09E-16	3.92E-18
Kr-87	n/a			4.33E-14	6.65E-16	2.48E-17
Kr-88	n/a			9.73E-14	1.18E-15	5.46E-17
Kr-89	n/a			9.89E-14	1.34E-15	5.62E-17
Np-237	M	8.17E-06	3.00E-08	7.70E-16	1.17E-17	3.71E-19
Np-239	M	4.04E-10	8.53E-11	7.26E-15	1.00E-16	3.89E-18
Pa-231	M	3.87E-05	1.82E-07	1.40E-15	1.96E-17	8.05E-19
Pa-234m	M	0.00E+00		3.42E-15	1.38E-16	2.05E-18
Pb-210	F	5.54E-07	3.55E-07	3.75E-17	6.80E-19	1.25E-20
Pb-211	F	1.65E-08	1.01E-10	4.12E-15	1.02E-16	2.44E-18
Pb-214	F	1.33E-08	7.70E-11	1.11E-14	1.64E-16	6.51E-18
Po-210	M	1.87E-06	1.21E-06	4.40E-19	6.16E-21	2.64E-22
Po-214	M	0.00E+00		3.75E-18	5.26E-20	2.25E-21
Po-218	M	0.00E+00		1.65E-20	2.35E-22	1.04E-23
Pu-238	M	2.49E-05	1.10E-07	2.55E-18	2.11E-20	5.27E-22
Pu-239	M	2.71E-05	1.21E-07	3.30E-18	4.18E-20	1.41E-21
Pu-240	M	2.71E-05	1.21E-07	2.52E-18	2.17E-20	5.41E-22
Pu-241	M	2.51E-07	1.13E-09	1.10E-19	1.73E-21	6.85E-23
Pu-242	M	2.58E-05	1.15E-07	5.87E-18	6.90E-20	2.60E-21
Ra-226	M	2.32E-06	1.27E-07	3.00E-16	4.09E-18	1.67E-19
Ra-228	M	2.01E-06	3.41E-07	2.71E-18	1.57E-20	6.72E-22
Rn-222	n/a			1.71E-17	2.51E-19	1.03E-20
Sb-125	M	3.56E-09	5.46E-10	1.88E-14	2.73E-16	1.12E-17
Sr-90	M	3.21E-08	2.39E-08	4.03E-16	6.52E-18	2.26E-19
Te-125m	M	1.09E-09	1.91E-10	2.52E-16	4.06E-18	5.07E-20
Te-129m	M	3.41E-09	8.90E-10	2.01E-15	5.14E-17	1.18E-18
Te-129	M	2.87E-11	6.07E-11	4.07E-15	1.13E-16	2.40E-18
Th-227	M	2.66E-06	1.34E-09	5.01E-15	7.00E-17	2.87E-18
Th-228	M	1.60E-05	3.11E-08	7.49E-17	1.11E-18	3.92E-20
Th-230	M	1.40E-05	5.99E-08	1.25E-17	2.05E-19	6.15E-21
Th-231	M	1.61E-10	1.71E-11	4.79E-16	7.36E-18	2.40E-19
Th-232	M	1.58E-05	7.05E-08	6.19E-18	1.04E-19	2.73E-21
Th-234	M	4.00E-09	5.93E-10	3.11E-16	5.06E-18	1.56E-19
Tl-207	n/a			1.52E-15	7.19E-17	8.84E-19
Tl-208	n/a			1.68E-13	2.04E-15	9.32E-17
U-232	M	5.24E-06	1.77E-07	9.20E-18	1.27E-19	3.92E-21
U-233	M	2.44E-06	3.54E-08	9.70E-18	1.33E-19	4.78E-21
U-234	M	2.40E-06	3.47E-08	5.15E-18	6.42E-20	1.87E-21

Table 10. Radionuclide dose coefficients (DCs) used for DOSEMM modeling.

Nuclide	Solubility Class[a]	Inhalation (Sv/Bq)[c]	Ingestion (Sv/Bq)[c]	Submersion (Sv-m^3/Bq-s)[c]	Ground Plane (Sv-m^2/Bq-s)[d]	Ground Volume (Sv-m^3/Bq-s)[d]
U-235	M	2.21E-06	3.18E-08	6.67E-15	9.07E-17	3.69E-18
U-238	M	2.09E-06	3.07E-08	2.65E-18	2.94E-20	8.66E-22
Xe-131m	n/a			3.08E-16	4.14E-18	9.98E-20
Xe-133	n/a			1.22E-15	2.09E-17	5.91E-19
Xe-135	n/a			1.13E-14	1.72E-16	6.58E-18
Xe-135m	n/a			1.86E-14	2.82E-16	1.12E-17
Xe-138	n/a			5.58E-14	7.60E-16	3.19E-17
Y-90	M	7.90E-10	5.63E-10	3.18E-15	1.47E-16	1.93E-18
Zn-65	M	2.15E-09	4.30E-09	2.69E-14	3.58E-16	1.59E-17

a. Solubility Types: S=slow, M=medium, F=fast, W=tritiated water, n/a= not applicable because inhalation DCs are zero. Solubility types were the default values in Table 5 of DOE-Std-1196-2021
b. The default solubility type for H-3 is M as a particulate however H-3 was assumed to be in the form of tritiated water.
c. DOE-Std-1196-2021 (DOE-2021)
d. FGR-15 (EPA 2021)

Table 11. Media intake rates used for CAP88 Version 4.1.

Parameter	CAP88 version 4.1
Inhalation rate (m^3 yr^{-1})	5256
Leafy vegetable ingestion (kg yr^{-1})	7.79
Other vegetable ingestion (kg yr^{-1})	76.2
Meat ingestion (kg yr^{-1})	84
Milk ingestion (L yr^{-1})	53

Dose Coefficients

Population dose calculations for prior ASERs were calculated with dose coefficients from DOE-Std-1196-2011 (DOE 2011) and FGR-13 (EPA 1999). For this ASER population dose calculation, the most up-to-date dose coefficients were used (DOE 2021 and EPA 2019). A comparison of the radionuclide specific pathway doses calculated with the old and new dose coefficients is presented in the results section.

Radioactive Decay and Ingrowth

DOSEMM allows for decay and ingrowth of radioactive progeny that deposit in soil. For the 1-year time frame considered none of the radionuclides in the source term have progeny that would have significant activity, except those that are short-lived and assumed to be in secular equilibrium. Dose coefficients for radionuclides that are assumed to be in secular equilibrium with their parent are included if the progeny half-life is less than a cutoff value. For inhalation and ingestion, radionuclide decay and ingrowth are already accounted for in the dose coefficient. The half-life cutoff for submersion is 24 hours and for ground exposure is 30 days. That is, radioactive progeny that have half-lives less than these values are assumed to be in secular

equilibrium with their parent and the dose coefficients are added. The dose coefficients for the radionuclides and progeny that were added together are presented in Table 12.

