Fuel Failure Addendum 160229

Assumptions

Regulatory Guide 1.183 provides assumptions that are acceptable to NRC for evaluating a fuel failure accident in a light water reactor. Of the postulated accidents leading up to fuel failure, the fuel handling accident is somewhat analogous to the type of fuel failure postulated for RINSC. The assumptions that are made for the analysis are:

1. One plate in an element is damaged to such an extent that total cladding integrity is lost. and that volatile fission products are completely available to for release to the primary coolant.
2. The reactor has been operated long enough for the fission product inventory to reach saturation.
3. Based on the assumptions accepted in Regulatory guide 1.183:

   A. Noble gases are unaffected by the pool water.
   B. The pool water retains 99.5% of the radioiodines that are released.
   C. The radioiodines are composed of 45% elemental, and 55% organic species.
   D. Activity released from the pool to confinement air occurs over a two hour period.
   E. All other fission products are retained either in the fuel, or in the pool water.

Source Term

1. Fission Rate

   A. The energy associated with each fission that occurs in the reactor is 200 MeV per fission.

   B. Converting from MeV to MW – Seconds:

$$\left[\frac{200\,MeV}{fission}\right]\left[\frac{1.6\,X\,10^{-13}\,Joule}{MeV}\right]\left[\frac{Watt-Second}{Joule}\right]\left[\frac{MW}{10^{6}\,Watt}\right]$$

   $3.2 \text{ X } 10^{-17}$ MW – second per fission

   C. Therefore the fission rate at 1 MW power is:

   $3.1 \text{ X } 10^{16}$ fission per MW – second

D. The RINSC reactor operates at a maximum power level of 2 MW, so the fission rate at full power operation is:

$$\left[\frac{3.1 X 10^{16} fission}{MW-\mathrm{sec}ond}\right]\left[\frac{2 MW}{1}\right]$$

$6.2 \text{ X } 10^{16}$ fission / second

2. Fission Nuclide Production Rate

A. The fission nuclide production rate for the i th fission product nuclide is the product of the fission rate and the fission product yield (γ_i) for the i th fission product:

Fission Nuclide Production Rate = ($6.2 \text{ X } 10^{16}$ fission / second)(γ_i)

3. Fission Nuclide Decay Rate

A. The fission nuclide decay rate for the i th fission product nuclide is the product of the decay constant for the i th fission product nuclide (λ_i), and the number of atoms of the nuclide that are present in the core (N_i):

Fission Nuclide Decay Rate = (λ_i)(N_i)

4. Fission Product Saturation

A. Fission product saturation occurs when the production rate and decay rate are the same. Therefore, for the i th fission product, saturation is when:

($6.2 \text{ X } 10^{16}$ fission / second)(γ_i) = (λ_i)($N_{i\ sat}$)

B. Therefore, if we wanted to estimate the number of atoms of the i th fission product in the core at saturation, it would be:

$$N_{i\,sat}=\left[\frac{6.2 X 10^{16} fission}{\mathrm{sec}ond}\right]\left[\frac{\gamma_i\, atoms}{fission}\right]\left[\frac{\mathrm{sec}ond}{\lambda_i}\right]$$

C. However, if we want to estimate the activity of the i th fission product in the core at saturation, it would be:

Activity (Bq) = (λ_i)($N_{i\ sat}$) = ($6.2 \text{ X } 10^{16}$ fission / second)(γ_i)

D. The activity can be converted to units of Ci by using the conversion factor:

1 Ci = 3.7 X 10^{10} Bq

E. If we make the simplifying assumption that the activity in the core is evenly spread over all of the fuel plates, the activity per fuel plate would be:

$$\left[\frac{22\,Plates}{Fuel\ Element}\right]\left[\frac{14\,Fuel\ Elements}{Core}\right]=\left[\frac{308\,Plates}{Core}\right]$$

Therefore the activity of the i th fission product per fuel plate is the activity in the core divided by 308 fuel plates

F. As an example, consider I-131 saturation in the core, which has a yield of γ = 0.0277 atoms per fission, and a decay constant of λ = 9.98 X 10^{-7} per second:

1. Saturation Activity in the Core:

$$\left[\frac{6.2\,X\,10^{16}\ fission}{\mathrm{sec}ond}\right]\left[\frac{0.0277I-131atoms}{fission}\right]$$

= 1.7 X 10^{15} I-131 atoms per second

= 1.7 X 10^{15} Bq I-131

$$\left[\frac{1.7X\,10^{15}\,Bq\,I-131}{1}\right]\left[\frac{Ci}{3.7\,X\,10^{10}\,Bq}\right]$$

= 4.64 X 10^{4} Ci

2. Saturation Activity in a Fuel Plate:

$$\left[\frac{4.64\,X\,10^{4}\,Ci}{Core}\right]\left[\frac{Core}{308\,Fuel\ Plates}\right]$$

= 1.51 X 10^{2} Ci per fuel plate

G. Most of the fission products do not get out of the fuel matrix. Of the isotopes that get into the pool water, there is so much solvent in comparison to solute that the vast majority of the isotopes would stay dissolved in the pool water. Lamarsh, *Introduction to Nuclear*

Engineering, Addison-Wesley Publishing Company, 1977, P. 535 provides a list of the fission products that are both volatile and long lived enough to potentially escape from the fuel matrix to the pool, as well as the decay constants and cumulative fission yields of each of those isotopes:

Total Source Term					
Nuclide	Decay Constant (/s)	Fission Yield (Atoms/Fission)	Core Activity (Bq)	Core Activity (Ci)	Single Plate Activity (Ci)
I-131	9.98E-07	0.0277	1.72E+15	4.64E+04	1.51E+02
I-132	8.44E-05	0.0413	2.56E+15	6.92E+04	2.25E+02
I-133	9.26E-06	0.0676	4.19E+15	1.13E+05	3.68E+02
I-134	2.21E-04	0.0718	4.45E+15	1.20E+05	3.91E+02
I-135	2.87E-05	0.0639	3.96E+15	1.07E+05	3.48E+02
Kr-85m	4.38E-05	0.0133	8.25E+14	2.23E+04	7.24E+01
Kr-85	2.04E-09	0.00285	1.77E+14	4.78E+03	1.55E+01
Kr-87	1.52E-04	0.0237	1.47E+15	3.97E+04	1.29E+02
Kr-88	6.90E-05	0.0364	2.26E+15	6.10E+04	1.98E+02
Xe-133m	3.55E-06	0.00189	1.17E+14	3.17E+03	1.03E+01
Xe-133	1.52E-06	0.0677	4.20E+15	1.13E+05	3.68E+02
Xe-135m	7.36E-04	0.0105	6.51E+14	1.76E+04	5.71E+01
Xe-135	2.09E-05	0.0672	4.17E+15	1.13E+05	3.66E+02

Note that the fission yields are cumulative, and include not only the yield of the nuclide, but also take into account the yields of the short lived precursors as well.

A conservative assumption is made that all of the available activity escapes into the pool water.

Release Fractions

NRC Regulatory Guide 1.183 July 2000 Appendix B Section 2 indicates that if the pool water depth over the fuel is greater than or equal to 23 feet, the release fractions from the pool water to the confinement air are:

1. Iodine 0.5%
2. Noble Gases 100%

If we continue with our I-131 example:

1. We concluded that there was 1.51 X 10^2 Ci of I-131 per fuel plate.

2. The noble gas activity in the confinement air is 100% of the total fission plate inventory, and the iodine activity is 0.5% of the concentration of the total fission plate inventory. Therefore, the I-131 activity that escapes from the fuel plate, is not retained in the pool water, and reaches the confinement air is:

(0.5%)(1.51 X 10^2 Ci of I-131)

= (0.005)(1.51 X 10^2 Ci of I-131)

= 7.54 X 10^{-1} Ci of I-131

Confinement Building

A negative pressure is maintained in the confinement building so that all of the air that exits the buiding will exit through a stack. If an airborne RAM release is detected, the Emergency Air Handling System is activated, and the airflow is directed through an emergency filter prior to reaching the stack.

