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VERIFICATION OF THE GASPAR DOSE ASSESSMENT MODULE USED IN MAXIGASP AND POPGASP

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SUMMARY

The GASPAR module utilized in MAXIGASP and POPGASP has been verified by hand calculations. The program operates as documented by the NRC [Eckerman et. al. 1980]. Equations used in the code to calculate downwind deposition rates, concentrations in air, on ground surfaces, and in vegetables, meat, and milk are provided in this report.

INTRODUCTION

The GASPAR code [Eckerman et. al. 1980] was written in 1977 by Oak Ridge National Laboratory for the Nuclear Regulatory Commission (NRC). The models in GASPAR calculate atmospheric concentrations, deposition rates, concentrations in foodstuffs, and radiation dose to individuals and populations resulting from chronic releases of radionuclides to the atmosphere [NRC 1977a]. Brief descriptions of GASPAR's subroutines and a schematic showing the transfer of data are given in Table 1 and Figure 1. The atmospheric transport models that feed GASPAR are contained in XOQDOQ [NRC 1977b; Sagendorf et. al. 1982]. XOQDOQ has been verified to calculate relative concentration (X/Q) and relative deposition (D/Q) at specific downwind locations for both maximum individual and population dose estimates [Bauer 1991].

GASPAR was originally designed [Eckerman et. al. 1980] to calculate "ALARA" and "NEPA" population dose estimates. The major difference in these estimates is that doses to the 50-mile population are considered ALARA doses and NEPA doses are calculated for the entire U.S. population. NEPA doses are calculated and printed by GASPAR but are not utilized by the SRS (the no-print option is not available). The NEPA dose calculations are not verified in this or any other SRS document.

ORGANIZATION

The GASPAR code is made up of twenty-six modules (subroutines, entry points, data blocks, etc.). These modules can be grouped into six classifications of code control: 1) supervision, 2) housekeeping, 3) input data, 4) input subroutines, 5) dose computations, and 6) output. The program diagram in Figure 1 shows the interactions between modules relative to data transfer. GASPAR is arranged so that it operates in either MAXIGASP or POPGASP to calculate radiation doses to humans resulting from atmospheric releases of radionuclides.

Table 1. Descriptions of GASPAR subroutines

Subroutine	Function
MAIN	Controls input, reads special locations, echos input.
DOSIT	Controls and executes computations and controls output.
PART	Computes doses of particulates, including iodine.
CARBON	Computes Carbon-14 doses.
NOBLE	Computes doses from noble gases.
TRITON	Computes tritium doses.
OUTSPL	Combines with BRKSPL to print individual doses.
OUTMAN	Combines with BRKMAN to print integrated population doses.
REDDF	Reads and prints dose factor library when requested.
SOURCE	Reads and prints source term. Catalogs source term items.
REDSIT	Reads and prints site-specific population and agricultural data.
REDMET	Reads met. data (printed by PRINTM, called by MAIN).
PRINTM	Prints site and met. data.
PRINTB	Prints changes to BLOCK DATA made through BLKDAT.
PRINTC	Prints cost-benefit table (2 copies).
ZERO1	Zeroes arrays.
ZERO2	Zeroes arrays.
ZERO3	Zeroes arrays.
BLKDAT	Reads various consumption and agricultural constants.
BLOCK DATA	Data read routine.
SRMAXI	Special output for MAXIGASP when JC(1)>0 and JC(6)>0.

CODE OPERATION

Procedures for executing dose calculation programs are given in EDGs Procedure Manual L15.16, "Environmental Dosimetry Procedures". The JCL (Job Control Language) needed to execute MAXIGASP and POPGASP, their input templates, and all accessed databases are maintained on the unclassified IBM Mainframe.

Valid ranges on input queries are given in Table 2. Many of the input parameters appear in MAXIGASP and POPGASP templates, however, the templates are not identical and some parameters are necessary for only one of the two codes, e.g., the choice of cow or goat milk consumption is only available for calculations of the maximum individual dose.

Input for the facility grade parameter is shown to be valid for all values between 0 and 1000 feet. The highest site elevation is approximately 400 feet above sea level, however, a value of 1000 is entered if the flat terrain option is requested.

Figure 1. GASPAR program schematic diagram.

