Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonized System of Classification and Labelling of Chemicals

Sub-Committee of Experts on the Transport of Dangerous Goods **3 December 2012**

Forty-second session
Geneva, 3 – 11 December 2012
Item 2(b) of the provisional agenda
Recommendations made by the Sub-Committee on its thirty-ninth, fortieth and forty-first sessions and pending issues: listing, classification and packing

Neutron radiation detectors

Transmitted by the Dangerous Goods Advisory Council (DGAC)

Introduction

1. In ST/SG/AC.10/C.3/2012/60 DGAC noted its intention of providing a risk analysis on the transport (including air transport) of neutron radiation detectors. An analysis has been carried out by the US government Brookhaven National Laboratory. Results of the analysis are discussed below.

Assumptions

2. The analysis considered a leak from a radiation detector on an aircraft to present the worst case transport scenario. Conservative assumptions were made in the analysis:

(a) Released BF_3 was assumed to remain in an unreacted form even though in even low humidity conditions, BF_3 forms a cloud of dense, white smoke which has a sharply acidic odour. While the aerosolized BF_3 would tend to settle out of the atmosphere through filtration or gravity this was not taken into account;

(b) It was assumed that BF_3 was released instantaneously. This would require a hole in a detector of 0.25 mm. A pinhole leak resulting in a more gradual release and lower predicted air concentrations is more likely;

(c) An aircraft pressure of 80.5 kPa was assumed. Given a maximum pressure of 105 kPa in radiation detectors, the maximum amount of BF_3 released from the largest detector would be 3 grams;

(d) Even though BF_3 detectors would be required to be packed in absorbent material, no account was taken of the effects of absorbent material and the packaging around it in the analysis;

(e) The National Advisory Committee on Acute Exposure Guideline Levels (AEGLs) has established values for single, non-repetitive exposures, not exceeding 8 hours for BF_3.

(i) AEGL 1 is the level that people could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects.

However, the effects are not disabling and are transient and reversible upon cessation of exposure.

(ii) AEGL2 is the level that people could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.

(iii) AEGL3 is the level that people could experience life-threatening health effects or death.

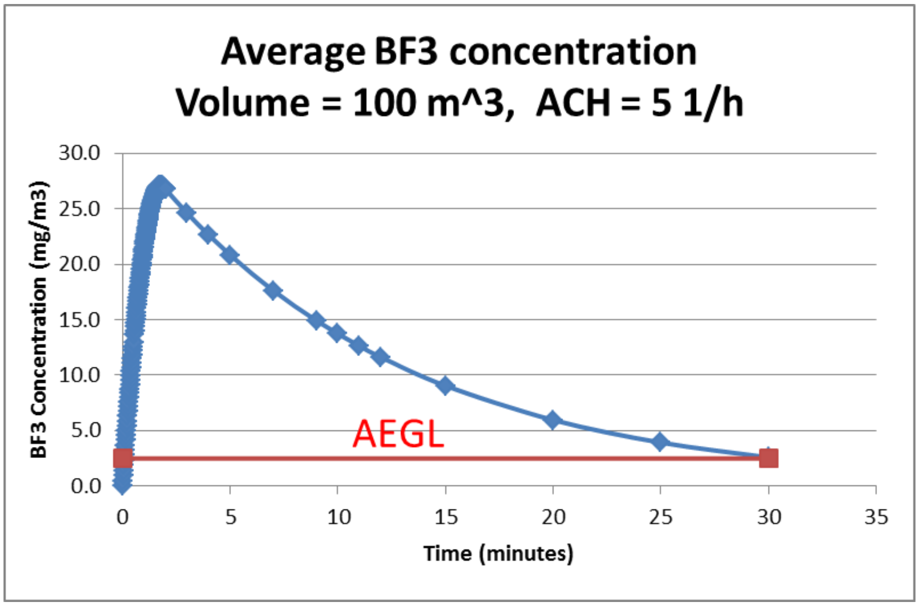
3. For BF3 the Interim Standard values are as follows:

	10 min	30 min	1 hour	4 hour	8 hour
AEGL 1 (mg/m^3)	2.5	2.5	2.5	2.5	2.5
AEGL 2 (mg/ m^3)	37	37	29	18	9.3
AEGL 3 (mg/ m^3)	110	110	88	55	28