Table 12. Radioactive progeny that are assumed to be in secular equilibrium the parent radionuclide and included with the parent.

Parent	Progeny	Pathway(s)
Ac-227	Th-227	ground exposure and submersion
Am-243	Np-239	ground exposure
Cs-137	Ba-137m	ground exposure
I-131	Xe-131m	ground exposure
Ra-226	Rn-222, Po-218, Pb-214, Bi-214, Po-214	ground exposure
Sr-90	Y-90	ground exposure and submersion
Te-129	Te-129m	ground exposure and submersion
U-238	Pa-234m, Th-234	ground exposure and submersion
Xe-138	Cs-138	ground exposure and submersion

RESULTS

The HYSPLIT/DOSEMM model was used to compute the effective dose at the MEI location and then calculate the dose at every grid node in the model domain for the MEI exposure scenario. Unlike years prior to 2019, the MEI was not at what is known as Frenchman's Cabin (located south of the INL at coordinates longitude -113.05666 and latitude 43.42690, UTM Zone 12 coordinates 333528E 4810276N) but at the receptor 6 location (see Figure 1) south-southeast of the MFC facility (-112.60029 longitude, 43.524604 latitude, UTM Zone 12 370677E 4820317N).

The DOSEMM calculated dose at the MEI was 6.59E-03 mrem yr^{-1} for 2021 which was less than the 2020 dose of 9.53E-03 mrem yr^{-1}. The dose by pathway for INL Site sources (Table 13) was highest for the direct inhalation pathways followed by ingestion of other vegetables and beef. Particulate radionuclides had the highest contribution to the total dose. Dose by radionuclide at the INL Site MEI location (Table 14) were highest for U-238, U-234, Cs-137, Cl-36, and Zn-65. For comparison, the CAP88 version 4.1 doses at the MEI location are also shown in Table 14. The CAP88 total dose was a about a factor of 10 greater than the HYSPLIT/DOSEMM dose. This difference is investigated and explained in the next section.

Table 13. Dose by pathway and radionuclide type at the INL Site MEI location for the HYSPLIT/DOSEMM model simulation for the 2021 ASER.

Pathway	Particulates (mrem yr^{-1})	Iodine (mrem yr^{-1})	Noble gas (mrem yr^{-1})	C-14, H-3 (mrem yr^{-1})	Total (mrem yr^{-1})
Inhalation, direct	2.72E-03	1.56E-06	0.00E+00	1.18E-06	2.72E-03
Inhalation, resuspension	2.55E-04	8.43E-07	0.00E+00	0.00E+00	2.56E-04
Ingestion, Leafy Veg	7.42E-05	3.95E-06	0.00E+00	3.10E-07	7.81E-05
Ingestion, Other Veg	7.94E-04	4.82E-05	0.00E+00	3.04E-06	8.42E-04
Ingestion Beef	1.77E-03	8.01E-06	0.00E+00	2.50E-06	1.78E-03
Ingestion Milk	4.17E-04	2.90E-05	0.00E+00	2.37E-06	4.46E-04
External, ground	2.61E-04	1.03E-05	0.00E+00	0.00E+00	2.71E-04
Submersion in air	1.92E-06	2.20E-08	1.95E-04	3.42E-11	1.82E-04
All Pathway	6.29E-03	1.02E-04	1.95E-04	9.40E-06	6.59E-03

Table 14. Dose by radionuclide at the INL Site MEI location for the HYSPLIT/DOSEMM and CAP88 version 4.1 model simulations for the 2021 ASER.

Radionuclide	DOSEMM Dose (mrem yr^{-1})	DOSEMM Fraction of Total	CAP88 Dose (mrem yr^{-1})	CAP88 Fraction of Total
Am-241	1.21E-06	0.02%	8.92E-05	0.13%
Ar-41	1.50E-04	2.27%	4.36E-04	0.65%
Br-82	1.20E-05	0.18%	3.50E-04	0.52%
C-14	9.77E-07	0.01%	7.78E-05	0.12%
Cl-36	8.99E-04	13.63%	4.02E-03	6.03%
Co-60	3.83E-07	0.01%	8.51E-05	0.13%
Cs-137	1.18E-03	17.85%	3.65E-02	54.73%
H-3	8.42E-06	0.13%	7.23E-04	1.08%
I-129	5.78E-06	0.09%	1.98E-05	0.03%
I-131	9.61E-05	1.46%	1.88E-04	0.28%
Kr-87	1.89E-15	0.00%	2.74E-05	0.04%
Kr-88	3.07E-05	0.47%	1.24E-04	0.19%
Kr-89	1.23E-08	0.00%	9.92E-06	0.01%
Pu-239	8.66E-07	0.01%	4.25E-05	0.06%
Pu-240	6.50E-07	0.01%	2.76E-05	0.04%
Sr-90	3.16E-06	0.05%	3.99E-04	0.60%
Te-129m	2.68E-06	0.04%	2.76E-05	0.04%
U-234	1.18E-03	17.90%	5.54E-03	8.31%
U-235	3.65E-04	5.54%	2.41E-03	3.61%
U-238	1.92E-03	29.08%	1.09E-02	16.35%
Xe-138	1.46E-05	0.22%	3.90E-05	0.06%
Zn-65	7.27E-04	11.03%	4.65E-03	6.97%
Total	6.59E-03	100.00%	6.67E-02	100.00%

The highest dose from IRC sources in Idaho Falls was calculated at a model node 305 m north of the RESL facility (longitude -112.03480, latitude 43.51865). The total dose was 3.97E-06 mrem/yr which is about three orders of magnitude lower than the dose for INL Site sources at the INL MEI location. Important radionuclides from the DOSEMM modeling for IRC facilities were Pu-239 (28.3%), Xe-133 (24.3%), Pu-238 (15.4%), and Am-241 (12.4 %). The CAP88 dose for IRC facilities was 6.02E-3 mrem yr^{-1} which was a factor of ~1500 greater than that calculated by HYSPLIT/DOSEMM, but this value was calculated 115m south-southeast from the facility. The HYSPLIT grid resolution (about 2 km) was such that this receptor could not be represented and therefore the nearest node was selected which was north of the IRC. Both CAP88 and HYSPLIT/DOSEMM had similar important radionuclides.