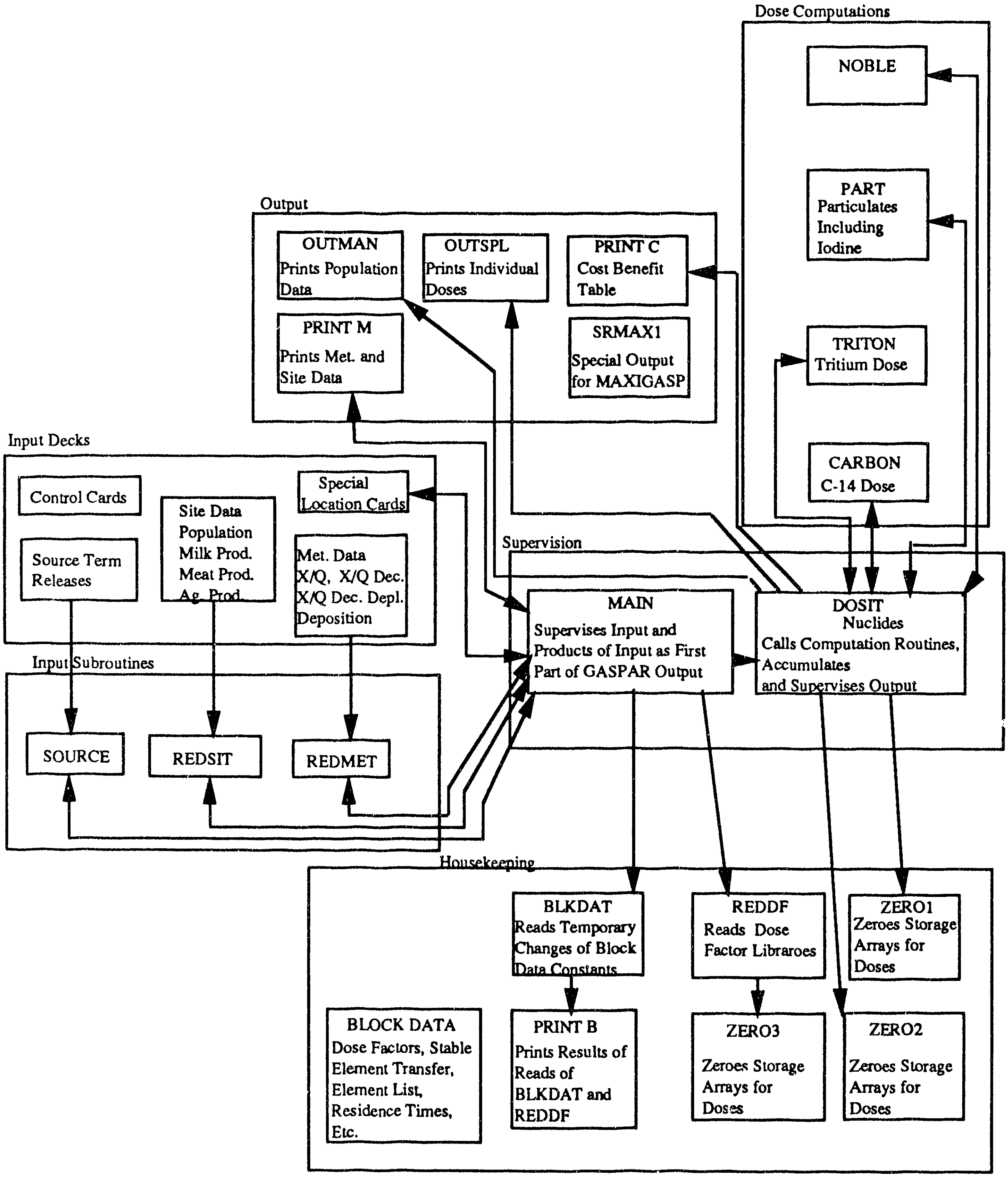

Table 2. Valid input ranges for MAXIGASP and POPGASP.

Parameter	Value
Number of Released Nuclides	1 - 100
Number of Release Points	1 - 5
Operating Period (yr)	1 - 201
Individual Consumption	MAX; AVG
Milk Ingestion	COW; GOAT
Facility Grade Elevation (ft)	0 - 1000
SRS Easting Coordinate	any onsite value
SRS Northing Coordinate	any onsite value
SRS Tower Met Data	A, C, D, F, H, K, or P
Vent Avg Air Velocity (m/s)	0 - 1000
Vent Inside Diameter (m)	0 - 50
Vent/Release Height (m)	0 - 100
Height of Vent's Building (m)	0 - 100
Min. Vertical Cross-Section (m^2)	0 - 10000
Selected Wind Height (m)	0 - 100
Heat Emission Rate (cal/s)	0 - 500
Fraction of Elemental Iodines	0 - 1
Release Amount (Ci)	zero - 10^6

DATABASES

Dose factors utilized in the calculation of atmospheric dose are maintained in two separate databases on the unclassified IBM mainframe and are accessed by the GASPAR module of MAXIGASP and POPGASP. One database exists for noble gases and the other contains all other nuclides. They include decay constants and external gamma-shine, inhalation, and ingestion dose factors for each radionuclide. The noble gas library has only decay constants and external cloud-shine dose factors. Other parameter values, such as stable element transfer coefficients, cattle feeding rates, buildup times, usage rates, etc. are coded directly into the FORTRAN as block-data subroutines.

The dose factor libraries, DFGAS30 and NDFMANEW, are resident in the TENVT.DATA.TMECA dataset and have been verified for accuracy [Hamby 1991b; Hamby 1991c]. Hardcopies of the libraries are maintained in EDG records as QA documentation.

INPUT FROM XOQDOQ

MAXIGASP and POPGASP access the same atmospheric transport and dosimetry models in the NRC codes XOQDOQ and GASPAR. XOQDOQ models the transport of radionuclides through the atmosphere while GASPAR estimates radiation dose to individuals or populations. Differences in MAXIGASP and POPGASP are seen upon examination of the input and output modules as well as the data transfer subroutines, however, the two computer codes access the same versions of XOQDOQ and GASPAR.