During facility re-licensing, the volume of the confinement building was determined to be approximately 203,695 cubic feet. The volume of the pool structure and water was determined to be 21,740 cubic feet, leaving 181,955 cubic feet of open space. The control room takes up about 3,612 cubic feet of this space. Converting the free volume of the confinement room to cubic centimeters:

$$\left[\frac{181955\,ft^3}{1}\right]\left[\frac{(12\,in)^3}{ft^3}\right]\left[\frac{(2.54\,cm)^3}{(in)^3}\right]=5.15\,X\,10^9\,cm^3$$

Total Concentration of RAM in the Confinement Air

If we assume that the total quantity of RAM that reaches the confinement air is spread uniformly throughout confinement, The concentration of each nuclide in the confinement building air would be:

(μCi of Nuclide in Confinement) / (5.15 X 10^9 cm^3) = μCi / cm^3

If we continue with our I-131 example:

1. We concluded that there was 7.54 X 10^{-1} Ci released to the confinement air.
2. Therefore, the concentration of I-131 inside the confinement building is:

   (7.54 X 10^{-1} Ci) / (5.15 X 10^9 cm^3) = 1.46 X 10^{-10} Ci / cm^3

   1.46 X 10^{-10} Ci / cm^3) (1 X 10^6 μCi / Ci) = 1.46 X 10^{-4} μCi / cm^3

Therefore, the average concentration of each of the major nuclides would be:

Total Release to Confinement Air				
Nuclide	**Single Plate Activity (Ci)**	**Release to Confinement (Ci)**	**Release to Confinement (microCi)**	**Confinement Concentration (microCi / cc)**
I-131	1.51E+02	7.54E-01	7.54E+05	1.46E-04
I-132	2.25E+02	1.12E+00	1.12E+06	2.18E-04
I-133	3.68E+02	1.84E+00	1.84E+06	3.57E-04
I-134	3.91E+02	1.95E+00	1.95E+06	3.79E-04
I-135	3.48E+02	1.74E+00	1.74E+06	3.38E-04
Kr-85m	7.24E+01	7.24E+01	7.24E+07	1.41E-02
Kr-85	1.55E+01	1.55E+01	1.55E+07	3.01E-03
Kr-87	1.29E+02	1.29E+02	1.29E+08	2.50E-02
Kr-88	1.98E+02	1.98E+02	1.98E+08	3.85E-02
Xe-133m	1.03E+01	1.03E+01	1.03E+07	2.00E-03
Xe-133	3.68E+02	3.68E+02	3.68E+08	7.15E-02
Xe-135m	5.71E+01	5.71E+01	5.71E+07	1.11E-02
Xe-135	3.66E+02	3.66E+02	3.66E+08	7.10E-02

Confinement Concentration after 5 Minutes

The total activity that is released into the confinement air from the pool is not released all at once. NRC Regulatory Guide 1.183 July 2000 Appendix B Section 4 indicates that it is acceptable to assume that this activity is released over a two hour period. If an assumption is made that the activity is released at a uniform rate, the concentration build-up rate inside confinement would be:

(microCi / cc) / (120 minutes) = microCi / cc-min

Continuing with the I-131 example:

(1.46E-04) / (120 minutes) = 1.23E-06 microCi / cc-minute

Facility evacuation drills have shown that confinement can be evacuated within five minutes of the occurrence of an event. If we make the conservative assumption that none of the activity is released from confinement for the first five minutes, the concentration inside confinement would be:

(microCi / cc-min)(5 min) = microCi / cc

Continuing with the I-131 example:

(1.23E-06 microCi / cc-min)(5 min) = 6.25E-06 microCi / cc

Therefore, the concentrations of the isotopes of interest after five minutes are:

Confinement Concentration after 5 Minutes			
Nuclide	Confinement Concentration microCi / cc	Confinement Concentration Build-Up Rate microCi / cc-min	Confinement Concentration After 5 Minutes microCi / cc
I-131	1.46E-04	1.22E-06	6.10E-06
I-132	2.18E-04	1.82E-06	9.09E-06
I-133	3.57E-04	2.98E-06	1.49E-05
I-134	3.79E-04	3.16E-06	1.58E-05
I-135	3.38E-04	2.81E-06	1.41E-05
Kr-85m	1.41E-02	1.17E-04	5.85E-04
Kr-85	3.01E-03	2.51E-05	1.25E-04
Kr-87	2.50E-02	2.09E-04	1.04E-03
Kr-88	3.85E-02	3.20E-04	1.60E-03
Xe-133m	2.00E-03	1.66E-05	8.32E-05
Xe-133	7.15E-02	5.96E-04	2.98E-03
Xe-135m	1.11E-02	9.24E-05	4.62E-04
Xe-135	7.10E-02	5.92E-04	2.96E-03

Emergency Filter

When the Emergency Air Handling System is activated, all of the air from the confinement room is exhausted through an emergency filter. The emergency filter consists of:

1. Roughing Filter
2. HEPA Filter
3. Charcoal Filter
4. HEPA Filter

The proposed Technical Specifications associated with the Emergency Filter efficiency are:

3.5.2.3 The emergency filter shall be at least 99% efficient at removing iodine.

3.5.2.4 The Emergency Filter System Exhaust Absolute Filter shall be certified by the manufacturer to have a minimum efficiency of 99.97% for removing 0.3 micron diameter particulates.

Therefore:

1. The concentration of airborne particles that are 0.3 microns or greater in the confinement room that will reach the stack is:

   (0.03%)(0.03%)(Confinement Concentration)

   = (0.0009%)(Confinement Concentration)

   = (0.00009)(Confinement Concentration)

= (9 X 10^{-5})(Confinement Concentration)

2. The concentration of iodine in the confinement room that will reach the stack is:

   (1%)(Confinement Concentration)

   = (0.01)(Confinement Concentration)

3. The noble gases are unaffected by the HEPA filters, but are slowed by the charcoal filter. We will assume that all of the noble gases are released to the stack.

4. If we continue with our I-131 example:

   A. We concluded that there the concnetration of I-131 in confinement was 1.46E-4 μCi / cm^3 in the confinement air.

   B. Therefore, the concentration of I-131 that is exhausted from the emergency air filter and reaches the stack is:

      (0.01)(1.46E-4 μCi / cm^3) = 1.46E-6 μCi / cm^3

Concentration of RAM in the Emergency Air Filter Exhaust

If we assume that the fraction of the iodine that is exhausted by the emergency filter is 0.01, and that all of the noble gases make it through the filter, the concentrations of RAM that reach the building exhaust stack are:

Release to Stack			
Nuclide	**Confinement Concentration (microCi / cc)**	**Emergency Air Filter Release Fraction**	**Emergency Air Filter Exhaust Concentration (microCi / cc)**
I-131	1.46E-04	1.00%	1.46E-06
I-132	2.18E-04	1.00%	2.18E-06
I-133	3.57E-04	1.00%	3.57E-06
I-134	3.79E-04	1.00%	3.79E-06
I-135	3.38E-04	1.00%	3.38E-06
Kr-85m	1.41E-02	100%	1.41E-02
Kr-85	3.01E-03	100%	3.01E-03
Kr-87	2.50E-02	100%	2.50E-02
Kr-88	3.85E-02	100%	3.85E-02
Xe-133m	2.00E-03	100%	2.00E-03
Xe-133	7.15E-02	100%	7.15E-02
Xe-135m	1.11E-02	100%	1.11E-02
Xe-135	7.10E-02	100%	7.10E-02

RAM Release Rate

Based on empirical data, when the Emergency Air Handling System is running, the average air flow rate out of the confinement building and through the emergency filter is:

Year	Clean-Up Blower Flow Rate (cfm)
2008	643
2009	1487
2010	1397
2011	775
2012	968
Average	1054

$$\left[\frac{1054\ ft^3}{\min}\right]\left[\frac{(12\,in)^3}{ft^3}\right]\left[\frac{(2.54\,cm)^3}{(in)^3}\right]\left[\frac{\min}{60\,s}\right]=4.97\ X\ 10^5\ \ cm^3/s$$

Despite the fact that there is a dilution blower, it is irrelevant because we are interested in the RAM release rate rather than the concentration that is being released from the stack.