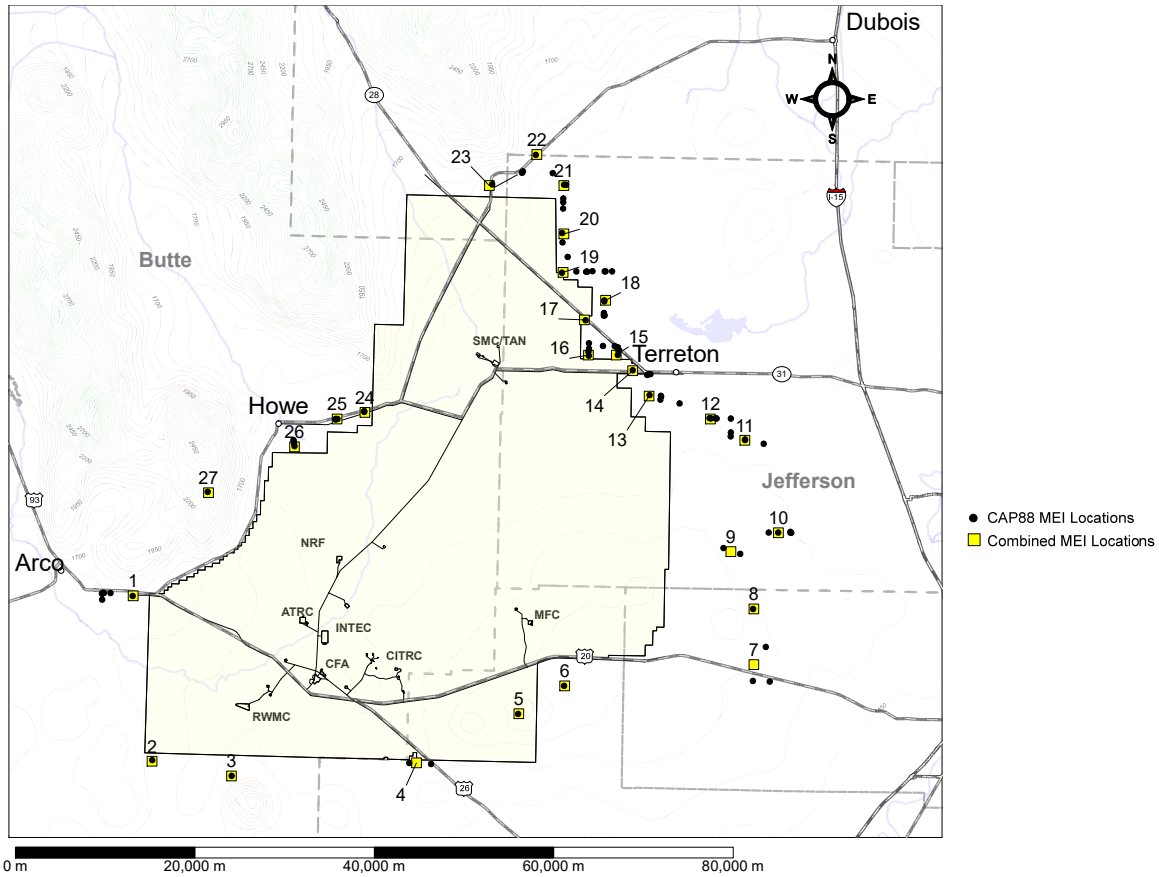

Figure 1. Maximally exposed individual locations surrounding the INL. The 27 locations (yellow circles) are a subset of 62 receptors (black dots) used in the CAP88 modeling. Locations that were close to one another were combined resulting in 27 unique locations.

Comparison with CAP88 Effective Dose at the INL Site MEI Location

CAP88 version 4.1 effective doses were calculated at receptor locations surrounding the INL Site that represent potential locations where a person might reside (Figure 1). The maximum effective dose for the MEI was calculated at receptor 6 in Figure 1. Receptor 6 corresponds to CAP88 receptor 54. The CAP88 version 4.1 MEI dose at receptor 6 was 6.67×10^{-2} mrem yr^{-1} whereas DOSEMM calculated a dose of 6.59×10^{-3} mrem yr^{-1} at this location. Doses were also calculated with DOSEMM for the list of 27 receptor locations illustrated in Figure 1 and the dose at the receptor 6 location was the highest which corresponds to the results from CAP88. The lower doses of the HYSPLIT/DOSEMM model are attributed to 1) the generally lower HYSPLIT dispersion factors compared to those from CAP88, and 2) 1-year buildup time in soil in DOSEMM for external exposure compared to 100-year buildup time in CAP88. Dispersion factors reflect differences in plume trajectory, turbulent diffusion, terrain complexities, plume depletion, and sector averaging between the HYSPLIT and CAP88 models. Releases from MFC accounted for most of the dose at the MEI. The average X/Q for HYSPLIT/DOSEMM for particle releases at MFC was 1.04E-08 s m^{-3}. Based on CAP88 modeling performed for year 2020, the X/Q at the MEI from MFC was ~4.0E-08 s m^{-3}. This represents a factor of 4 difference in airborne concentration and deposition between CAP88 and HYSPLIT/DOSEMM.

In addition to the dispersion factors, CAP88 assumes a 100-year build up time in soil when computing external exposure whereas DOSEMM only includes the buildup that occurs for the source input time (i.e., 1-year). A 100-year buildup time is used in DOSEMM for accumulation of activity in vegetables, milk, and meat. Radionuclide buildup in surface soil for DOSEMM and CAP88 is given by

$$C(t) = \frac{\psi}{k}\left(1 - e^{-kt}\right) \quad (1)$$

where

$C(t)$ = surface soil concentration as a function of time, t (Ci m^{-2})
ψ = surface deposition rate (Ci m^{-2} s^{-1})
k = effective removal rate constant (s^{-1}).

The effective removal rate constant includes radioactive decay and leaching. Radionuclides with significant gamma exposure from deposition in the surface soil are Cs-137 and Co-60. These radionuclides have high sorption coefficients and thus loss by leaching is minimal. Assuming no leaching, the ratio of the Cs-137 surface concentration with 100-year buildup to that of 1-year buildup was 38.9 and for Co-60 the ratio is 7.99, although most of the external dose for 2021 is from Cs-137. This difference accounts for the higher relative dose contribution from Cs-137 and Co-60 in CAP88 compared to DOSEMM. Thus, taking the HYSPLIT/DOSEMM dose of 6.59E-03 and multiplying by 3.85 to account for the difference in X/Q values (4.0E-08 s/m^3/1.04E-08 s/m^3 = 3.85) gives a total dose of 2.52E-02 mrem. The external dose from HYSPLIT/DOSEMM adjusted for the X/Q (2.71E-4 mrem × 3.85 = 1.04E-3 mrem) is then increased by a factor of 38.9 to account for the 100-year buildup in soil modeled in CAP88 (1.04E-3 mrem × 38.9 = 4.06E-2 mrem). The total adjusted HYSPLIT/DOSEMM dose is then 2.52E-02 mrem + 4.06E-2 mrem = 6.59E-02 mrem which accounts for most of the difference between CAP88 and HYSPLIT/DOSEMM doses. Other differences were in the dose coefficients, which CAP88 used values from DOE-Std-1196-2011 (DOE 2011) and FGR-13 (EPA 1999) whereas the HYSPLIT/DOSEMM modeling used the most recent compilations (DOE 2021 and EPA 2019). A comparison of the doses using these different tabulations of dose coefficients is presented in the next section