The transport models of XOQDOQ are described in the NRC Regulatory Guide 1.111 [1977b] and verified by Bauer [1991]. When calculating downwind air concentrations for radionuclides, the Regulatory Guide 1.111 states:

> "For conservative estimates of radioactive decay, an overall half-life of 2.26 days is acceptable for short-lived noble gases and of 8 days for all iodines released to the atmosphere. Alternatively, the actual half-life of each radionuclide may be used. The decay time used should be the calculated time of travel between the source and receptor based on the airflow model used."

For radionuclide transport at the SRS, actual radioactive decay is calculated for each nuclide released to the atmosphere. GASPAR accepts only four outputs from the XOQDOQ computer code: 1) relative air concentration, X/Q; 2) relative air concentration decayed by 2.26 days; 3) relative air concentration decayed and depleted for 8 days; and 4) relative deposition, D/Q. The nondecayed X/Q and the 2.26 day decayed X/Q are used to calculate the travel time from the source to the receptor (see section on deposition).

DEPOSITION

Deposition of iodines and particulates can occur by several mechanisms. The primary removal mechanism of atmospheric material is gravitational settling or contact with the ground, vegetation, or other ground cover such as buildings (dry deposition). Wet deposition, whereby gases and particulates are removed from an atmospheric plume by precipitive scavenging (rain, sleet, snow). For long-term averages, such as those calculated in MAXIGASP and POPGASP, dose calculations considering only dry deposition are not usually changed significantly by the consideration of wet deposition [NRC 1977b]. Wet deposition should be considered at sites that have a well-defined rainy season corresponding to the grazing season [NRC 1977b].

Rainfall at the SRS averages 48.2 inches annually (from 1952 to 1987). Average monthly rainfall rates range between 2.5 and 5 inches per month. The SRS does not have a rainy season, however, the months of November and December typically have less rain than other months [Hunter 1990]. Since there is not a well-defined rainy season, wet deposition would be insignificant at the SRS for long-term averages. It is, therefore, not considered in MAXIGASP and POPGASP.

Tritium and Carbon-14. Dry deposition of these nuclides is not considered. Specific activity models for tritium and C-14 utilize atmospheric concentrations to estimate vegetation concentrations.

Iodines. Deposition rates, d_i, for iodine isotopes are estimated using,

$$d_i \left[\frac{\mu Ci}{m^2 \ yr}\right] = \frac{D}{Q}\left[\frac{1}{m^2}\right] \bullet Q_i\left[\frac{Ci}{yr}\right] \bullet F_I \bullet 10^6\left[\frac{\mu Ci}{Ci}\right] \bullet e^{(31.62-\lambda_i)\,t_T}$$

where D/Q is the relative deposition value calculated in XOQDOQ, Q_i is the radionuclide release rate, F_I is the fraction of iodine that is assumed to be elemental, λ_i is the nuclide-specific decay constant and t_T is the plume travel time from the source to the receptor. Iodine-131 establishes a deposition equilibrium on ground surfaces with a half-life of approximately 8 days [Till 1983]. Deposition equilibrium with an eight-day half-life is assumed for all nuclides. The factor of 31.62 yr^{-1} in the exponent accounts for this equilibrium. The iodine deposition rate equation includes a factor to account for the fraction of the release that is in elemental form. The fraction in the gaseous form does not deposit on ground surfaces.

The parameter t_T is the average amount of time required for the effluent to reach the receptor (site boundary for maximum individual calculations or specific annular distance for population calculations). The XOQDOQ program calculates a decayed and a non-decayed χ/Q. The decayed χ/Q is obtained by assuming the effluent is radioactive with a half-life of 2.26 days [NRC 1977b]. The value of t_T is found by solving the radioactive decay equation used in XOQDOQ to calculate a 2.26 day decayed relative air concentration,

$$\frac{\chi_D}{Q} = \frac{\chi}{Q}\, e^{-(112\ \mathrm{yr}^{-1})\, t_T}$$

where the value 112 yr^{-1} is the decay constant for a 2.26 day half-life. The effluent travel time (in years) is then,

$$t_T = \frac{-\ln\left(\frac{\chi_D/Q}{\chi/Q}\right)}{\left(\frac{\ln 2 \bullet 365\ \mathrm{d}}{2.26\ \mathrm{d} \bullet 1\ \mathrm{yr}}\right)}$$

where χ_D/Q and χ/Q are the decayed and non-decayed relative air concentrations at the receptor and are obtained from XOQDOQ output. The plume travel time is used in subsequent equations to account for radioactive decay, ground deposition, and plume depletion.

Other Nuclides. Deposition rates for all remaining nuclides are determined using,

$$d_i\left[\frac{\mu\mathrm{Ci}}{\mathrm{m}^2\ \mathrm{yr}}\right] = \frac{D}{Q}\left[\frac{1}{\mathrm{m}^2}\right] \bullet Q_i\left[\frac{\mathrm{Ci}}{\mathrm{yr}}\right] \bullet 10^6\left[\frac{\mu\mathrm{Ci}}{\mathrm{Ci}}\right] \bullet e^{(31.62-\lambda_i)\, t_T}$$

where all parameters have been previously defined. The deposition equilibrium coefficient for iodine (31.62 yr^{-1}) is applied to all other nuclides as well. Deposition is modeled for all radionuclides other than tritium, carbon-14, and noble gases.