Consequently, the release rate of the RAM from the stack is:

$$\left[\frac{Emergency\ Filter\ \ Exhaust\ Concentration\ \mu Ci}{cm^3}\right]\left[\frac{Emergency\ Filter\ \ Exhaust\ Flowrate\ cm^3}{s}\right]=\frac{\mu Ci}{s}$$

Continuing with the I-131 example, the concentation of I-131 in the emergency filter exhaust was 9.19 X 10^{-10} μCi / cm^3, so the I-131 release rate is:

$$\left[\frac{1.46\ X\ 10^{-6}\ \ \mu Ci}{cm^3}\right]\left[\frac{4.97\ X\ 10^5\ \ cm^3}{s}\right]=7.27\ X\ 10^{-1}\ \ \mu Ci/s$$

Overall:

Stack RAM Release Rate				
Nuclide	Release to Confinement Air (micro Ci)	Confinement Air Concentration (micro Ci / cc)	Emergency Air Filter Exhaust Concentration (micro Ci / cc)	Stack RAM Release Rate (micro Ci / s)
I-131	7.54E+05	1.46E-04	1.46E-06	7.27E-01
I-132	1.12E+06	2.18E-04	2.18E-06	1.08E+00
I-133	1.84E+06	3.57E-04	3.57E-06	1.77E+00
I-134	1.95E+06	3.79E-04	3.79E-06	1.88E+00
I-135	1.74E+06	3.38E-04	3.38E-06	1.68E+00
Kr-85m	7.24E+07	1.41E-02	1.41E-02	6.98E+03
Kr-85	1.55E+07	3.01E-03	3.01E-03	1.50E+03
Kr-87	1.29E+08	2.50E-02	2.50E-02	1.24E+04
Kr-88	1.98E+08	3.85E-02	3.85E-02	1.91E+04
Xe-133m	1.03E+07	2.00E-03	2.00E-03	9.92E+02
Xe-133	3.68E+08	7.15E-02	7.15E-02	3.55E+04
Xe-135m	5.71E+07	1.11E-02	1.11E-02	5.51E+03
Xe-135	3.66E+08	7.10E-02	7.10E-02	3.53E+04

Atmospheric Dispersion

q

The assumptions made for release to the atmosphere are:

1. Conditions are Pasquill Type F
2. Wind speed is one meter per second
3. Wind direction is constant over the entire duration of the release

Conditions are assumed to be Pasquill Type F. Atmospheric stability is a measure of the turbulence in the plume, and it affects the rate of dispersion of the plume. The more turbulent the air is, the greater the dispersion rate. There are six classifications of atmospheric stability, ranging from Pasquill Type A through Pasquill Type F, in which A is extremely unstable, and F is moderately stable. Consequenly, the assumption of Pasquill Type F is conservative because it minimizes the dispersion rate, and maximizes the airborne RAM concentrations at ground level.

The wind speed is assumed to be one meter per second. Higher wind speeds increase dilution because the RAM released per unit time is added to a larger volume of air passing by the release point. Consequently, this assumption is conservative.

Wind direction is assumed to be constant, As a result, all of the concentration of RAM will be along one line of direction, rather than dispersed across more than one direction. Consequently, this assumption is conservative.

Atmoshperic dispersion calculations estimate the concentration of some material in air for a given release rate, under specified atmospheric conditions, at some distance away from the source. A Gaussian Straight Line Plume Model is used. Section 1.3.2 of NRC Regulatory Guide 1.145 (November 1982 Rev. 1) indicates that the equation for stack releases under nonfumigation conditions is:

$$\frac{\chi}{Q}=\frac{1}{\pi\sigma_y\sigma_z u_h}e^{\left[\frac{-h_e^2}{2\sigma_z^2}\right]}$$

Where:

1. X is the concetration of the material in the air (Activity / Volume)
2. Q is the material release rate (Activity / Time)
3. σ_y is the horizontal dispersion coefficient (Distance)
4. σ_z is the vertical dispersion coefficient (Distance)
5. h_s is the stack height above the plant grade (Distance)
6. h_t is the maximum terrain height above plant grade between the release point, and the point of interest (Distance)
7. h_e is the effective stack height = $h_s - h_t$ with $h_e = 0$ if $h_t > h_s$ (Distance)
8. u_h is the average wind speed of the plume at the release height (Distance / Time)
9. t is the plume travel time to the point of interest (Time)
10. x is the downwind distance (Distance)
11. y is the horizontal distance at right angles to the plume centerline (Distance)
12. z is the height above the ground (Distance)

The release is at the level of the stack (h_s = 115 ft), with no significant change in terrain height between the release point and the site boundary (h_t = 0), so the effective stack height is:

$h_e = h_s - h_t = 35\text{m} = 0 = 115$ ft

= (115 ft)(12 in / ft)(2.54 cm / in)(m / 100 cm)

= 35 m

The minimum distance between the reactor core and the site boundary is 48 meters. RINSC has the authority to prevent the public from entering this boundary. Consequently, we are interested in the concentration at 48 meters from the source. The dispersion coefficients take this distance into account.

The dispersion coefficents are quantitative measures of how much the plume has spread out in the horizontal (y) and vertical (z) directions. The material concentration in the plume as a function of distance from the plume centerline is a Gaussian distribution, with maximum concentration at the centerline. The dispersion coeficients are the standard deviations in each direction. Therefore, 68% of the plume is within σ_y distance form the centerline in the y – direction, and σ_z distance from the centerline in the z – direction. Based on dispersion coefficient curves given in the US Atomic Energy Commission's

”Meteorology and Atomic Energy, 1968“, pp. 102 – 103 for Pasquill Type F conditions, the dispersion coeficients for a point 48 meters from the source are:

METEOROLOGY AND ATOMIC ENERGY—1968

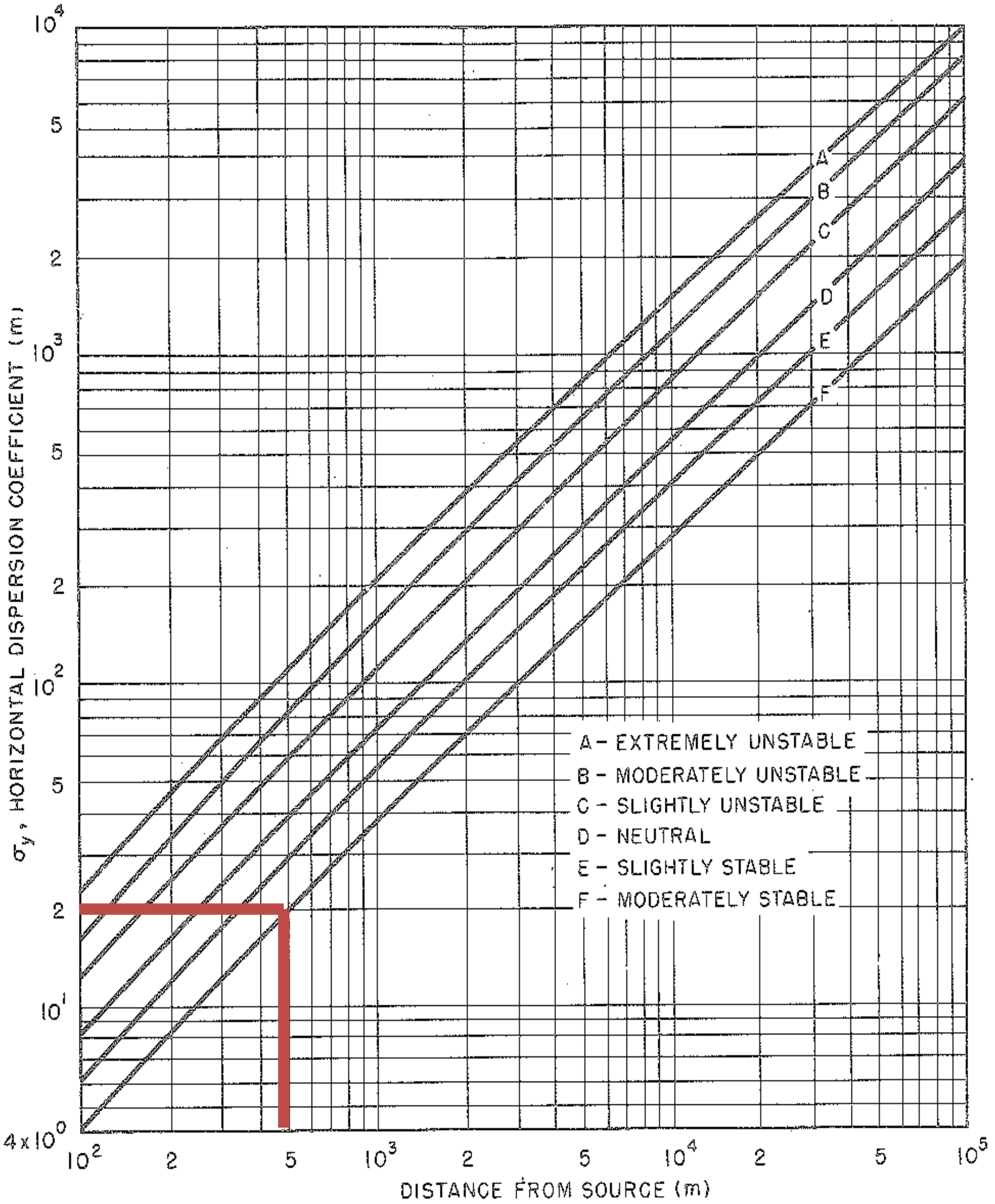

Fig. 3.10—Lateral diffusion, σ_y, vs. downwind distance from source for Pasquill’s turbulence types.

Therefore, at 48 meters, σ_y = 2.0 meters.

DIFFUSION IN THE LOWER LAYERS OF THE ATMOSPHERE

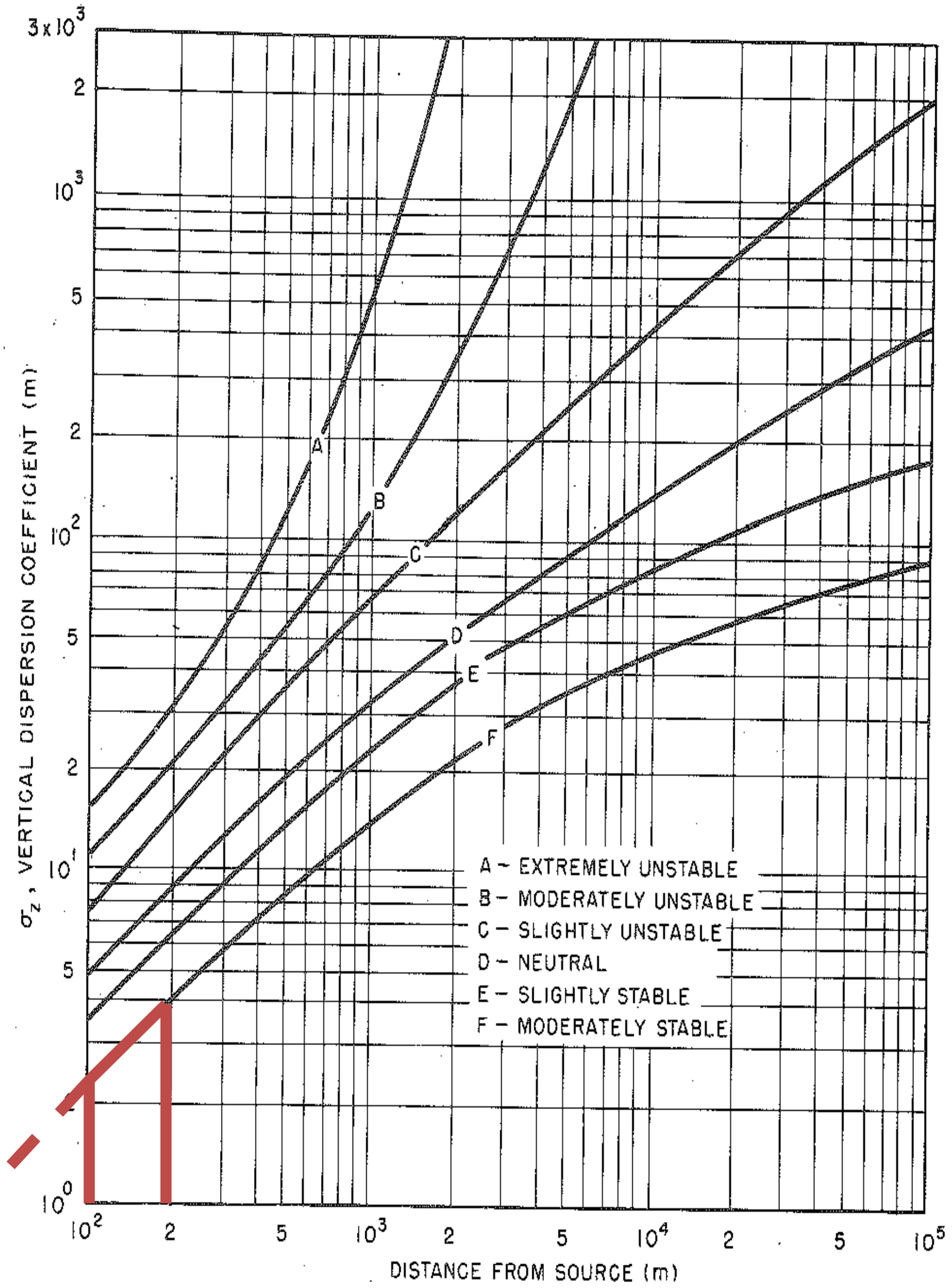

Fig. 3.11—Vertical diffusion, σ_z, vs. downwind distance from source for Pasquill's turbulence types.

Using linear extrapolation to determine what σ_z would be at 48 meters:

For curve F on the graph, two data points are:

$x_1 = 100$ m	$y_1 = 2.4$ m
$x_2 = 200$ m	$y_2 = 4$ m

The slope of the line is:

$$m = \frac{(y_2 - y_1)}{(x_2 - x_1)} = \frac{(4\,m - 2.4\,m)}{(200\,m - 100\,m)} = \frac{1.6\,m}{100\,m} = 0.016$$

The point – slope form of the line is:

$(y_2 - y_1) = m(x_2 - x_1)$

The y – intercept occurs at point (0,b):

$(y_2 - b) = m(x_2 - 0)$

$(y_2 - b) = mx_2$

$y_2 - mx_2 = b$

$b = y_2 - mx_2$

$b = (4\text{ m}) - (0.016)(200\text{ m}) = 0.8\text{ m}$

Consequently, the general equation is:

$y = mx + b$

$y = (0.016)\,x + 0.08\text{ m}$

For our case x = 48 m, so σ_z is:

$\sigma_z = y = (0.016)(48\text{ m}) + 0.08\text{ m} = 1.568\text{ m}$

Therefore:

$\sigma_y = 2.0$ meters
$\sigma_z = 1.5$ meters

We are interested in the RAM concentration at ground level (z = 0). The highest concentration will be along the plume centerline (y = 0). Therefore, the equation used to calculate the concentration for only the downwind sector, and for only one wind speed and one stability class is:

$$\frac{\chi}{Q}=\frac{1}{\pi\,\sigma_y\,\sigma_z\,u_h}e^{\left[\frac{-h_e^2}{2\sigma_z^2}\right]} = \frac{1}{\pi(2m)(1.5m)(1\ m/s)}e^{\left[\frac{-(35m)^2}{(2)(1.5m)^2}\right]} = 2.8\ \mathrm{X}\ 10^{-120}\ \mathrm{s/m^3}$$

$$\left[\frac{2.8X10^{-120}\,s}{m^3}\right]\left[\frac{m^3}{(100\,cm)^3}\right]=2.8\,X\,10^{-114}\,s/cm^3$$

This is the factor by which the release rate from the stack is reduced and converted to the concentration at the site boundary.

$$\frac{\chi}{Q} = 2.8\,X\,10^{-114}\,s/cm^2$$

$$\chi\left(\frac{Activity}{cm^3}\right) = \left[\frac{2.8\,X\,10^{-114}\,s}{cm^3}\right]\left[\frac{Q\ Activity}{s}\right] = \left[\frac{2.8\,X\,10^{-114}\,Q\ Activity}{cm^3}\right]$$

The RAM release rate from the stack (Q), is the same as the release rate from the emergnecy filter since the exhaust from the filter goes directly into the stack. The dilution blower increases the volume of air that the RAM is in, but it does not affect the amount of activity that is released as a function of time.

Therefore the concentrations 48 meters down wind (X) is predicted to be:

$(2.8\ \mathrm{X}\ 10^{-114}\ \mathrm{s / cm^3})$(Isotope Release Rate μCi / s) = Concentration $\mu\mathrm{Ci / cm^3}$

Continuing with the I-131 example, the release rate of I-131 from the emergency filter was 7.27E-1 μCi / s, so the concentration of I-131 that is predicted to be 48 meters down wind of the facility is:

$$\left[\frac{7.27\,X\,10^{-1}\,\mu Ci}{s}\right]\left[\frac{2.8\,X\,10^{-114}\,s}{cm^3}\right]=2.03\,X\,10^{-114}\,\mu Ci/cm^3$$

This means that the concentrations of the radionuclides at the site boundary are:

Site Boundary Concentration			
Nuclide	Emergency Air Filter Exhaust Concentration (microCi / cc)	Stack Release Rate (microCi / s)	Site Boundary Concentration (microCi / cc)
I-131	1.46E-06	7.27E-01	2.05E-114
I-132	2.18E-06	1.08E+00	3.05E-114
I-133	3.57E-06	1.77E+00	5.00E-114
I-134	3.79E-06	1.88E+00	5.31E-114
I-135	3.38E-06	1.68E+00	4.72E-114
Kr-85m	1.41E-02	6.98E+03	1.97E-110
Kr-85	3.01E-03	1.50E+03	4.21E-111
Kr-87	2.50E-02	1.24E+04	3.50E-110
Kr-88	3.85E-02	1.91E+04	5.38E-110
Xe-133m	2.00E-03	9.92E+02	2.79E-111
Xe-133	7.15E-02	3.55E+04	1.00E-109
Xe-135m	1.11E-02	5.51E+03	1.55E-110
Xe-135	7.10E-02	3.53E+04	9.93E-110

Dose Calculation Background Information

Health effects of radiation dose are separated into two categories:

A. Stochastic Effects – These effects are probabilistic, and are due to random ionization events. Consequently, there is no threshold for these effects, and the probability of occurrence is proportional to the dose received. Cancer is an example of these types of effects.

B. Non-Stochastic Effects – These effects depend on the amount of dose received beyond a minimum threshold, and the amount of damage depends on the magnatude of the dose. Skin erythmia is an example of a non-stochastic effect.

The objective of dose limits are to minimize the risk of stochastic effects, and to prevent the occurrence of non-stochastic effects. The dose limits have been designed to be independent of whether or not the radiation dose is uniform or non-uniform. This is achieved by having “effective dose“ limits in which the “effective dose“ takes into consideration the risk due to the irradiation of each individual organ and equates it to the risk associated with a uniform irradiation of the whole body.

Important definitions that can be found in 10 CFR 20:

A. Allowable Limit on Intake (ALI) – This is the amoung of RAM taken into the body via ingestion or inhalation that would lead to a committed effective dose equivalent of 5 Rem, or 50 Rem to any individual tissue or organ.

B. Derived Air Concentration (DAC) – This is the concentration of a given radionuclide in air which if inhaled at a rate of 2 X 10^4 cm^3 per minute for one working year (2000 hours) would result in reaching the ALI.

Therefore, as an example, I-131 has a DAC = 2 X 10^{-8} μCi / cm^3 and an ALI = 50 μCi so the relationship between ALI and DAC is:

$$ALI = \left[\frac{2\,X\,10^{-8}\ \mu Ci}{cm^3}\right]\left[\frac{2\,X\,10^{4}\ cm^3}{\min}\right]\left[\frac{60\min}{hr}\right]\left[\frac{2000\,hr}{1}\right] = 48\,\mu Ci \approx 50\,\mu Ci$$

This means that if the reference man were to breath in the DAC for 2000 hours, at a rate of 2 x 10^4 μCi / minute, then they will have an uptake equivalent to the ALI.

C. Derived Air Concentration - Hour (DAC - Hour) –This is the product of the concentration of RAM in the air expressed as a fraction or multiple of the DAC, and the exposure time expressed in hours.

D. Absorbed Dose (D) – This is a measure of the radiation energy that is absorbed per unit mass of material of interest.

E. Dose Equivalent (H) – This is the product of the absorbed dose in tissue, quality factor (Q), and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv). In general:

H = DQ

F. Quality Factor (Q) – This is a regulatoraly defined factor to account for the fact that the type and energy of the incident radiation has an effect on the amount of biological damage that is produced per unit of absorbed energy (absorbed dose).

G. Tissue Dose Equivalent (H_T) – This is the dose equivalent to a specific tissue or organ due to external sources.

H. Committed Dose Equivalent ($H_{T,50}$) – This is the dose equivalent to organs or tissues of reference (T) that will be received from a single intake of radioactive material by an individual that will be accumulated over the 50-year period following the intake.

I. Effective Dose Equivalent (H_E) – This equates the risk of a non-uniform external dose, or internal dose to the risk associated with a dose that is distributed uniformly over the whole body. A regulatoraly defined weighting factor (W_T) is used for each organ, and the overall effective dose equivalent is:

$H_E = \Sigma\, W_T H_T$

This is the sum of the products of the dose equivalent to the organ or tissue (H_T) and the weighting factors (W_T) applicable to each of the body organs or tissues that are irradiated ($H_E = \Sigma W_T H_T$).

J. Committed Effective Dose Equivalent ($H_{E,50}$) – This is the effective dose equivalent accumulated over a 50 year period as a result of a single intake of radioactive material. In general:

$$H_{E,50} = \Sigma W_T H_{T,50}$$

This is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues ($H_{E,50} = \Sigma W_T H_{T,50}$).