Dose Coefficient Comparison

A comparison of the doses at the INL MEI was made using the dose coefficients used in all prior ASERs (DOE 2011; EPA 1999) and the dose coefficients used in this ASER for 2021, which represent the most recent compilations of dose coefficients (DOE 2021; EPA 2019). The recent compilations of dose coefficients produced a total dose of 6.59E-3 mrem which was slightly lower that the total dose calculated with the earlier compilations of 7.54E-3 mrem (Table 15). Some radionuclides and pathways showed greater differences than others (e.g., Am-241, Br-82, Cl-36, Sr-90) while other radionuclides showed little difference in the total dose (e.g., H-3, Kr-88, Kr-89), while others showed little difference in the total dose but large differences in individual pathways (e.g., Cl-36). All of the noble gasses exhibited little difference. A few radionuclides and pathways exhibited higher doses using the recent compilation of dose coefficients (e.g., Cs-137 for inhalation, Zn-65 for inhalation and ingestion).

Table 15. Ratio of doses calculated with DOE (2021) and EPA (2019) to doses calculated with DOE (2011) and EPA (1999).

Pathway	Inhalation	Ingestion	External exposure from ground sources	Submersion	Total
Am-241	0.37	0.29	0.43	0.74	0.36
Br-82	0.28	0.89	1.39	0.98	1.18
Cl-36	0.05	1.07	2.23	3.88	1.07
Co-60	1.01	0.95	0.67	0.98	0.71
Cs-137	1.82	1.00	0.68	0.92	0.94
Pu-239	0.54	0.48	0.15	0.88	0.54
Pu-240	0.54	0.48	0.04	0.76	0.54
Sr-90	0.82	0.87	1.38	4.09	0.87
Te-129m	0.47	0.21	0.98	1.07	0.36
U-234	0.63	0.70	0.11	0.84	0.64
U-235	0.65	0.68	0.65	0.79	0.66
U-238	0.67	0.69	1.24	0.83	0.67
Zn-65	1.19	1.10	0.76	0.89	1.07
I-129	0.99	0.87	0.29	0.89	0.87
I-131	0.69	0.75	0.66	0.95	0.74
Ar-41				0.96	0.96
Kr-87				1.09	1.09
Kr-88				1.00	1.00
Kr-89				1.02	1.02
Xe-138				1.00	1.00
C-14	0.44	0.27		14.84	0.28
H-3	1.02	1.02			1.02
Total	0.65	0.91	0.74	0.90	0.87

Total Effective Dose Isopleth Map

An isopleth map of total effective dose across the model domain based on the MEI receptor scenario is shown in **Error! Reference source not found.**. The receptor 6 MEI location (CAP88 receptor 54) is indicated by the blue star near the southern INL boundary and south of the MFC facility. The isopleths reflect the southwest to northeast prevailing winds at the INL and terrain features. An ASCII text file containing the effective dose by exposure pathway at each of the model grid nodes is provided in the file *EffectiveTotal.dat*. As expected, doses from the Idaho Falls facilities were not discernable in the dose contours.

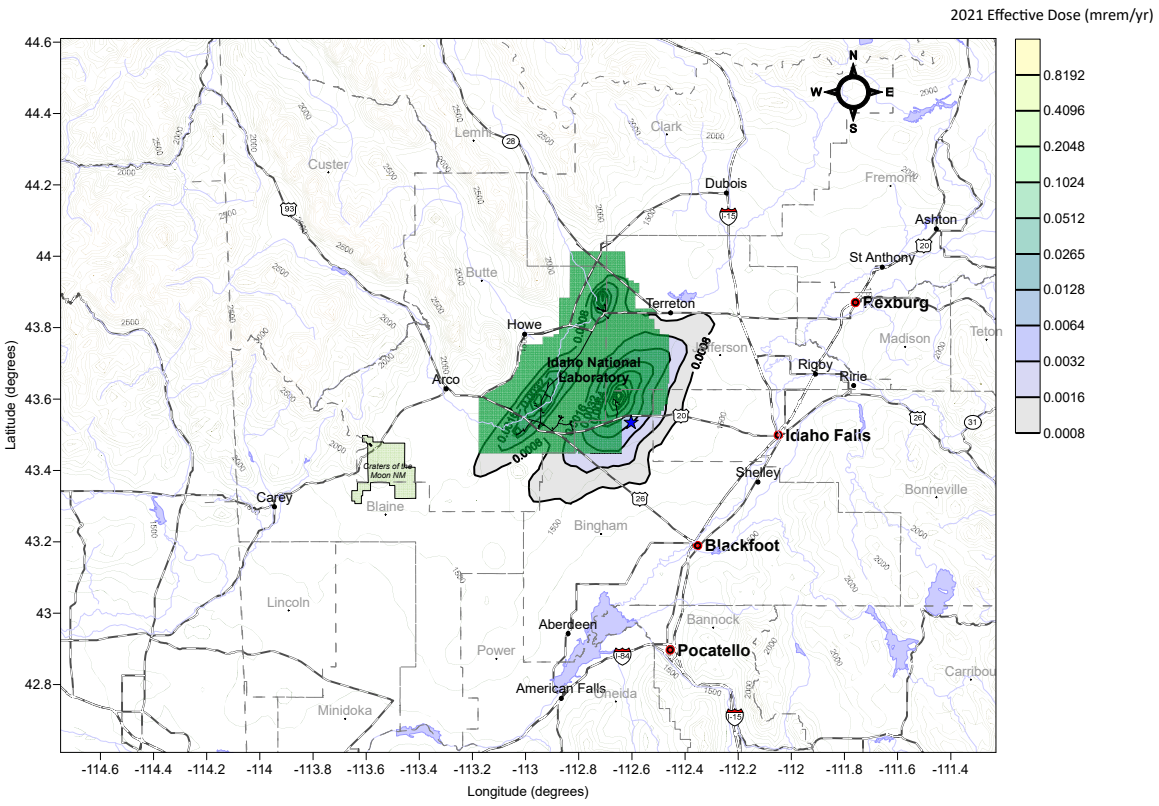

Figure 2. Isopleth map to total effective dose based on the MEI exposure scenario. The MEI at receptor 6 location is depicted as a blue star south of the INL southern boundary and near the MFC facility.

