Introduction:

An important aspect of the radiation safety program for nuclear reactors and isotope production/handling facilities is the control of airborne and liquid radioactive effluents and the consequent dose to members of the public.

Control (regulatory and operational) of the emission levels is established by conservatively analyzing the actual and potential exposure pathways for members of the public and calculating the activity which would have to be released to lead to exposure at the public dose limit. This level of release is referred to as the Derived Release Limit and it is typically referenced ion the facility operating licence.

In Canada, calculation of Derived Release Limits is governed by a CSA standard – CAN/CSA-N288.1-M87 Guidelines for Calculating Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operation of Nuclear Facilities. These notes are based on that standard.

Critical Group Concept:

The DRL is calculated for a group of people – or a hypothetical group of people – chosen to be representative of those expected to receive the highest doses. The critical group is chosen to be relatively homogeneous with respect to those factors that affect the intake. The dose limit is then compared with the mean weighted dose to the group. It is recognized that, because of the innate variability within an apparently homogeneous group, some members of the critical group will receive more than the mean dose. However, the conservative assumptions made throughout the calculations are felt to be sufficient to provide reasonable assurance that the doses actually received will usually be lower than the dose limit. Because of the differences in exposure pathways for adults and infants, the standard requires that a DRL be calculated for each.

For internal exposures, the critical group should be chosen so that there is a ratio of not more than three between the maximum and the average of any parameter (e.g. milk consumption rate) that affects the dose.

The alternative to the "critical group" approach – often adopted when the exposed population is very small, is the "exceptional individual". In this case, an individual with limiting habits and characteristics is chosen as the basis for calculation. For example, in calculating DRLs for radioiodine emissions at the McMaster Nuclear Reactor, DRLs are chosen based on a hypothetical infant that spends 100% of the time at the point of maximum ground concentration of iodine. This is done in lieu of obtaining and maintaining defensible occupancy data for the spaces around the reactor.

The Generalized Environmental Transfer Model:

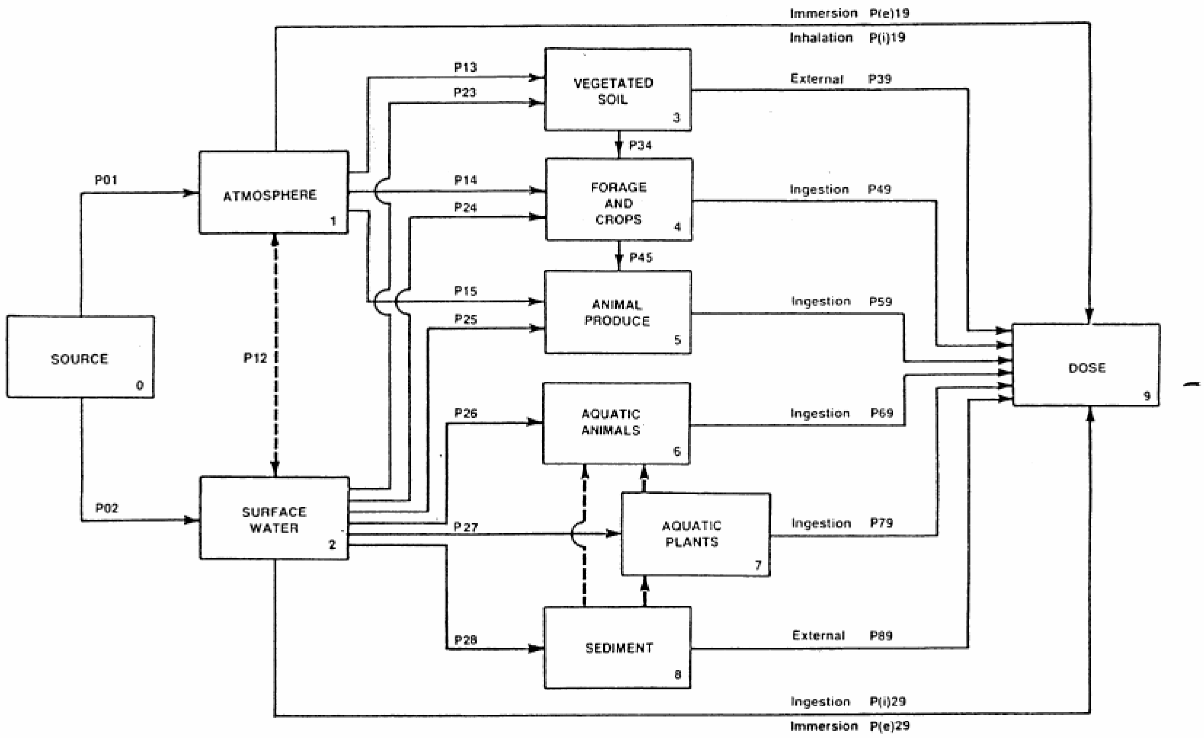
Figure 1 (from the CSA standard) shows a generalized model of transfer compartments of radioactive material from release, through the environment, to exposure of humans.