K. Deep Dose Equivalent (DDE) – This is the whole body dose at a depth of 1 cm due to an external exposure.

L. Total Effective Dose Equivalent (TEDE) – This is the sum of the DDE due to an external dose, and the CEDE due to an internal dose from an intake of radioactive material. In general:

TEDE = DDE + CEDE

Regulatory Limits

Regulatory limits on dose are defined in 10 CFR 20:

Occupational Dose Limits

A. TEDE = 5 rem / yr [10 CFR 20.1201(a)(1)(i)]
B. DDE + CDE to any individual organ or tissue = 50 rem / yr [10 CFR 20.1201(a)(1)(ii)]
C. The DAC and ALI may be used to determine the individual's dose and to demonstrate compliance with dose limits. [10 CFR 20.1201(d)]
D. If the only intake of radionuclides is by inhalation, the total effective dose equivalent limit is not exceeded if the sum of the deep-dose equivalent divided by the total effective dose equivalent limit, and one of the following, does not exceed unity [10 CFR 20.1202(b)]:

    (1) The sum of the fractions of the inhalation ALI for each radionuclide, or
    (2) The total number of derived air concentration-hours (DAC-hours) for all radionuclides divided by 2,000, or
    (3) The sum of the calculated committed effective dose equivalents to all significantly irradiated[1] organs or tissues (T) calculated from bioassay data using appropriate biological models and expressed as a fraction of the annual limit.

E. If the identity and concentration of each radionuclide in a mixture are known, the fraction of the DAC applicable to the mixture for use in calculating DAC-hours must be either [10 CFR 20.1204(e)]:

  (1) The sum of the ratios of the concentration to the appropriate DAC value (e.g., D, W, Y) from appendix B to part 20 for each radionuclide in the mixture; or
  (2) The ratio of the total concentration for all radionuclides in the mixture to the most restrictive DAC value for any radionuclide in the mixture.

F. In order to calculate the committed effective dose equivalent, the licensee may assume that the inhalation of one ALI, or an exposure of 2,000 DAC-hours, results in a committed effective dose equivalent of 5 rems (0.05 Sv) for radionuclides that have their ALIs or DACs based on the committed effective dose equivalent. [10 CFR 20.1204(h)(1)]

G. When the ALI (and the associated DAC) is determined by the nonstochastic organ dose limit of 50 rems (0.5 Sv), the intake of radionuclides that would result in a committed effective dose equivalent of 5 rems (0.05 Sv) (the stochastic ALI) is listed in parentheses in table 1 of appendix B to part 20. In this case, the licensee may, as a simplifying assumption, use the stochastic ALIs to determine committed effective dose equivalent. However, if the licensee uses the stochastic ALIs, the licensee must also demonstrate that the limit in § 20.1201(a)(1)(ii) is met. [10 CFR 20.1204(h)(2)]

Dose Limits for Individual Members of the Public

A. TEDE = 100 mrem / yr [10 CFR 20.1301(a)(1)]
B. A licensee shall show compliance with the annual dose limit in § 20.1301 by [10 CFR 20.1302(b)]:

  (1) Demonstrating by measurement or calculation that the total effective dose equivalent to the individual likely to receive the highest dose from the licensed operation does not exceed the annual dose limit; or
  (2) Demonstrating that:

    (i) The annual average concentrations of radioactive material released in gaseous and liquid effluents at the boundary of the unrestricted area do not exceed the values specified in table 2 of appendix B to part 20; and
    (ii) If an individual were continuously present in an unrestricted area, the dose from external sources would not exceed 0.002 rem (0.02 mSv) in an hour and 0.05 rem (0.5 mSv) in a year.

Therefore, based on the regulations, we must show that:

A. The occupational doses to individuals inside confinement are no greater than:

   1. TEDE = 5 rem
   2. DDE + CDE to any individual organ or tissue = 50 rem / yr

B. The dose to the public at the site boundary is no greater than:

   1. TEDE = 100 mrem / yr

External Immersion Dose vs. Internal Dose

For the fuel failure accident we are concerned about the doses that individuals will recieve due to airborne radioactive materials. The airborne RAM that is released in these types of accidents consist of halogens, such as iodine, and noble gases, such as xenon and krypton.

When halogens are inhaled, part of what is inhaled is taken up and incorporated into the body. Consequently, these isotopes cause not only an external immersion dose, but also a committed internal dose.

Noble gases are inert, so when they are inhaled, they are not taken up and incorporated into the body. Consequently, these isotopes only cause an external immersion dose and do not contribute to an internal dose.

During a fuel failure accident, the principle halogen that is released as an airborne RAM source is iodine. When iodine is uptaken into the body, it concentrates in the thyroid. As a result, the internal dose associated with a fuel failure accident would be the Committed Dose Equivalent ($H_{T,50}$) to the thyroid due to iodine.

During a fuel failure accident, the principle noble gases that are released as airborne RAM sources are krypton and xenon. These isotopes, in addition to the iodine isotopes are the are the sources for the external immersion dose. As a result, the external immersion dose that is associated with a fuel failure accident is the Deep Dose Equivalent (DDE) to the whole body due to the iodine, krypton, and xenon isotopes.

Use of the DAC to determine the Deep Dose Equivalent (DDE)

The DAC for any given nuclide can be found in 10 CFR 20 Appendix B. For Kr-85, the inhalation value of the DAC for occupational exposure are given to be:

A. DAC = 1 X 10^{-4} μCi / cm^3

   This means that if an individual is immersed in a concentration of 1 X 10^{-4} μCi / cm^3 Kr-85 for 2000 hours, they would receive a DDE of 5 Rem whole body.

If and individual is immersed in an air concentration equivalent to one DAC, the average dose rate that they would be receiving would be:

A. Whole Body:

$$\left[\frac{5\,rem}{(2000\,hr)}\right] = 2.5\,mrem/hr$$

Since this is the dose rate that is associated with an airborne RAM concentration of one DAC, we can relate the dose rate associated with being immersed in an airborne RAM concentration of one DAC by:

$$\left[\frac{2.5\ mrem\ per\ hr}{DAC}\right] = 2.5\ mrem/DAC - hr$$

We can express the concentration of any RAM in air as a fraction or multiple of the DAC:

DAC Fraction (Multiple) = (Air Concentration) / (DAC)

Therefore, if we had a concentration of 1.25 X 10^{-4} µCi / cm^3 of Kr-85 in the confinement air (the confinement concentration after 5 minutes), the DAC fraction (multiple) if the occupational DAC were 1 X 10^{-4} µCi / cm^3 would be:

DAC Fraction (Multiple) = (Air Concentration) / (DAC)

$$= \left[\frac{1.25\ X\ 10^{-4}\ \mu Ci}{cm^3}\right]\left[\frac{Kr-85\ DAC}{1\ X\ 10^{-4}\ \mu Ci/cm^3}\right]$$

= 1.25 DAC

If we know the concentration of RAM in air as a fraction or multiple of the DAC, then we can determine the dose rate that that an individual immersed in the air would recieve. Continuing with the Kr-85 example:

$$\left[\frac{2.5\,mrem}{DAC-hr}\right]\left[\frac{1.25\ DAC}{1}\right] = 3.125\,mrem/hr$$

For a mixture of airborne radionuclides, the total dose rate can be determined either by summing the individual DAC fractions and multiplying the sum by the dose rate per DAC - hr:

$$\left[\frac{2.5\,mrem}{DAC-hr}\right]\left[\frac{\sum DAC\ Fractions}{1}\right] = Total\ Dose\,Rate\ \ (mrem/hr)$$

Or by finding the dose rate associated with each nuclide and summing the individual dose rates to get the total dose rate:

$$\sum\left[\left(\frac{2.5\ mrem}{DAC-hr}\right)\left(\frac{DAC\ Fraction}{1}\right)\right] = Total\ Dose\ Rate\ (mrem/hr)$$

Consider:

A. Suppose that the air has a concentration of 1.25 X 10^{-4} μCi / cm^3 of Kr-85, and 5.85 X 10^{-4} μCi / cm^3 of Kr-85m in it. The DAC fractions are:

(Air Concentration) / (DAC)