NUCLIDE CONCENTRATIONS IN THE ATMOSPHERE

Tritium and Carbon-14. Downwind atmospheric concentrations, χ_i, of tritium and C-14 are estimated using,

$$\chi_i\left[\frac{\mu\mathrm{Ci}}{\mathrm{m}^3}\right] = \frac{\chi}{Q}\left[\frac{\mathrm{sec}}{\mathrm{m}^3}\right] \bullet Q_i\left[\frac{\mathrm{Ci}}{\mathrm{yr}}\right] \bullet 10^6\left[\frac{\mu\mathrm{Ci}}{\mathrm{Ci}}\right] \bullet 3.17\mathrm{x}10^{-8}\left[\frac{\mathrm{yr}}{\mathrm{sec}}\right]$$

Since both tritium and carbon-14 have relatively long half-lives, radiological decay is not taken into account when estimating downwind concentration for these nuclides.

Noble Gases. Air concentrations of noble gases are estimated by,

$$\chi_i \left[\frac{\mu\text{Ci}}{\text{m}^3}\right] = \frac{\chi}{Q}\left[\frac{\text{sec}}{\text{m}^3}\right] \bullet Q_i\left[\frac{\text{Ci}}{\text{yr}}\right] \bullet 10^6\left[\frac{\mu\text{Ci}}{\text{Ci}}\right] \bullet 3.17\text{x}10^{-8}\left[\frac{\text{yr}}{\text{sec}}\right] \bullet e^{-\lambda_i t_T}$$

where the exponential accounts for radioactive decay during transit to the maximum individual receptor. The value of t_T is determined in the same manner as for the calculation of deposition rate.

Iodines. Iodine concentrations in the atmosphere are determined using,

$$\chi_i \left[\frac{\mu\text{Ci}}{\text{m}^3}\right] = \left\{\left(\frac{\chi_D}{Q} \bullet (1 - F_I)\right) + \left(\frac{\chi_{DD}}{Q} \bullet F_I \bullet e^{31.62\, t_T}\right)\right\}\left[\frac{\text{sec}}{\text{m}^3}\right] \bullet Q_i\left[\frac{\mu\text{Ci}}{\text{sec}}\right] \bullet e^{-\lambda_i t_T}$$

where the χ_D represents a decayed concentration and χ_{DD} represents a decayed and depleted concentration. The factor in brackets calculates a weighted relative air concentration accouting for the deposition of the elemental fraction. The exponential term in brackets accounts for deposition equilibrium and is applied only to the depleted χ/Q (χ_{DD}) An exponential term is also included in this equation to account for radioactive decay during plume transit.

Other Nuclides. Air concentrations of the remaining nuclides (those not considered above), are calculated using,

$$\chi_i \left[\frac{\mu\text{Ci}}{\text{m}^3}\right] = \frac{\chi_{DD}}{Q}\left[\frac{\text{sec}}{\text{m}^3}\right] \bullet Q_i\left[\frac{\text{Ci}}{\text{yr}}\right] \bullet 10^6\left[\frac{\mu\text{Ci}}{\text{Ci}}\right] \bullet 3.17\text{x}10^{-8}\left[\frac{\text{yr}}{\text{sec}}\right] \bullet e^{(31.62-\lambda_i)t_T}$$

where all terms have been defined previously. Again, the positive rate coefficient in the exponential term (31.62 yr^{-1}) accounts for deposition equilibrium between the air and ground surface.

NUCLIDE CONCENTRATIONS IN VEGETATION

Tritium. A specific activity model describes the uptake of tritium in vegetation. Tritium concentrations in vegetation are determined directly from the concentrations of tritium in atmospheric moisture. Equilibrium is assumed to be achieved in a short time relative to an annual release. The concentration of tritium in vegetation, C_T^v, is determined by,

$$C_T^v\left[\frac{\mu\text{Ci}}{\text{kg}}\right] = \frac{\chi_T\left[\frac{\mu\text{Ci}}{\text{m}^3}\right] \bullet 0.75 \bullet 0.5}{H\left[\frac{\text{kg}}{\text{m}^3}\right]}$$

where χ_T is the atmospheric concentration, 0.75 is the fraction of plant mass that is water, 0.5 is the assumed concentration ratio of plant tritium to atmospheric tritium, and H is the annual average absolute humidity (11 g/m^3 for the SRS). Studies [Bauer and Hamby, 1991; Hamby 1992] show that dose estimates for the vegetation consumption pathway are somewhat sensitive to the parameters in this model. A site-specific value is being developed for the plant-tritium-to-atmospheric-tritium ratio.

Carbon-14. The C-14 model for vegetation concentrations is similar to the tritium model. The equation,

$$C_C^v [\frac{\mu Ci}{kg}] = \frac{\chi_C [\frac{\mu Ci}{m^3}] \cdot F_t \cdot 0.11}{0.00016 [\frac{kg}{m^3}]}$$

is used to estimate C-14 vegetation concentrations, C_C^v. The parameter F_t is defined as the ratio of the total annual release time to the total annual time during which photosynthesis occurs (taken to be 4380 hours). If atmospheric releases occur more than half the year, the value of F_t is unity. The fraction of total plant mass that is natural carbon is represented by 0.11 and 0.00016 is the concentration of natural carbon in the atmosphere.