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APPENDIX A: PROCESSING INSTRUCTIONS FOR NETCDF FILES FROM NOAA HYSPLIT

1. NetCDF files will come in a separate zip file for each facility. Opening the zip file will create a new directory. There should be 12 files in each zip file comprising 12 months of data.

2. After extracting all the zip files in a directory for the given year (i.e. 2016files), run the runncdump.pl Perl script. You first have to modify the directory names in the User Input block at the top of the script.

```
# runncdump.pl
# This script runs ncdump and extracts concentration and deposition varaibles for each
month and each facility
# Written by A.S. Rood, 06/19/17 for Wastren Inc

# -------------------------- User Input ---------------------------------------
#@dirlst = ("ATR_surface_2016","CFA_surface_2016");

# enter the directory name for each source
@dirlst =
("ATR_stack_2016","INTEC_stack_2016","INTEC_surface_2016","MFC_stack_2016","NRF_surface_2
016","RWMC_surface_2016");

# ------------------------ End of User Input --------------------------------

$ndir=$#dirlst;

for $i (0..$ndir)
{
   print "$dirlst[$i]\n";
   $cline=$dirlst[$i] . "/*.nc >junk";
   system "ls $cline";
   open(LST,"<junk");
   while ($line=<LST>)
   {
     chomp $line;
     $ofile=$line;
     $ofile =~ s/nc/asc/;
     $cline="ncdump -v con1,con2,con3,dep2,dep3 ".$line." >$ofile";
     print "$cline\n";
     system "$cline";
   }

}
```

3. The output files from ncdump are ASCII files that are then processed through ppnetcdf.f95. A separate parameter definition file is needed for each source. A sample parameter definition file is below.

```
INTEC_stack   5                              [srcname] [nvar]
con1,con2,con3,dep2,dep3              [varnames]
tracerxq,partxq,iodinexq,partpq,iodinepq      [specielist]
1  1  1  2  2                          [vtypeindx]
'../latlon.asc'                            [flatlon]
-1 -1 -1 -1                           [iminx][iminy[imaxx][imaxy]
12                                    [zone]
12                                    [nnetcdf]
Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec       [ncdfnames]
INTEC_stack_2018_01.asc                              [dfile]
INTEC_stack_2018_02.asc                              [dfile]
INTEC_stack_2018_03.asc                              [dfile]
```

```
INTEC_stack_2018_04.asc                                  [dfile]
INTEC_stack_2018_05.asc                                  [dfile]
INTEC_stack_2018_06.asc                                  [dfile]
INTEC_stack_2018_07.asc                                  [dfile]
INTEC_stack_2018_08.asc                                  [dfile]
INTEC_stack_2018_09.asc                                  [dfile]
INTEC_stack_2018_10.asc                                  [dfile]
INTEC_stack_2018_11.asc                                  [dfile]
INTEC_stack_2018_12.asc                                  [dfile]
```

4. The file latlon.asc is produced from ncdump by

ncdump –v lat,lon [ncdumpfile] > latlon.asc

This file should be the same for all sources, and all remaining years provided the grid spacing and origins do not change. You will need the lat lon file before you run ppnetcdf.f95. A latlon file is shown below

```
netcdf ATR_stack_2018_01 {
dimensions:
        x = 177 ;
        y = 101 ;
variables:
        float lat(y) ;
                string lat:long_name = "Latitude of grid points" ;
                string lat:units = "deg N" ;
        float lon(x) ;
                string lon:long_name = "Longitude of grid points" ;
                string lon:units = "deg W" ;
        double xutm(x, y) ;
                string xutm:long_name = "UTM easting" ;
                string xutm:units = "m" ;
                xutm:zone = 12 ;
                string xutm:datum = "WGS84" ;
        double yutm(x, y) ;
                string yutm:long_name = "UTM northing" ;
                string yutm:units = "m" ;
                yutm:zone = 12 ;
                string yutm:datum = "WGS84" ;
        float con1(x, y) ;
                string con1:long_name = "Monthly average concentration species 1" ;
                string con1:units = "g m-3" ;
                con1:layer_bottom_m_agl = 0.f ;
                con1:layer_top_m_agl = 50.f ;
                string con1:deposition_vel = "0.0000 m/s" ;
                string con1:release_rate = "1.0 g/s" ;
        float con2(x, y) ;
                string con2:long_name = "Monthly average concentration species 2" ;
                string con2:units = "g m-3" ;
                con2:layer_bottom_m_agl = 0.f ;
                con2:layer_top_m_agl = 50.f ;
                string con2:deposition_vel = "0.0018 m/s" ;
                string con2:release_rate = "1.0 g/s" ;
        float con3(x, y) ;
                string con3:long_name = "Monthly average concentration species 3" ;
                string con3:units = "g m-3" ;
                con3:layer_bottom_m_agl = 0.f ;
                con3:layer_top_m_agl = 50.f ;
                string con3:deposition_vel = "0.0350 m/s" ;
                string con3:release_rate = "1.0 g/s" ;
        float dep2(x, y) ;
                string dep2:long_name = "Monthly average dry deposition species 2" ;
                string dep2:units = "g m-2" ;
```

```
                string dep2:deposition_vel = "0.0018 m/s" ;
                string dep2:release_rate = "1.0 g/s" ;
        float dep3(x, y) ;
                string dep3:long_name = "Monthly average dry deposition species 3" ;
                string dep3:units = "g m-2" ;
                string dep3:deposition_vel = "0.0350 m/s" ;
                string dep3:release_rate = "1.0 g/s" ;

// global attributes:
                string :description = "HYSPLIT monthly average concentration and
depositon" ;
                string :facility = "ATR" ;
                string :release_type = "stack" ;
                :source_lat = 43.589f ;
                :source_lon = -112.9671f ;
                :source_hgt_m_agl = 76.2f ;
                :model_top_m_msl = 6500. ;
                :grid_center_lat = 43.6f ;
                :grid_center_lon = -113.f ;
                :grid_spacing_lat = 0.02f ;
                :grid_spacing_lon = 0.02f ;
                string :release_start = "2016-12-31 0000 MST" ;
                string :release_end = "2017-02-01 0000 MST" ;
                string :averaging_start = "2017-01-01 0000 MST" ;
                string :averaging_end = "2017-02-01 0000 MST" ;
                :setup_cfg_rev = 6 ;
                :stack_dia_m = 1.524f ;
                :stack_exit_vel_ms = 10.03f ;
                :stack_exit_temp_K = 293.f ;
                string :contact = "Richard Eckman" ;
                string :email = "richard.eckman@noaa.gov" ;
                string :data_version = "1.0" ;
data:

 lat = 42.6, 42.62, 42.64, 42.66, 42.68, 42.7, 42.72, 42.74, 42.76, 42.78,
    42.8, 42.82, 42.84, 42.86, 42.88, 42.9, 42.92, 42.94, 42.96, 42.98, 43,
    43.02, 43.04, 43.06, 43.08, 43.1, 43.12, 43.14, 43.16, 43.18, 43.2,
    43.22, 43.24, 43.26, 43.28, 43.3, 43.32, 43.34, 43.36, 43.38, 43.4,
    43.42, 43.44, 43.46, 43.48, 43.5, 43.52, 43.54, 43.56, 43.58, 43.6,
    43.62, 43.64, 43.66, 43.68, 43.7, 43.72, 43.74, 43.76, 43.78, 43.8,
    43.82, 43.84, 43.86, 43.88, 43.9, 43.92, 43.94, 43.96, 43.98, 44, 44.02,
    44.04, 44.06, 44.08, 44.1, 44.12, 44.14, 44.16, 44.18, 44.2, 44.22,
    44.24, 44.26, 44.28, 44.3, 44.32, 44.34, 44.36, 44.38, 44.4, 44.42,
    44.44, 44.46, 44.48, 44.5, 44.52, 44.54, 44.56, 44.58, 44.6 ;

 lon = -114.76, -114.74, -114.72, -114.7, -114.68, -114.66, -114.64, -114.62,
    -114.6, -114.58, -114.56, -114.54, -114.52, -114.5, -114.48, -114.46,
    -114.44, -114.42, -114.4, -114.38, -114.36, -114.34, -114.32, -114.3,
    -114.28, -114.26, -114.24, -114.22, -114.2, -114.18, -114.16, -114.14,
    -114.12, -114.1, -114.08, -114.06, -114.04, -114.02, -114, -113.98,
    -113.96, -113.94, -113.92, -113.9, -113.88, -113.86, -113.84, -113.82,
    -113.8, -113.78, -113.76, -113.74, -113.72, -113.7, -113.68, -113.66,
    -113.64, -113.62, -113.6, -113.58, -113.56, -113.54, -113.52, -113.5,
    -113.48, -113.46, -113.44, -113.42, -113.4, -113.38, -113.36, -113.34,
    -113.32, -113.3, -113.28, -113.26, -113.24, -113.22, -113.2, -113.18,
    -113.16, -113.14, -113.12, -113.1, -113.08, -113.06, -113.04, -113.02,
    -113, -112.98, -112.96, -112.94, -112.92, -112.9, -112.88, -112.86,
    -112.84, -112.82, -112.8, -112.78, -112.76, -112.74, -112.72, -112.7,
    -112.68, -112.66, -112.64, -112.62, -112.6, -112.58, -112.56, -112.54,
    -112.52, -112.5, -112.48, -112.46, -112.44, -112.42, -112.4, -112.38,
    -112.36, -112.34, -112.32, -112.3, -112.28, -112.26, -112.24, -112.22,
    -112.2, -112.18, -112.16, -112.14, -112.12, -112.1, -112.08, -112.06,
    -112.04, -112.02, -112, -111.98, -111.96, -111.94, -111.92, -111.9,
    -111.88, -111.86, -111.84, -111.82, -111.8, -111.78, -111.76, -111.74,
    -111.72, -111.7, -111.68, -111.66, -111.64, -111.62, -111.6, -111.58,
    -111.56, -111.54, -111.52, -111.5, -111.48, -111.46, -111.44, -111.42,
    -111.4, -111.38, -111.36, -111.34, -111.32, -111.3, -111.28, -111.26,
    -111.24 ;
}
```