The quantity of radioactivity in compartment i is denoted as X_i.

The transfer parameter P_{ij} is the fraction of the contents of compartment I transferred to compartment j under steady state. So, at steady state, the quantity in compartment j arising from compartment i is given by $P_{ij}X_i$ and the total quantity in compartment j is given by

$X_j = \Sigma_i P_{ij}X_i$ where the summation is over all of the compartments i transferring into j.

In the model, $X_0(a)$ is the initial release rate to atmosphere and $X_0(w)$ is the release rate to water. It is the practice to calculate release limits independently for each pathway and for each radionuclide.



Units for Generalized Transfer Compartments

Compartment	Units
0 (Source)	$Bq \cdot s^{-1}$
1 (Atmosphere)	$Bq \cdot m^{-3}$
2 (Surface water)	$Bq \cdot L^{-1}$
3 (Vegetated soil)	$Bq \cdot m^{-2}$
4 (Forage and crops)	$Bq \cdot kg^{-1}$
5 (Animal produce)	$Bq \cdot kg^{-1}$
6 (Aquatic animals)	$Bq \cdot kg^{-1}$
7 (Aquatic plants)	$Bq \cdot kg^{-1}$
8 (Sediment)	$Bq \cdot kg^{-1}$
9 (Dose)	$Sv \cdot a^{-1}$

Units for Transfer Parameters

Transfer parameter	Compartments	Units
P_{01}	Source→Atmosphere	$s \cdot m^{-3}$
$P(i)_{19}$	Atmosphere→Dose (inhalation)	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^3$
$P(e)_{19}$	Atmosphere→Dose (immersion)	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^3$
P_{13}	Atmosphere→Vegetated soil	m
P_{14}	Atmosphere→Forage + crops	$m^3 \cdot kg^{-1}$
P_{15}	Atmosphere→Animal produce	$m^3 \cdot kg^{-1}$
P_{34}	Vegetated soil→Forage + crops	$m^2 \cdot kg^{-1}$
P_{39}	Vegetated soil→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^2$
P_{45}	Forage + crops→Animal produce	$kg \cdot kg^{-1}$
P_{49}	Forage + crops→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot kg$
P_{59}	Animal produce→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot kg$
P_{02}	Source→Surface water	$s \cdot L^{-1}$
P_{23}	Surface water→Vegetated soil	$L \cdot m^{-2}$
P_{24}	Surface water→Forage + crops	$L \cdot kg^{-1}$
P_{25}	Surface water→Animal produce	$L \cdot kg^{-1}$
P_{26}	Surface water→Aquatic animals	$L \cdot kg^{-1}$
P_{27}	Surface water→Aquatic plants	$L \cdot kg^{-1}$
P_{28}	Surface water→Sediment	$L \cdot kg^{-1}$
$P(i)_{29}$	Surface water→Dose (ingestion)	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot L$
$P(e)_{29}$	Surface water→Dose (immersion)	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot L$
P_{69}	Aquatic animals→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot kg$
P_{79}	Aquatic plants→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot kg$
P_{89}	Sediment→Dose	$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot kg$

Calculation of the DRL

The DRL is calculated for releases to the atmosphere is calculated by

$$DRL = \frac{E_{\text{limit}}(Sv \cdot a^{-1})}{\left[\dfrac{X_9}{X_0(a)}\right](Sv \cdot a^{-1} \cdot Bq^{-1} \cdot s)}$$

And that for releases to surface water is obtained by substituting $X_0(a)$ with $X_0(w)$.