Other Nuclides. The concentration of other nuclides in vegetation is determined using,

$$C_i^v [\frac{\mu Ci}{kg}] = d_i [\frac{\mu Ci}{m^2 yr}] \cdot \left\{ \frac{r_i (1-e^{-\lambda_i^w t_e})}{Y_v [\frac{kg}{m^2}] \lambda_i^w [\frac{1}{yr}]} + \frac{B_i^v (1-e^{-\lambda_i t_b})}{P [\frac{kg}{m^2}] \lambda_i [\frac{1}{yr}]} \right\} \cdot e^{-\lambda_i t_h}$$

where d_i is the deposition rate determined earlier, r_i is the fraction of the nuclide deposited that remains on the surface of the plant, λ_i^w represents both weathering and radioactive losses, t_e is the crop exposure time, Y_v is the crop productivity, B_i^v is the element-specific soil/plant uptake ratio, λ_i is the radioactive decay constant, t_b is the time over which the buildup of radionuclides occurs, P is the surface soil density, and t_h is the hold-up time after harvest (allowing for decay before consumption).

The two expressions in the brackets account for contamination via foliar deposition and root uptake, respectively. All particulate nuclides are assumed to be fully retained on vegetation (r=1) while only 20% of the iodines are retained (r=0.2). The loss constant, λ_i^w, accounts for losses through physical weathering (14 day half-life) and radioactive decay. Values of Y_v, t_e, and t_h vary depending on the type of crop and whether the vegetation is for human consumption or is to be used as fodder [Hamby 1991a].

Concentrations in four types of vegetation are calculated in GASPAR. These four types along with their associated parameter values are given in Table 3.

Table 3. Parameter values for vegetation concentrations.

Parameter	Other Vegetables	Leafy Vegetables†	Pasture Grass	Stored Feed
r (iodines)	0.2	same	same	same
r (particulates)	1.0	same	same	same
λ_w (yr^{-1})	$18.07 + \lambda_i$	same	same	same
t_e (yr)	0.192	0.192	0.0822	0.192
Y_v (kg m^{-2})	0.7	0.7	1.8	0.7
B_i	element specific	same	same	same
λ_i (yr^{-1})	nuclide specific	same	same	same
t_b (yr)	scenario specific	same	same	same
P (kg m^{-2})	240	same	same	same
t_h (yr)	0.164 (0.0384)*	0.00274	0	0.247
d_i (μCi m^{-3} yr^{-1})	nuclide specific	same	same	same

†consumption of leafy vegetables not considered for population dose calculations.
*value in parentheses is for population dose calculations.

NUCLIDE CONCENTRATIONS IN MEAT AND MILK

All Nuclides. Concentrations of radionuclides in meat and milk are determined from feed concentrations, fodder intake rates, and element-specific feed-to-meat/feed-to-milk transfer factors. The equations for meat and milk concentration estimates are essentially identical with the exception of the feed transfer coefficient. Concentrations are estimated using,

$$C_i^{meat}\,[\frac{\mu Ci}{kg}] = C_i^{fodder}\,[\frac{\mu Ci}{kg}] \cdot F_i^f\,[\frac{d}{kg}] \cdot Q_F[\frac{kg}{d}] \cdot e^{-\lambda_i t_s}$$

$$C_i^{milk}\,[\frac{\mu Ci}{L}] = C_i^{fodder}\,[\frac{\mu Ci}{kg}] \cdot F_i^m\,[\frac{d}{L}] \cdot Q_F[\frac{kg}{d}] \cdot e^{-\lambda_i t_f}$$

where C_i^{fodder} is the nuclide concentration in cattle feed (determined below), F_i^f and F_i^m are the feed transfer coefficients, Q_F is the cattle feed rate. The exponential term accounts for radiological decay from the time of slaughter/milking to the time of consumption where λ_i is the nuclide-specific decay constant, t_s is the transport time for meat, and t_f is the transport time for milk. Values for these parameters are given in Table 4.

Table 4. Parameter assignments in GASPAR for meat and milk ingestion dose calculations†.

Parameter	Meat	Milk (cow)	Milk (goat)
Feed consumption rate (kg/d)	44	44	6
Milking/Slaughter to consumption (d)	6	2(3)	2(3)
Fraction of year on pasture	1.00	1.00	0.79
Fraction intake from pasture*	0.75	0.56	0.85

†values in parentheses are for population dose estimates.
*while on pasture.

The nuclide concentration in fodder is estimated based on the fraction of time cattle spend on pasture and the fraction of that time that is spent consuming fresh pasture grass. The equation,

$$C_i^{fodder}\left[\frac{\mu Ci}{kg}\right] = f_p\, f_s\, C_i^p\left[\frac{\mu Ci}{kg}\right] + \left\{f_p(1-f_s) + (1-f_p)\right\} C_i^s\left[\frac{\mu Ci}{kg}\right]$$

is used to calculate a fodder concentration by weighting the concentrations of pasture grass, C_i^p, and stored feed, C_i^s. The parameter f_p is the fraction of time cattle spend on pasture and f_s is the fraction of time that cattle eat fresh grass while on pasture.