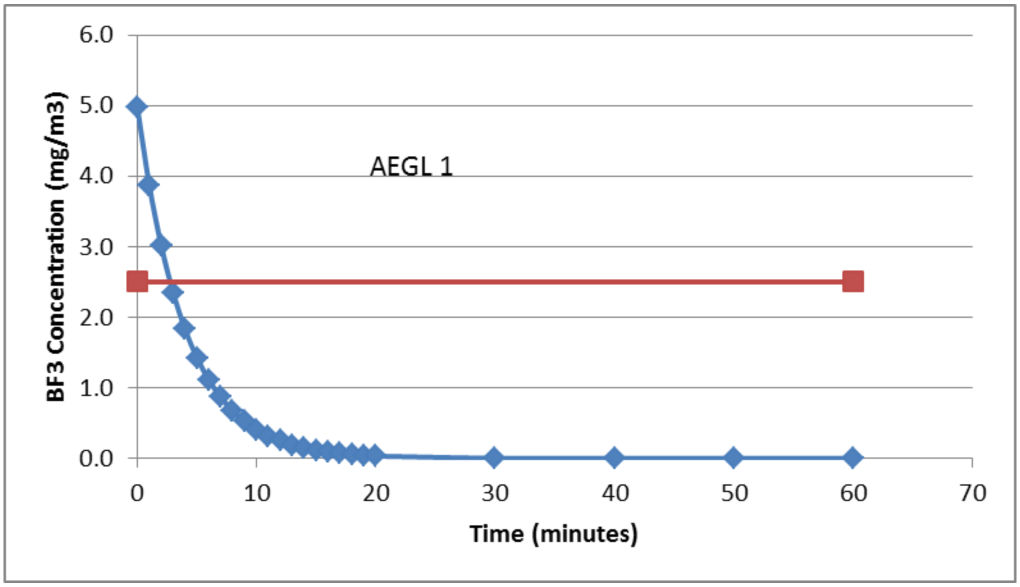
4. The AEGL 1 is the lowest of all the standards and was used as a benchmark for calculations in the analysis.

Analysis results

5. Based on the very conservative assumptions described above, the following graph shows the concentration profile in a 100 m^3 volume (approximately a 1 freight container volume; example aircraft volumes are 100 m3 (small cargo plane), 600 m^3 (Boeing 747F), 1000 m^3 (Airbus) and 1300 m^3 (Antonov AN-225)) assuming five air changes per hour (a conservative exchange rate):



6. Far less severe conditions would be anticipated in larger aircraft. A more likely cargo aircraft size would be 600 m^3 (20 air changes per hour) where the concentration profile would be as follows:



Additional Brookhaven testing

Effects of absorbent material

7. The DGAC proposal would require that absorbent material surround each radiation detector. Tests demonstrate that 200 grams of absorbent (activated alumina) absorb 36 grams of BF_3. In tests simulating a leak from a packed radiation detector, no detectable concentration of BF_3 was measured.

Drop tests

8. Detectors were dropped unpackaged from a height of 4.6 m in two orientations (on the through fittings and on the opposite). There was no leakage. Other tests where the detector tubes were crushed also resulted with no loss of contents.

Fire conditions

9. Assuming a fire temperature of 500^{o}C, the pressure in a detector would rise to 200 kPa gauge. Considering the required minimum burst pressure of 1800 kPa for a detector tube no loss of contents is expected under fire conditions.

Summary

10. Considering the conservative assumptions, it is DGAC’s opinion that the risk analysis results summarized demonstrate a low level of risk and support the proposal in document -2012/60. The risk analysis covering vapour dispersion is attached.

Annex

Evaluation of Air Concentrations in a Hypothetical Release of BF3 from a neutron detector in an Aircraft

DRAFT

November 21, 2012

Terry Sullivan

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Introduction

LND Inc. is developing an augmented risk assessment profile for the boron trifluoride (BF_3) neutron detector in an effort to respond to proposed modifications to the dangerous goods shipping regulations. Brookhaven National Laboratory has performed an evaluation of the potential release rates of boron trifluoride (BF_3) gas from a pin hole leak in a pressurized container to support LND Inc.

BF_3 gas is used in neutron detectors that monitor nuclear radiation. The detectors are filled with BF_3 to less than absolute pressure (at sea level) meaning that there would be little or no release of gas under normal conditions. The detectors are hermetically sealed and have a burst pressure on the order of 1400 PSIG making them essentially fire proof.