In rare instances, the release may be limited by the limit for equivalent dose to the skin – in that case the effective dose limit must be replaced with the equivalent dose limit in the calculation.

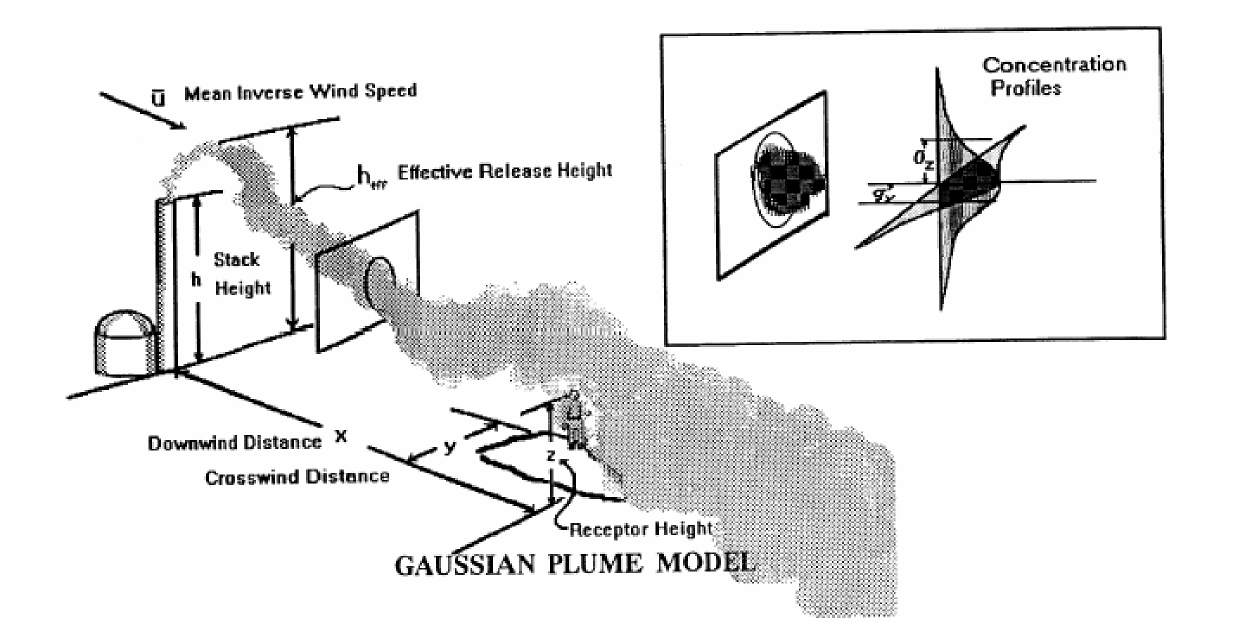
The general method for calculating a DRL is as follows:

- ☐ Identify exposure pathways and critical groups.
- ☐ Develop the appropriate expression for $\left[\frac{X_9}{X_0(a)}\right]$ and $\left[\frac{X_9}{X_0(w)}\right]$
- ☐ Select appropriate transfer parameter values.
  - o Default values are included in the standard but the use of site specific values is encouraged.
- ☐ Calculate the DRL based on the effective dose limit
  - o Values are to be calculated separately for adults and infants
- ☐ Calculate the DRL based on the equivalent dose limits (if necessary)
  - o Values are to be calculated separately for adults and infants
- ☐ Select the lowest value of the DRL calculated.