Where the DAC is defined in 10 CFR 20 for each isotope

B. For Kr-85 the DAC fraction has been previously calculated to be 1.25 DAC.

C. For Kr-85m, given that the DAC is 2 X 10^{-5} μCi / cm^3, the DAC fraction is:

(5.85 X 10^{-4} μCi / cm^3) / (2 X 10^{-5} μCi / cm^3) = 29.25 DAC

D. Therefore the total DAC fraction is:

Total DAC Fraction = 1.25 DAC + 29.25 DAC = 30.5 DAC

E. Therefore the deep dose equivalent is:

$$\left[\frac{2.5\,mrem}{DAC-hr}\right]\left[\frac{30.5\ DAC}{1}\right]=76.25\ mrem/hr$$

Confinement Deep Dose Equivalent

Facility evacuation drills show that in the event of an evacuation, the confinement building can be evacuated within 5 minutes. Using the confinement concentration after five minutes, and taking into consideration that individuals inside confinement will only be exposed for five minutes, the projected dose from the gas release for individuals inside confinement when the fuel failure occurs is:

$$\left[\frac{2.5\,mrem}{DAC-hr}\right]\left[\frac{DAC\ Fraction}{1}\right]\left[\frac{5\min}{1}\right]\left[\frac{hr}{60\min}\right]=DDE(mrem)$$

For the isotopes of interest:

Confinement Air Immersion Dose					
Nuclide	**Confinement Concentration (microCi / cc)**	**Occupational DAC (microCi / cc)**	**DAC Fraction**	**Immersion DAC (DAC-hr)**	**Deep Dose Equivalent mrem**
I-131	6.10E-06	2.00E-08	3.05E+02	2.54E+01	6.35E+01
I-132	9.09E-06	3.00E-06	3.03E+00	2.52E-01	6.31E-01
I-133	1.49E-05	1.00E-07	1.49E+02	1.24E+01	3.10E+01
I-134	1.58E-05	2.00E-05	7.90E-01	6.58E-02	1.65E-01
I-135	1.41E-05	7.00E-07	2.01E+01	1.67E+00	4.19E+00
Kr-85m	5.85E-04	2.00E-05	2.93E+01	2.44E+00	6.10E+00
Kr-85	1.25E-04	1.00E-04	1.25E+00	1.05E-01	2.61E-01
Kr-87	1.04E-03	5.00E-06	2.09E+02	1.74E+01	4.35E+01
Kr-88	1.60E-03	2.00E-06	8.01E+02	6.68E+01	1.67E+02
Xe-133m	8.32E-05	1.00E-04	8.32E-01	6.93E-02	1.73E-01
Xe-133	2.98E-03	1.00E-04	2.98E+01	2.48E+00	6.21E+00
Xe-135m	4.62E-04	9.00E-06	5.14E+01	4.28E+00	1.07E+01
Xe-135	2.96E-03	1.00E-05	2.96E+02	2.46E+01	6.16E+01

Therefore, if someone remains in confinement for five minutes, they will receive a dose of:

$\sum$ Individual DDE = 395 mrem

Site Boundary Deep Dose Equivalent

Section 1.3 of NRC Regulatory Guide 1.145 (November 1982 Rev. 1) indicates that a conservative estimation of site boundary doses can be determined by it assuming that an individual spends two hours at the site boundary immediately following an accident. The deep dose equivalent would be the sum of the dose equivalents from each of the isotopes of interest.

For the isotopes of interest:

Site Boundary Air Immersion Dose					
Nuclide	Site Boundary Concentration (microCi / cc)	Occupational DAC (microCi / cc)	DAC Fraction	Immersion DAC (DAC-hr)	Deep Dose Equivalent mrem
I-131	2.05E-114	2.00E-08	1.02E-106	2.05E-106	5.12E-106
I-132	3.05E-114	3.00E-06	1.02E-108	2.04E-108	5.09E-108
I-133	5.00E-114	1.00E-07	5.00E-107	9.99E-107	2.50E-106
I-134	5.31E-114	2.00E-05	2.65E-109	5.31E-109	1.33E-108
I-135	4.72E-114	7.00E-07	6.75E-108	1.35E-107	3.37E-107
Kr-85m	1.97E-110	2.00E-05	9.83E-106	1.97E-105	4.92E-105
Kr-85	4.21E-111	1.00E-04	4.21E-107	8.43E-107	2.11E-106
Kr-87	3.50E-110	5.00E-06	7.01E-105	1.40E-104	3.50E-104
Kr-88	5.38E-110	2.00E-06	2.69E-104	5.38E-104	1.35E-103
Xe-133m	2.79E-111	1.00E-04	2.79E-107	5.59E-107	1.40E-106
Xe-133	1.00E-109	1.00E-04	1.00E-105	2.00E-105	5.00E-105
Xe-135m	1.55E-110	9.00E-06	1.72E-105	3.45E-105	8.62E-105
Xe-135	9.93E-110	1.00E-05	9.93E-105	1.99E-104	4.97E-104

Therefore, if a member of the general public remains at the site boundary for two hours, they will receive a dose of:

$\sum$ Individual DDE = 2.39 X 10^{-103} mrem

Use of the DAC to determine the Committed Dose Equivalent to the Thyroid (CDE)

The ALI and DAC for any given nuclide can be found in 10 CFR 20 Appendix B. For I-131, the inhalation values for occupational exposure are given to be:

A. ALI = 50 μCi

This means that an intake of 50 μCi of I-131 will lead to a CEDE of 5 Rem, or 50 Rem to any individual tissue or organ. Since iodine concentrates in the thyroid, the ALI is based on a dose of 50 Rem to the thyroid.

B. DAC = 2 X 10^{-8} μCi / cm^3

This means that if an individual inhales concentration of 2 X 10^{-8} μCi / cm^3 I-131 at a rate of 2 X 10^4 cm^3 per minute for 2000 hours, they would intake enough of the radionuclide to receive a CEDE of 5 Rem whole body, or 50 Rem to any individual tissue or organ:

If an individual is immersed in an air concentration equivalent to one DAC, the average dose rate that they would be receiving would be:

A. Individual Tissue or Organ (in this case Thyroid):

$$\left[\frac{50\,rem}{2000\,hr}\right] = 25\,mrem/DAC - hr$$

Since this is the dose rate that is associated with an airborne RAM concentration of one DAC, we can relate the dose rate associated with being immersed in an airborne RAM concentration of one DAC by:

$$\left[\frac{25\ mrem\ per\ hr}{DAC}\right] = 25\ mrem/DAC - hr$$

We can express the concentration of any RAM in air as a fraction or multiple of the DAC:

DAC Fraction (Multiple) = (Air Concentration) / (DAC)

Therefore, if we had a concentration of 6.10 X 10^{-6} μCi / cm^3 of I-131 in the confinement air, the DAC fraction (multiple) if the occupational DAC were 2 X 10^{-8} μCi / cm^3 would be:

DAC Fraction (Multiple) = (Air Concentration) / (DAC)

$$= \left[\frac{6.10\ X\ 10^{-6}\ \mu Ci}{cm^3}\right]\left[\frac{I - 131\ DAC}{2\ X\ 10^{-8}\ \mu Ci/cm^3}\right]$$

= 305 DAC

If we know the concentration of RAM in air as a fraction or multiple of the DAC, then we can determine the dose rate that that an individual immersed in the air would recieve. Continuing with the Kr-85 example:

$$\left[\frac{2.5\,mrem}{DAC - hr}\right]\left[\frac{305\ DAC}{1}\right] = 762.5\,mrem/hr$$

If there is more than one nuclide in the air with the same dose rate associated with exposure (either whole body or individual organ), then the DAC fractions can be added together before determining the dose rate. Consider:

A. Suppose that the air has a concentration of 6.10 X 10^{-6} μCi / cm^3 of I-131, and 9.09 X 10^{-6} μCi / cm^3 of I-132 in it. The DAC fractions are:

(Air Concentration) / (DAC)

Where the DAC is defined in 10 CFR 20 for each isotope

B. For I-131 the DAC fraction has been previously calculated to be 305 DAC.

C. For I-132, given that the DAC is 3 X 10^{-6} µCi / cm^3, the DAC fraction is:

(9.09 X 10^{-6} µCi / cm^3) / (3 X 10^{-6} µCi / cm^3) = 3.03 DAC

D. Therefore the total DAC fraction is:

Total DAC Fraction = 305 DAC + 3.03 DAC = 308 DAC

E. For the iodines, the committed dose to the thyroid is also dependent on the amount of time that the individual is immersed. If an individual were only in the concentration of iodine for 5 minutes (0.083 hr), then the DAC fraction can be reduced:

Immersion DAC = (DAC)(Immersion Time)

Immersion DAC = (308 DAC)(0.083 hr) = 25.6 DAC - hr

F. Both of these DACs are based on a committed thyroid dose of 50 rem per year, which means that the dose rate associated with an air concentration of one DAC is 25 mrem / DAC - hr.