5. For each source, five output variables are stored in the ASCII NetCDF file: con1, con2, con3, dep2, dep3. The variable con1 is a conservative tracer and therefore has no corresponding deposition file. The variable con2 and dep2 are X/Q and Psi/Q values for light particles and con3 and dep3 are X/Q and Psi/Q values for iodine respectively. Deposition velocities are listed in the latlon.asc file. Output from ppnetcdf.f95 contains the dosemm X/Q and Psi/Q files.

APPENDIX B: DEVELOPING SOURCE TERM FILES FOR DOSEMM ASER ASSESSMENT

The source term for DOSEMM was developed using the CAP88 database for NESHAPS (NESHAPv41-INL_CAP88DoseCalculator2021.mdb) for the INL Site using several queries. The query "DoseAtMEIByNuclide" was run to derive the list of significant radionuclides and facilities that would be modeled. The query outputs the dose at the MEI by radionuclide sorted in descending order. This list was pasted into the spreadsheet "SourceTerm2021.xlsx" and all radionuclides that contributed more than 0.01% to the total were included in the DOSEMM model simulation (Table B-1)

Table B-1. Radionuclides from INL Site facilities that contributed to more than 0.01% of the total CAP88 dose at the MEI.

Nuclide	SumOfDose(mrem/yr)	ReceptorNum	Fraction	Cumulative
Cs-137	3.65E-02	54	54.71%	54.71%
U-238	1.09E-02	54	16.34%	71.05%
U-234	5.54E-03	54	8.30%	79.36%
Zn-65	4.65E-03	54	6.97%	86.33%
Cl-36	4.02E-03	54	6.03%	92.35%
U-235	2.41E-03	54	3.61%	95.97%
H-3	7.23E-04	54	1.08%	97.05%
Ar-41	4.36E-04	54	0.65%	97.70%
Sr-90	3.99E-04	54	0.60%	98.30%
Br-82	3.50E-04	54	0.52%	98.83%
I-131	1.88E-04	54	0.28%	99.11%
Kr-88	1.24E-04	54	0.19%	99.29%
Am-241	8.92E-05	54	0.13%	99.43%
Co-60	8.51E-05	54	0.13%	99.55%
C-14	7.78E-05	54	0.12%	99.67%
Pu-239	4.25E-05	54	0.06%	99.74%
Xe-138	3.90E-05	54	0.06%	99.79%
Te-129m	2.76E-05	54	0.04%	99.83%
Pu-240	2.76E-05	54	0.04%	99.88%
Kr-87	2.74E-05	54	0.04%	99.92%
I-129	1.98E-05	54	0.03%	99.95%
Kr-89	9.92E-06	54	0.01%	99.96%

In prior years ASER's the radionuclide cutoff was 0.1% of the total MEI dose and radionuclides that contributed to greater than 1% of the total dose from a facility at the MEI. For the 2021 ASER, a simpler method was used that just looked at all radionuclides that contributed to more than 0.01% of the total CAP88 dose at the MEI. A new table was created within the database (DOSEMMradionuclides) that contained this list of radionuclides. A second query was written to

extract the DOSEMM source term by facility that was later processed with the Perl script "MkSrcTerm.pl". The SQL for the DOSEMM_ST query is

```
SELECT Releases.FacilityID, Releases.Radionuclide, Sum(Releases.Q) AS SumOfQ
FROM Releases INNER JOIN DOSEMMradionuclides ON Releases.Radionuclide =
DOSEMMradionuclides.Radionuclide
GROUP BY Releases.FacilityID, Releases.Radionuclide;
```

In a likewise manner, the database "NESHAPv41-IRC_CAP88DoseCalculator2021.mdb" covered releases from Idaho Falls facilities and the "DoseAtMEIByNuclide" was run to generate the list of radionuclides that contributed greater than 0.1% to the total CAP88 dose at the MEI. The 0.1% cutoff was used for Idaho Falls facilities at the IRC because all releases originated from one release point. For DOSEMM runs, Xe-135 and I-129 were also included because these radionuclides were shown to be important from past ASER runs.