Transfer Parameters for Airborne Releases

In previous sections, we have seen how to calculate the dose from immersion and inhalation arising from exposure to airborne radioactivity. Various dose coefficients and dose conversion factors are available that will allow us to calculate the dose, provided we know the time integrated concentration. The first step in calculating the DRL for airborne releases is, thus, to determine the airborne concentration to which the critical group will be exposed.

The transfer parameter P_{01} represents the process of atmospheric dispersion. The standard contains extensive guidance for calculating the long term average concentrations in air at distances within a radius of 20km from an isolated source. The model applied is a version of the Gaussian Plume Model in which the meander and dispersion of the plume are assumed to produce a plume downwind of the release point with vertical and horizontal concentration profiles resembling a Gaussian curve characterized by standard deviations of σ_z and σ_y respectively. This is shown in Figure 2 from the Health Physics and Radiological Health Handbook.



We are neglecting, for the moment, radioactive decay and other plume depletion mechanisms such as deposition and washout.

The transfer parameter is given by:

$$P_{01}(x,\theta_j,z) = \frac{1}{\sqrt{2\pi}\theta x}\sum \frac{f_{ijk}}{\sigma_{zi}\bar{u}_k} F(h,z,\sigma_{zi})(s\cdot m^{-3})$$

where

$$F(h,z,\sigma_{zi}) = \exp\left[-\frac{(z-h)^2}{2\sigma^2_{zi}}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma^2_{zi}}\right]$$

θ_j = angle subtended by sector j (radians)

x = downwind distance from the source (m)

$\bar{u}_k$ = mean windspeed associated with windspeed interval k ($m\cdot s^{-1}$)

h = effective height of release (m)

z = height above ground at which air concentration is calculated (m)

σ_{zi} = standard deviation of teh plume width in the vertical direction associated with stability category i (m)

f_{ijk} = joint probability of occurance of stability category i with wind direction into sector j and windspeed interval k

When possible, the actual values of f_{ijk} obtained form site data should be used. Default values for weather parameters are supplied in the standard and it is suggested that using these default values will not introduce an error of more than about 30% for any location in Canada. Often, the stability category and windspeed frequencies are combined – so that each stability category is associated with a characteristic mean wind speed. In addition, the transfer parameter is usually evaluated at ground level (z = 0). With these two assumptions, the expression simplifies to:

$$P_{01}(x,\theta_j,z) = \frac{f_j n}{(2\pi)^{\frac{3}{2}} x}\sum_{i=1}^{6} \frac{f_j}{\sigma_{zi}\bar{u}_i} F(h,0,\sigma_{zi})(s\cdot m^{-3})$$

where

$$F(h,0,\sigma_{zi}) = 2\exp\left[-\frac{h^2}{2\sigma^2_{zi}}\right]$$

f_i = frequency of occurrence of stability category i

f_j = Frequency with which the wind blows into sector j (from site wind rose)

n = number of sectors ($n = \frac{2\pi}{\theta_j}$)

$\bar{u}_i$ = the mean wind speed at a height of 10m (associated with stability category i)

Weather Stability Categories:

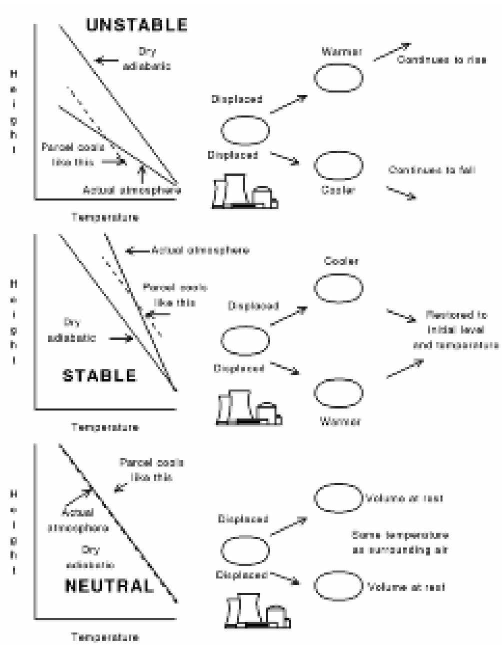
The stability categories are summarized in the following table from IAEA Tecdoc 1162.