E. Therefore the committed dose to the thyroid for an individual that is immersed for 5 minutes in air with a concentration of 6.10 X 10^{-6} µCi / cm^3 of I-131 and 9.09 X 10^{-6} µCi / cm^3 of I-132 would be:

$$\left[\frac{25\,mrem}{DAC-hr}\right]\left[\frac{25.6\ DAC-hr}{1}\right]=639\,mrem$$

Confinement Committed Dose to the Thyroid (CDE)

Halogens are an inhalation hazard because they are absorbed into the body. The halogen of interest in the case of a fuel failure is iodine. Iodine concentrates in the thyroid. Consequently, the DAC for each isotope of Iodine is based on the amount of isotope that will result in a 50 rem dose to the thyroid over a 2000 hour year. We have calculated that an individual immersed in air with a concentration of RAM in it equivalent to one DAC would lead to an internal dose rate of 25 mrem / hr to the thyroid.

Facility evacuation drills show that in the event of an evacuation, the confinement building can be evacuated within 5 minutes. Thererfore the projected dose from the gas release for individuals inside confinement when the fuel failure occurs is:

$$\left[\frac{25\,mrem}{DAC-hr}\right]\left[\frac{DAC\,Fraction}{1}\right]\left[\frac{5\,\min}{1}\right]\left[\frac{hr}{60\,\min}\right]=CDE\,(mrem)$$

For the isotopes of interest:

Confinement Internal Dose					
Nuclide	Confinement Concentration (microCi / cc)	Occupational DAC (microCi / cc)	DAC Fraction	Immersion DAC (DAC-hr)	Committed Dose Equivalent (mrem)
I-131	6.10E-06	2.00E-08	3.05E+02	2.54E+01	6.35E+02
I-132	9.09E-06	3.00E-06	3.03E+00	2.52E-01	6.31E+00
I-133	1.49E-05	1.00E-07	1.49E+02	1.24E+01	3.10E+02
I-134	1.58E-05	2.00E-05	7.90E-01	6.58E-02	1.65E+00
I-135	1.41E-05	7.00E-07	2.01E+01	1.67E+00	4.19E+01

Therefore, if someone remains in confinement for five minutes, they will receive a committed does to the thyroide of:

$\sum$ Individual CDE = 995 mrem

Site Boundary Committed Dose to the Thyroid (CDE)

Section 1.3 of NRC Regulatory Guide 1.145 (November 1982 Rev. 1) indicates that a conservative estimation of site boundary doses can be determined by it assuming that an individual spends two hours at the site boundary immediately following an accident. The deep dose equivalent would be the sum of the dose equivalents from each of the isotopes of interest.

For the isotopes of interest:

Site Boundary Internal Dose					
Nuclide	Site Boundary Concentration (microCi / cc)	Occupational DAC (microCi / cc)	DAC Fraction	Immersion DAC (DAC-hr)	Committed Dose Equivalent mrem
I-131	2.05E-114	2.00E-08	1.02E-106	2.05E-106	5.12E-105
I-132	3.05E-114	3.00E-06	1.02E-108	2.04E-108	5.09E-107
I-133	5.00E-114	1.00E-07	5.00E-107	9.99E-107	2.50E-105
I-134	5.31E-114	2.00E-05	2.65E-109	5.31E-109	1.33E-107
I-135	4.72E-114	7.00E-07	6.75E-108	1.35E-107	3.37E-106

Therefore, if someone remains at the site boundary for two hours, they will receive a committed dose to the thyroid of:

$\sum$ Individual CDE = 8.02 X 10^{-105} mrem

Determination of the Committed Effective Dose Equivalent (CEDE):

The committed dose equivalent (CDE) is the cumulative dose that an individual organ in the body would receive due to the uptake of a radioisotope, over a 50 year period. An effective dose equivalent (H_E) uses a tissue weighting factor (W_T) to equate the risk associated with a non-uniform dose, to the risk associated with a uniformly distributed whole body dose. If the weighting factor is applied to the CDE, then we get the committed effective dose equivalent (CEDE), which provides a measure of what the risk associated with the dose to the individual organ would be if it were evenly distributed in the whole body:

$$\text{CEDE} = (W_T)(\text{CDE})$$

10 CFR 20.2003 Defines the weighting factor (W_T) for the thyroid to be:

$$W_{\text{Thyroid}} = 0.03$$

Confinement Committed Effective Dose Equivalent (CEDE)

The committed dose equivalent (CDE) for an individual that is in confinement for five minutes was found to be 2.39 X 10^4 mrem. Consequently, the CEDE for this individual is:

$$\text{CEDE} = (995 \text{ mrem})(0.03) = 29.9 \text{ mrem}$$

Site boundary Committed Effective Dose Equivalent (CEDE)

The committed dose equivalent (CDE) for an individual that is at the site boundary for two hours was found to be 8.02 X 10^{-105} mrem. Consequently, the CEDE for this individual is:

$$\text{CEDE} = (8.02 \text{ X } 10^{-105} \text{ mrem})(0.03) = 2.41 \text{ X } 10^{-106} \text{ mrem}$$

Determination of the Total Effective Dose Equivalent (TEDE):

The total effective dose equivalent (TEDE) is the sum of the dose due to external sources (DDE) and internal sources (CEDE):

$$\text{TEDE} = \text{DDE} + \text{CEDE}$$

Confinement Total Effective Dose Equivalent (TEDE):

$$\text{TEDE} = 395 \text{ mrem} + 29.9 \text{ mrem} = 425 \text{ mrem}$$

Site Boundary Total Effective Dose Equivalent (TEDE):

$$\text{TEDE} = 2.39 \text{ X } 10^{-103} \text{ mrem} + 2.41 \text{ X } 10^{-106} \text{ mrem} = 2.39 \text{ X } 10^{-103} \text{ mrem}$$

Conclusion

10 CFR 20 provides radiation dose limits to radiation workers, and to the general public. For radiation worker, the limits are:

50 rem / yr to an individual organ (CDE)

5 rem / yr whole body (TEDE)

For members of the general public, the limits are:

100 mrem / yr

The doses that an individual is predicted to receive due to a fuel failure event in which the core has reached saturation activity is based on the following assumptions:

A. Individuals inside confinement recognize the problem and evacuate within five minutes.
B. Individuals that are exposed outside confinement remain at the site boundary for two hours.

In all cases, the predicted doses are well below the regulatory limit. A summary of the predicted doses, and any regulatory limit associated with the dose is:

Dose Summary			**Dose Limits**	
Confinement Dose			Occupational Limits	General Public Limits
	Committed Dose to Thyroid	9.95E+02 mrem	50 rem / yr	
	CEDE	2.98E+01 mrem		
	Immersion	3.95E+02 mrem		
	TEDE	4.25E+02 mrem	5 rem / yr	100 mrem / yr
Site Boundary Dose				
	Committed Dose to Thyroid	8.02E-105 mrem	50 rem / yr	
	CEDE	2.41E-106 mrem		
	Immersion	2.39E-103 mrem		
	TEDE	2.39E-103 mrem	5 rem / yr	100 mrem / yr