Table B-2. Radionuclides from Idaho Falls facilities at the IRC that contributed to more than 0.1% of the total CAP88 dose at the MEI.

Nuclide	SumOfDose(mrem/yr)	ReceptorNum	Fraction	Cumulative
Pu-239	1.58E-03	10	25.46%	25.46%
Am-241	1.02E-03	10	16.44%	41.90%
Xe-133	1.02E-03	10	16.44%	58.34%
Pu-238	8.61E-04	10	13.88%	72.21%
Cs-134	4.81E-04	10	7.75%	79.96%
Ra-226	3.69E-04	10	5.95%	85.91%
Cs-137	1.82E-04	10	2.93%	88.84%
U-233	1.28E-04	10	2.06%	90.90%
U-232	1.24E-04	10	2.00%	92.90%
Ac-227	9.70E-05	10	1.56%	94.47%
Ba-133	6.82E-05	10	1.10%	95.57%
Sr-90	6.20E-05	10	1.00%	96.56%
Eu-154	3.92E-05	10	0.63%	97.20%
Np-237	3.89E-05	10	0.63%	97.82%
Eu-152	2.96E-05	10	0.48%	98.30%
Pa-231	2.76E-05	10	0.44%	98.74%
I-125	2.24E-05	10	0.36%	99.11%
Zn-65	1.44E-05	10	0.23%	99.34%
Am-243	1.04E-05	10	0.17%	99.51%
Co-60	8.12E-06	10	0.13%	99.64%

Radionuclides are assigned to these four classes:

PART – Particulates
I – Iodine
NG – noble gas
C14H3 – carbon-14 and tritium

For the 2021 DOSEMM run, all facilities were included in the simulation regardless of contribution with the exception of CITRC, which had doses substantially lower than any of the other facilities. A Perl script was written where the input to the script is the radionuclide release rates (Ci/yr) for each facility. As stated earlier, the radionuclide release rates by facility were extracted using the query DOSEMM_ST. The Perl script MkSrcTerm.pl was then used to generate the DOSEMM release files from the database queries that were saved to text files. The first few records of the text file from the DOSEMM_ST query for INL Site sources are shown below

File SourceTerm2021.txt

```
FacilityID,Radionuclide,SumOfQ
CFA,Am-241,7.49999999999917e-12
CFA,Ar-41,4.7e-05
CFA,Br-82,8.29e-07
CFA,C-14,2.0000282e-09
CFA,Co-60,2.10899999999977e-11
CFA,Cs-137,3.74999999999959e-08
CFA,H-3,0.51
CFA,I-129,1.29299999999986e-18
CFA,I-131,2.51099999999972e-12
CFA,Kr-87,7.08e-05
CFA,Kr-88,3.75e-03
CFA,Pu-239,1.28399999999986e-11
CFA,Pu-240,1.25399999999986e-12
CFA,Sr-90,2.10299999999977e-12
CFA,Te-129m,7.16999999999921e-14
CFA,U-234,6.56999999999928e-12
CFA,U-235,2.41499999999973e-13
CFA,U-238,3.56999999999961e-13
CFA,Xe-138,5.9e-05
CFA,Zn-65,9.44999999999896e-14
INTEC,Am-241,3.14000003671031e-04
INTEC,C-14,0.03
INTEC,Cl-36,5.024e-06
INTEC,Co-60,1.6400000075953e-05
```

The entire source term file for Idaho Falls facilities is shown below

File SourceTerm2021IRC.txt

```
FacilityID,Radionuclide,SumOfQ_Ci
IRC,Ac-227,5.39e-09
IRC,Am-241,1.02e-07
IRC,Am-243,1.04e-09
IRC,Ba-133,3.59e-07
IRC,Co-60,1.160000002e-08
IRC,Cs-134,9.626e-07
IRC,Cs-137,1.65765e-07
IRC,Eu-152,4.49e-08
IRC,Eu-154,7.690015e-08
```

```
IRC,I-125,4.88e-08
IRC,I-129,1.1e-10
IRC,Np-237,6.48e-09
IRC,Pa-231,1.15e-09
IRC,Pu-238,7.83e-08
IRC,Pu-239,1.32e-07
IRC,Ra-226,7.53e-08
IRC,Sr-90,7.04e-08
IRC,U-232,3.18e-08
IRC,U-233,1.64e-07
IRC,Xe-133,0.46
IRC,Xe-135,1.24e-04
IRC,Zn-65,1.3105e-07
```