TABLE E9. RELATIONSHIP BETWEEN STABILITY CLASS AND WEATHER CONDITIONS

Surface wind speed [m/s]	Daytime insolation (solar radiation)			Night time conditions [a]		Day or night
	Strong	Moderate	Slight	Thin overcast or > 4/8 cloudiness	≤ 3/8 cloudiness	Heavy overcast
< 2	A	A-B	B	-	-	D
2	A-B	B	C	E	F	D
4	B	B-C	C	D	E	D
6	C	C-D	D	D	D	D
> 6	C	D	D	D	D	D

Reference: [24], p. 591.

[a] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.



Pasquill Stability Category i	Frequency (%)	Mean Wind Speed (m s^{-1})
A	1	1
B	6	2
C	10	5
D	56	5
E	10	3
F	17	2

The plume dispersion parameter σ_{zi} is a function of downwind distance, x, stability category and the type of terrain. The following equations are provided for calculating σ_{zi}:

Table D2
Equations for Calculating Plume Dispersion Parameters
(See Appendix G, Item 1.)

$$\sigma_{zi}(x) = g_i(x) \cdot F(Z_0;x)$$

where

$$g_i(x) = a_1 x^{b_1} (1 + a_2 x^{b_2})^{-1}$$

and

$$F(Z_0;x) = \ln \left[c_1 x^{d_1} \left(1 + \frac{1}{c_2 x^{d_2}} \right) \right]; Z_0 > 10 \text{ cm}$$

$$F(Z_0;x) = \ln \left[c_1 x^{d_1} \left(\frac{1}{1 + c_2 x^{d_2}} \right) \right]; Z_0 < 10 \text{ cm}$$

Note: *The parameter Z_0 is the surface roughness length, and some examples are given in Table D5 (Smith, 1972; Pasquill, 1974). For rural conditions a value of Z_0 = 40 cm is appropriate. Values of the other parameters are given in Tables D3 and D4.*

Stability Category	Coefficients			
	a_1	b_1	a_2	b_2
A	0.112	1.06	5.38×10^{-4}	0.815
B	0.130	0.950	6.52×10^{-4}	0.750
C	0.112	0.920	9.05×10^{-4}	0.718
D	0.098	0.889	1.35×10^{-3}	0.688
E	0.0609	0.895	1.96×10^{-3}	0.684
F	0.0638	0.783	1.36×10^{-3}	0.672

Roughness Length Z_0 (cm)	c_1	d_1	c_2	d_2
1 (lawn grass, bodies of water)	1.56	0.0480	6.25×10^{-4}	0.45
4 (ploughed land)	2.02	0.0269	7.76×10^{-4}	0.37
10 (open grassland)	e	0	0	0
40 (rural areas)	5.16	-0.098	18.6	-0.225
100 (cities and forests)	7.37	-0.0957	4.29×10^{3}	-0.60
400 (cities with tall buildings)	11.7	-0.128	4.59×10^{4}	-0.78

- a surface roughness of 40 cm is the default value
- if actual wind roses are used, then K should be calculated for each sector by substituting appropriate value of f_j and n.
- the actual stack height can be used in most cases.

Average Dilution Factors

the standard provides graphs of the long-term average dilution factors for typical Canadian conditions calculated utilizing the provided default values. These are shown in the figure below.