Concentrations of nuclides in goat's milk are determined in the same manner as cow's milk and beef except using different values (see Table 4) for feed consumption rate and the fraction of time spent on pasture and eating pasture grass.

SHINE DOSE

Plume-Shine. Dose to offsite individuals and the population from gamma shine is estimated in GASPAR only for the noble gases. The plume-shine dose from these nuclides has been determined to be significantly higher than doses resulting from other nuclides [NRC 1977a]. The gamma dose from a particular noble gas in an atmospheric plume is calculated from,

$$D_i^p\,[\text{mrem}] = \chi_i\left[\frac{\mu Ci}{m^3}\right] \cdot SF \cdot DF_i^p\left[\frac{\text{mrem}\ m^3}{\text{yr}\ \mu Ci}\right] \cdot 1\,[\text{yr}]$$

where SF is a shielding factor accouting for the fraction of time spent indoors and DF_i^p is the nuclide specific plume-shine dose factor. The value of SF is taken to be 0.7 for individuals, meaning that the individual is assumed to be exposed 70% of the time.

Population dose is estimated using average plume concentrations in each of 160 sector/annulus segments; 16 sectors and 10 annuli with distance ranges of 0-1, 1-2, 2-3, 3-4, 4-5, 5-10, 10-20, 20-30, 30-40, and 40-50 miles. Population dose from plume shine is calculated using the following equation:

$$D_i^p\ [\text{per-rem}] = DF_i^p\ [\frac{\text{mrem m}^3}{\text{yr }\mu\text{Ci}}] \bullet 1\ [\text{yr}] \bullet SF \bullet \sum_{k=1}^{160} \left\{ \chi_{ik}\ [\frac{\mu\text{Ci}}{\text{m}^3}] \bullet N_k\ [\text{persons}] \right\}$$

where χ_{ik} is the plume concentration of nuclide i in area-segment k, N_k is the number of people (all ages) residing within each population segment, and SF is equal to 0.5. The age distribution of the population is not considered for this pathway because external dose is independent of age.

Ground-Shine. Ground-shine doses are calculated for all particulate, gamma-emitting nuclides. The dose accounts for buildup over the plant lifetime and is given by,

$$D_i^g\ [\text{mrem}] = d_i\ [\frac{\mu\text{Ci}}{\text{m}^2\text{ yr}}] \bullet SF \bullet DF_i^g\ [\frac{\text{mrem m}^2}{\text{yr }\mu\text{Ci}}] \bullet \frac{1 - e^{-\lambda_i t_b}}{\lambda_i}\ [\text{yr}] \bullet 1\ [\text{yr}]$$

where DF_i^g is the nuclide-specific ground-shine dose factor and the exponential term accounts for the ground-surface buildup and subsequent radiological decay. Nuclide-specific doses are summed for the total dose.

The population dose from ground-shine is calculated using,

$$D_i^g\ [\text{per-rem}] = DF_i^g\ [\frac{\text{mrem m}^2}{\text{yr }\mu\text{Ci}}] \bullet 1\ [\text{yr}] \bullet SF \bullet \frac{1 - e^{-\lambda_i t}}{\lambda_i}\ [\text{yr}] \bullet \sum_{k=1}^{160} \left\{ d_{ik}\ [\frac{\mu\text{Ci}}{\text{m}^3\text{ yr}}] \bullet N_k\ [\text{persons}] \right\}$$

where d_{ik} is the deposition rate of nuclide i in area-segment k. Again, external dose is independent of age, therefore, the age distribution of the population is not considered.

INHALATION DOSE

Inhalation dose is determined for the maximum individual and the population assuming a constant breathing rate and a constant concentration throughout the year of exposure. The nuclide-specific dose is estimated by,

$$D_i^{inh}\ [\text{mrem}] = \chi_i\ [\frac{\mu\text{Ci}}{\text{m}^3}] \bullet BR\ [\frac{\text{m}^3}{\text{yr}}] \bullet DF_i^{inh}\ [\frac{\text{rem}}{\mu\text{Ci}}] \bullet 1000\ [\frac{\text{mrem}}{\text{rem}}] \bullet 1\ [\text{yr}]$$

where BR is the breathing rate and DF_i^{inh} is the nuclide-specific inhalation dose factor. A breathing rate of 8000 m^3/yr is assumed for maximum individual and population dose estimates in GASPAR.

If age-specific dose factors are available, population dose for age-group p, due to the inhalation of radionuclides in the air is given by,

$$D_{ip}^{inh}\ [\text{per-rem}] = DF_{ip}^{inh}\ [\frac{\text{rem}}{\mu\text{Ci}}] \bullet BR_p\ [\frac{\text{m}^3}{\text{yr}}] \bullet 1\ [\text{yr}] \bullet f_p \bullet \sum_{k=1}^{160} \left\{ \chi_{ik}\ [\frac{\mu\text{Ci}}{\text{m}^3}] \bullet N_k\ [\text{persons}] \right\}$$

where BR_p is the average breathing rate for age-group p and f_p is the fraction of the population in the p age-group. If age-specific dose factors are not available, adult dose factors are used with adult breathing rates and the whole population is assumed to be adult. POPGASP is currently configured to calculate population dose under the assumption that the population is 100% adult.