The Perl script then uses the information in the header portion of the script to extract the important radionuclides and write DOSEMM compatible files. For some sources such as MFC stack releases and releases from TAN and SMC, the same X/Q value is used. In these cases, the release quantities may be summed into one release file within the script. Alternatively, each source may be run separately. The Perl script is below.

```
# mkSourceTerm.pl
# This script makes the dosemm source term files from a datatabase printout of the entre
source term
# ------------- User Input ----------------

# The sourcein array are the names of the sources provided in the CAP88 DB
      @sourcein =("CFA","INTEC","INTEC-MS","MFC","MFC-MS","MFC-TREAT","NRF","RTC","RTC-
ATR","RWMC","SMC","TAN-TSF");  # INL sourcs

# The sourceout array are the sources in the same order, renamed (if applicable) that
will be provided to dosemm
      @sourceout = ("CFA","INTEC","INTEC-MS","MFC","MFC-MS","NRF","RTC","RTC-
ATR","RWMC","SMC");


# The srcinclude array indicates what sources to add to one another. 0 = add no sources,
1=add the next source, 2=add the next two sources etc.
      @srcinclude = (0,    0,      0,       0,      1,     0,     0,      0,     0,
1);  # INL sources
# input File
      $filein="SourceTerm2021.txt";

# Suffix contcatenated with sources files by effluent type
      @types = ("-PART1.rel","-I.rel","-NG.rel","-C14H3.rel");
#      @types = ("-PART2.rel");
# radionuclides in each type - MUST be in the same order that are in the release files
#     @particle = ("Am-241","Br-82","Cl-36","Co-60","Cs-137","Pu-239","Pu-240");   # INL
radionuclides for PART1 releases
     @particle = ("Sr-90","Te-129m","U-234","U-235","U-238","Zn-65");   # additional INL
radionuclides for PART2 releses

      @iodine = ("I-129","I-131");   # INL
      @ngas = ("Ar-41","Kr-87","Kr-88","Kr-89","Xe-138");  #INL
      @c14h3 = ("C-14","H-3"); #INL

      $year="2021";
# ------------- End of User Input ----------------
     $nsrcin=$#sourcein;
     $nsrcout=$#sourceout;
     %srctermin=0.;
```

```
# ------------ Read db file ---------------------
     open(IN,"<$filein");
     $line=<IN>;
     while($line=<IN>)
     {
        chop $line;                          # remove return
#        $line =~ s/^[ ]+//;                  # delete initial spaces
        @field = split /[ ,]+/, $line;       # split into fields with space or comma
delimiter
        print "$field[0],$field[1],$field[2]  ";
        $stermin{$field[0]}{$field[1]}=$field[2]/3.1536E7;             # convert from
Ci/yr to Ci/s
        print "$field[0] $field[1] $stermin{$field[0]}{$field[1]}\n";
     }
     close IN;

# ------ Loop to write release files --------------------

     for $i (0..$#sourceout)
     {
#  particulates
          $fileout=$sourceout[$i] . $types[0];
          open(OUT,">$fileout");
          print OUT "Year  Month ";
          for $j (0..$#particle) {printf OUT "%-11s",$particle[$j]}
          print OUT "  Ci/s Sources: ";
          $ii=getindx();

          print "$i  $ii\n";
          for $m (0..$srcinclude[$i])
          {
                 print OUT "$sourcein[$ii] ";
                 $ii=$ii+1;
          }
          print OUT "\n";

          for $k (1..12)
          {
                 printf OUT "%-4d  %-2d   ",$year,$k;
                 for $j (0..$#particle)
                 {
                     $val=0;
                     $ii=getindx();
                     for $m (0..$srcinclude[$i])
                     {
                            #print "$sourceout[$i]
$stermin{$sourcein[$ii]}{$particle[$j]}\n";
                            $val=$val+$stermin{$sourcein[$ii]}{$particle[$j]};
                            $ii=$ii+1;
                     }
                     printf OUT " %-10.3e",$val;
                 }
                 print OUT "\n";
          }
          close OUT;

#  iodine
          $fileout=$sourceout[$i] . $types[1];
          open(OUT,">$fileout");
          print OUT "Year  Month ";
          for $j (0..$#iodine) {printf OUT "%-11s",$iodine[$j]}
          print OUT "  Ci/s Sources: ";
          $ii=getindx();
          for $m (0..$srcinclude[$i])
          {
                 print OUT "$sourcein[$ii] ";
                 $ii=$ii+1;
          }
          print OUT "\n";
```

```
          for $k (1..12)
          {
                 printf OUT "%-4d  %-2d   ",$year,$k;
                 for $j (0..$#iodine)
                 {
                     $val=0;
                     $ii=getindx();
                     for $m (0..$srcinclude[$i])
                     {
                            #print "$sourceout[$i]
$stermin{$sourcein[$ii]}{$particle[$j]}\n";
                            $val=$val+$stermin{$sourcein[$ii]}{$iodine[$j]};
                            $ii=$ii+1;
                     }
                     printf OUT " %-10.3e",$val;
                 }
                 print OUT "\n";
          }
          close OUT;

#  ngas
          $fileout=$sourceout[$i] . $types[2];
          open(OUT,">$fileout");
          print OUT "Year  Month ";
          for $j (0..$#ngas) {printf OUT "%-11s",$ngas[$j]}
          print OUT "  Ci/s Sources: ";
          $ii=getindx();
          for $m (0..$srcinclude[$i])
          {
                 print OUT "$sourcein[$ii] ";
                 $ii=$ii+1;
          }
          print OUT "\n";

          for $k (1..12)
          {
                 printf OUT "%-4d  %-2d   ",$year,$k;
                 for $j (0..$#ngas)
                 {
                     $val=0;
                     $ii=getindx();
                     for $m (0..$srcinclude[$i])
                     {
                            #print "$sourceout[$i]
$stermin{$sourcein[$ii]}{$particle[$j]}\n";
                            $val=$val+$stermin{$sourcein[$ii]}{$ngas[$j]};
                            $ii=$ii+1;
                     }
                     printf OUT " %-10.3e",$val;
                 }
                 print OUT "\n";
          }
          close OUT;

#  c14 and h3
          $fileout=$sourceout[$i] . $types[3];
          open(OUT,">$fileout");
          print OUT "Year  Month ";
          for $j (0..$#c14h3) {printf OUT "%-11s",$c14h3[$j]}
          print OUT "  Ci/s Sources:";
          $ii=getindx();
          for $m (0..$srcinclude[$i])
          {
                 print OUT "$sourcein[$ii] ";
                 $ii=$ii+1;
          }
          print OUT "\n";

          for $k (1..12)
```

```
          {
                 printf OUT "%-4d  %-2d   ",$year,$k;
                 for $j (0..$#c14h3)
                 {
                     $val=0;
                     $ii=getindx();
                     for $m (0..$srcinclude[$i])
                     {
                            #print "$sourceout[$i]
$stermin{$sourcein[$ii]}{$particle[$j]}\n";
                            $val=$val+$stermin{$sourcein[$ii]}{$c14h3[$j]};
                            $ii=$ii+1;
                     }
                     printf OUT " %-10.3e",$val;
                 }
                 print OUT "\n";
          }
          close OUT;
     }

     sub getindx()
     {
       if($i>0)
       {
         $kk=0;
         for $j (1..$i)
         {
           $kk=$kk+1+$srcinclude[$j-1];
         }
       }
       else {$kk=0;}
       return $kk;

     }
```

The script produces a DOSEMM release file. The release file for noble gases from a single source (the MFC stack) is provided below. In the case of MFC stacks where releases from the main stack and the TREAT stack are combined, the release file documents the sources that are included in the release rates.

```
Year  Month Ar-41     Kr-87      Kr-88      Kr-89      Xe-138   Ci/s Sources: MFC-MS MFC-
TREAT
2021  1     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  2     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  3     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  4     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  5     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  6     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  7     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  8     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  9     2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  10    2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  11    2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
2021  12    2.565e-06  3.330e-07  3.016e-07  1.084e-06  5.137e-07
```

The remainder of the release files along with all other input and output files are provided in the electronic distribution.