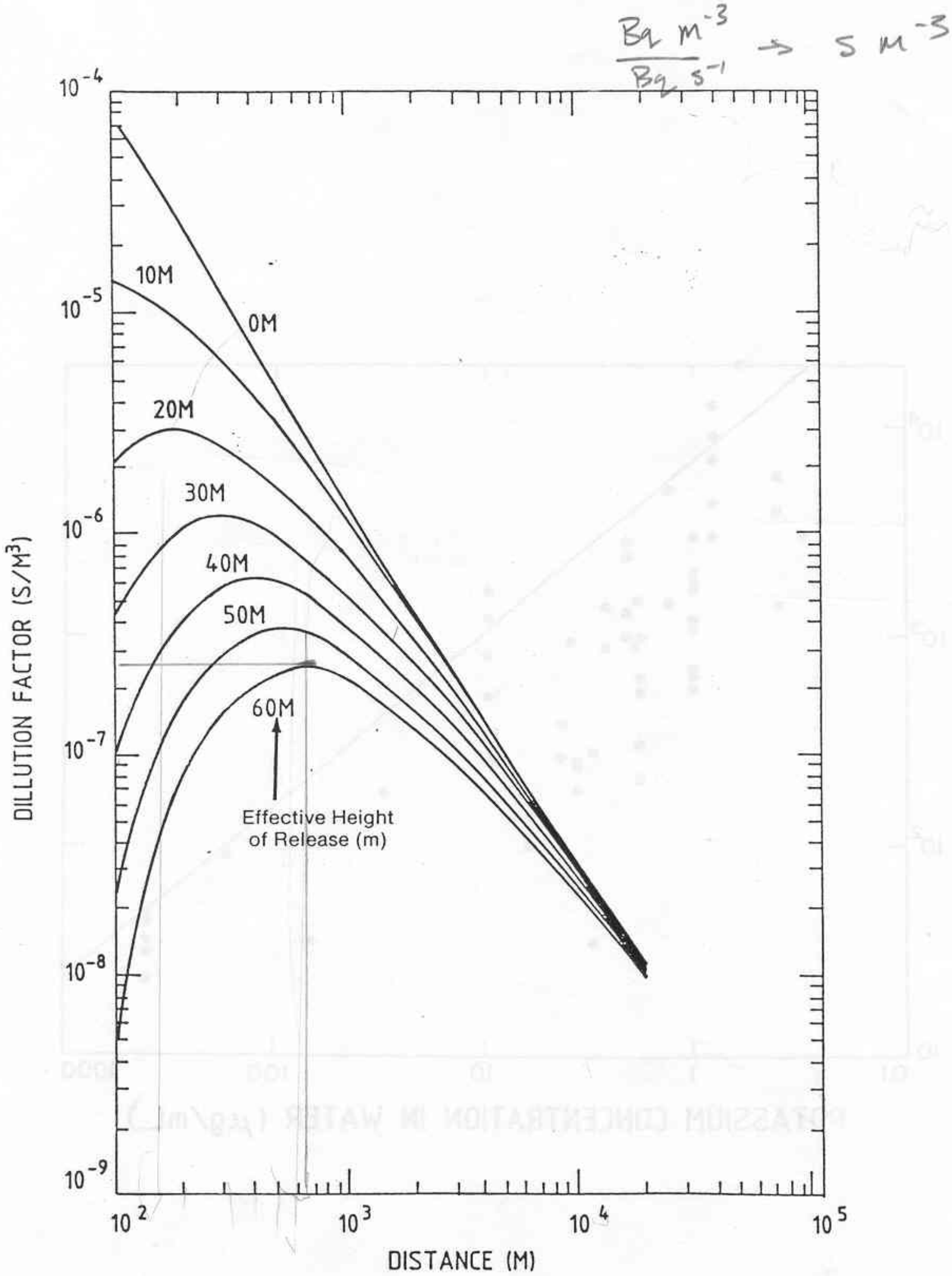


Figure A1
Long-Term Average Dilution Factors for Typical Canadian Weather and Uniform Wind Rose

Deposition on Vegetated Soil

Other exposure pathways for airborne contamination that must be considered arise from fallout onto vegetated soil and crops and intakes by animals leading to dose by external exposure and internal exposure through ingestion of contaminated crops and animal produce. The standard provides tables of the relevant transfer parameters (P_{13}, P_{14}, P_{34}, P_{45}) to be used in conjunction with data on the critical group's consumption habits.