FOOD INGESTION DOSE

Dose to the maximum individual is estimated for ingestion of foodstuffs including vegetables, meat, and milk. Radionuclide intakes through the vegetation consumption pathway considers vegetables as being classified as either "leafy" or "other". "Other" includes fruits, grains, produce, and below ground vegetables. The dose via vegetable consumption for a one-year period is calculated using,

$$D_i^{veg}\,[\text{mrem}] = \left\{ C_i^v\, U^v\, f_v + C_i^l\, U^l\, f_l \right\} [\frac{\mu Ci}{yr}] \bullet DF_i^{ing}\, [\frac{rem}{\mu Ci}] \bullet 1000\, [\frac{mrem}{rem}] \bullet 1\, [yr]$$

where C_i^l and C_i^v are radionuclide concentrations in the leafy and other vegetables, U^l and U^v are consumption rates of the two vegetable classifications, f_l is the fraction of leafy vegetables consumed that originated in the home garden, and f_v is the fraction of other vegetables that are home grown.

Individual dose from meat and milk consumption is calculated in the same manner, using the equations:

$$D_i^{meat}\,[\text{mrem}] = C_i^{meat}\, [\frac{\mu Ci}{kg}] \bullet U^f\, [\frac{kg}{yr}] \bullet DF_i^{ing}\, [\frac{rem}{\mu Ci}] \bullet 1000\, [\frac{mrem}{rem}] \bullet 1\, [yr]$$

$$D_i^{milk}\,[\text{mrem}] = C_i^{milk}\, [\frac{\mu Ci}{L}] \bullet U^m\, [\frac{L}{yr}] \bullet DF_i^{ing}\, [\frac{rem}{\mu Ci}] \bullet 1000\, [\frac{mrem}{rem}] \bullet 1\, [yr]$$

where the parameters have already been defined. The ingestion dose factor, DF_i^{ing}, is nuclide-specific and is the same value for water, vegetable, meat, and milk consumption.

ALARA population dose is calculated by GASPAR based on the assumption that the food consumed by the population within 50 miles of the SRS center is produced in the 50-mile region. If production rates exceed consumption needs, food is exported from the region (consumption of which is included in the NEPA dose estimate). Equations for the estimation of age-specific population dose via consumption of vegetables, meat, and milk are given below.

$$D_{ip}^{veg}\,[\text{per-rem}] = DF_{ip}^{ing}\, [\frac{rem}{\mu Ci}] \bullet 1\, [yr] \bullet f_p \bullet U_p^v\, [\frac{kg}{yr}] \bullet N\, [per] \bullet \sum_{k=1}^{160} \left\{ C_{ik}^{veg}\, [\frac{\mu Ci}{kg}] \bullet \frac{VEG_k}{VEGT} \right\}$$

$$D_{ip}^{meat}\,[\text{per-rem}] = DF_{ip}^{ing}\, [\frac{rem}{\mu Ci}] \bullet 1\, [yr] \bullet f_p \bullet U_p^f\, [\frac{kg}{yr}] \bullet N\, [per] \bullet \sum_{k=1}^{160} \left\{ C_{ik}^{meat}\, [\frac{\mu Ci}{kg}] \bullet \frac{MET_k}{METT} \right\}$$

$$D_{ip}^{milk}\ [\text{per-rem}] = DF_{ip}^{ing}\ [\frac{\text{rem}}{\mu\text{Ci}}] \cdot 1\ [\text{yr}] \cdot f_p \cdot U_p^m\ [\frac{\text{L}}{\text{yr}}] \cdot N\ [\text{per}] \cdot \sum_{k=1}^{160} \left\{ C_{ik}^{milk}\ [\frac{\mu\text{Ci}}{\text{L}}] \cdot \frac{MLK_k}{MLKT} \right\}$$

Dose factors, DF_{ip}^{ing}, and consumption rates, U_p, are age-specific and the parameter N represents the number of persons served by the total production within an 80-km radius of the site (see Table 5). The consumption of home-grown leafy vegetables is not considered when calculating population dose. Therefore, the rate for vegetable consumption is that for non-leafy or produce. The subscript, p, signifies the age group to which the dose factor applies.

Table 5. Consumption and population parameters for estimation of vegetable, meat, and milk population dose.

Parameter	Units	Vegetable	Meat	Milk
Consumption Rate	kg/yr	163	43	120
Pop. Served	persons	3.09×10^5	3.39×10^5	9.25×10^5
Total Production	kg	5.041×10^7	1.457×10^7	1.110×10^8

The parameter C_{ik} is the average concentration of nuclide i in vegetation, meat, or milk within area-segment k. The variables VEG_k, MET_k, and MLK_k represent the mass of commodity produced in area-segment k and VEGT, METT, and MLKT are the total production mass within 80-km. The expressions that follow the summation symbols provide a weighted nuclide concentration for estimating the average nuclide concentration in foods within the dose assessment region.

CODE VERIFICATION

Concentrations of foodstuffs, etc. do not appear in the MAXIGASP and POPGASP output. Therefore, for the purposes of comparison to hand calculations, only final dose estimates were compared to the computer output. Eight example problems of MAXIGASP have been executed and compared to an EXCEL spreadsheet developed for the purpose of verifying GASPAR. Output from the XOQDOQ portion of MAXIGASP was used as input to the spreadsheets. All dose estimates calculated by MAXIGASP (GASPAR) are identical (within rounding) to spreadsheet calculations (see Table 6). The IBM mainframe printouts and spreadsheet hardcopies are maintained in EDG QA files.

Table 6. Comparison of GASPAR to hand calculations of maximum individual dose.

Nuclide	GASPAR†	Hand-Calculation††	% Diff.
H-3	9.2×10^{-7}	9.1×10^{-7}	1.1
C-14	3.6×10^{-4}	3.6×10^{-4}	-
Ar-41	1.4×10^{-6}	1.4×10^{-6}	-
Co-60	1.3×10^{-1}	1.3×10^{-1}	-
Se-75	4.9×10^{-3}	4.9×10^{-3}	-
Kr-85	3.9×10^{-9}	3.9×10^{-9}	-
Kr-85m	2.3×10^{-7}	2.3×10^{-7}	-
Kr-87	7.7×10^{-7}	7.7×10^{-7}	-
Kr-88	3.8×10^{-6}	3.8×10^{-6}	-
Sr-90	6.2×10^{-2}	6.2×10^{-2}	-
Zr-95	3.6×10^{-3}	3.6×10^{-3}	-
Nb-95	1.6×10^{-3}	1.6×10^{-3}	-
Ru-103	2.1×10^{-3}	2.1×10^{-3}	-
Ru-106	3.1×10^{-2}	3.1×10^{-2}	-
I-129	6.7×10^{-1}	6.7×10^{-1}	-
I-131	9.1×10^{-3}	9.1×10^{-3}	-
I-133	1.4×10^{-4}	1.4×10^{-4}	-
I-135	1.4×10^{-5}	1.4×10^{-5}	-
Xe-131m	1.5×10^{-8}	1.5×10^{-8}	-
Xe-133	6.0×10^{-8}	6.0×10^{-8}	-
Xe-135	3.9×10^{-7}	3.9×10^{-7}	-
Cs-134	8.2×10^{-2}	8.2×10^{-2}	-
Cs-137	1.4×10^{-1}	1.4×10^{-1}	-
Ce-141	3.9×10^{-4}	3.9×10^{-4}	-
Ce-144	8.1×10^{-3}	8.1×10^{-3}	-
Os-185	3.8×10^{-3}	3.8×10^{-3}	-
U-234	5.7×10^{-1}	5.7×10^{-1}	-
U-235	5.7×10^{-1}	5.7×10^{-1}	-
U-238	5.2×10^{-1}	5.2×10^{-1}	-
Np-237	3.3×10^{0}	3.3×10^{0}	-
Pu-238	3.1×10^{0}	3.1×10^{0}	-
Pu-239	3.4×10^{0}	3.4×10^{0}	-
Am-241	3.6×10^{0}	3.6×10^{0}	-
Cm-242	9.2×10^{-2}	9.2×10^{-2}	-
Cm-244	1.8×10^{0}	1.8×10^{0}	-
Cf-252	8.0×10^{-1}	8.0×10^{-1}	-

†calculated using MAXIGASP on the unclassified IBM Mainframe.

††calculated using an EXCELspreadsheet.

Because of the complexity of calculating population dose in each of 160 area-segments, population dose calculations have been hand-checked using two nuclides, tritium and Argon-41. Methods for calculating population dose for a given pathway are identical for each nuclide, therefore, checks using various nuclides are not necessary. The inhalation and consumption pathways are verified using tritium and the plume-shine pathway is verified by Ar-41. The ground-shine doses were not verified in the population dose calculation since verification was accomplished for individual doses and since the calculation is similar to plume-shine dose. The population dose module of GASPAR was checked by using the EXCEL spreadsheet and summing the cumulative doses in each of the 160 area-segments. Because of the number of mathematical steps involved, slightly larger rounding differences are expected between POPGASP and hand-calculated results. Differences by pathway did not exceed 3% nor did they exceed 1.5% for the total dose calculation. The results from this comparison are shown in Table 7.

Table 7. Comparison of GASPAR to hand calculations of population dose.

Pathway	GASPAR†	Hand-Calculation††	% Diff.
Plume-Shine*	3.5×10^{-5}	3.5×10^{-5}	0
Inhalation	3.6×10^{-5}	3.5×10^{-5}	2.8
Vegetable Consumption	7.4×10^{-6}	7.6×10^{-6}	2.7
Meat Consumption	1.2×10^{-6}	1.2×10^{-6}	0
Milk Consumption	4.3×10^{-6}	4.2×10^{-6}	2.4
TOTAL	8.4x10-5	8.3x10-5	1.2

†calculated using MAXIGASP on the unclassified IBM Mainframe.

††calculated using an EXCELspreadsheet similar to that used for maximum individual dose with modifications to calculate average dose in a given area-segment.

*plume-shine estimated for 1 curie of Ar-41.

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