The detectors are authorized to fly in cargo aircraft at a maximum fill pressure of 105kPa at 20°C. In an airplane, the atmospheric pressure drops as the planes elevation increases and there could be a pressurized release of BF_3 if a hole were to form in the canister. For the purpose of this assessment, the gas properties at the assumed worst-case pressure differential are considered for all scenarios modeled

BF_3 Chemistry and Exposure Limits

Under normal atmospheric conditions, if BF_3 were released it is expected that most (if not all) of the BF_3 would react rapidly with atmospheric moisture to form a hydrate of aerosol sized droplets of BF3. The hydrate of BF_3 typically is visible as a dense, white cloud at a level less than 1ppm. The hydrates are acidic and can cause corrosion. BF_3 is extremely hygroscopic and will be attracted to items with moisture. Although, it is likely that BF_3 hydrates will form quickly, for the purposes of this study it is assumed that the BF_3 moves with the air and chemical reactions are not considered.

As a framework for the risk assessment national guidance on exposure limits has been collected. The Permissible Exposure Limit (PEL) established by the US Occupational Safety and

Health Administration (OSHA) is 1 ppm (3 mg/m^3) ceiling. The American Congress of

Governmental Industrial Hygienists (ACGIH) has also confirmed an air borne Threshold

Limit Value (TLV) of 1 ppm ceiling. Ceiling values are not to be exceeded. The National Institute of Occupational Safety and Health (NIOSH) has established an Immediately Dangerous to Life and Health (IDLH) exposure level for BF_3 of 25 ppm.

The National Advisory Committee on Acute Exposure Guideline Levels (AEGLs) has established values for single, non-repetitive exposures, not exceeding 8 hours for BF_3.

- AEGL 1 is the level that people could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- AEGL2 is the level that people could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL3 is the level that people could experience life-threatening health effects or death.

Table 1 Boron Trifluoride (CAS - 7637-07-2) Interim Standards

	10 min	30 min	1 hour	4 hour	8 hour
AEGL 1 (mg/m^3)	2.5	2.5	2.5	2.5	2.5
AEGL 2 (mg/m^3)	37	37	29	18	9.3
AEGL 3 (mg/m^3)	110	110	88	55	28

(http://www.epa.gov/opptintr/aegl/pubs/rest166.htm, accessed 11/9/2012).

The AEGL 1 is the lowest of all the standards and will be used as a benchmark for calculations in this report.

Gas Discharge Models

The discharge of pressurized gas to the air has been will studied for accident release evaluations. The fundamental equations are well known and available from several sources. This discussion follows the one available at this web page (http://www.air-dispersion.com/msource.html#Gas Discharge). When a hole is formed in a pressurized gas container the gas will begin to discharge to the atmosphere. The gas velocity through that opening may be choked (i.e., has attained a maximum) or non-choked. Choked velocity, which is also referred to as sonic velocity, occurs when the ratio of the absolute source pressure to the absolute downstream ambient pressure is equal to or greater than $[(k + 1) / 2]^{k / (k - 1)}$, where k is the isentropic expansion factor defined as the ratio of specific heat at constant pressure to specific heat at constant volume of the discharged gas. For many gases, k ranges from about 1.09 to about 1.7, and thus $[(k + 1) / 2]^{k / (k - 1)}$ ranges from 1.7 to about 2.1 which means that choked velocity usually occurs when the absolute source vessel pressure is at least 1.7 to 2.1 times as high as the absolute ambient atmospheric pressure. In general, this will not be the case for BF_3 neutron detectors being transported in aircraft due to the low pressure (1.05 kPa at 20 °C) in the detector.

When the gas velocity is choked, the equation for the mass flow rate is:

$$Q = C\,A\,\sqrt{k\,\rho\,P\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \tag{1}$$

or this equivalent form:

$$Q = C\,A\,P\,\sqrt{\left(\frac{k\,M}{Z\,R\,T}\right)\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \tag{2}$$

Whenever the ratio of the absolute source pressure to the absolute downstream ambient pressure is less than $[(k + 1) / 2]^{k / (k - 1)}$, then the gas velocity is non-choked (i.e., sub-sonic) and the equation for mass flow rate is:

$$Q = C\,A\,\sqrt{2\,\rho\,P\left(\frac{k}{k-1}\right)\left[\left(\frac{P_A}{P}\right)^{2/k} - \left(\frac{P_A}{P}\right)^{(k+1)/k}\right]} \tag{3}$$

or this equivalent form:

$$Q = C\,A\,P\sqrt{\left(\frac{2\,M}{Z\,R\,T}\right)\left(\frac{k}{k-1}\right)\left[\left(\frac{P_A}{P}\right)^{2/k} - \left(\frac{P_A}{P}\right)^{(k+1)/k}\right]} \qquad (4)$$

where:

Q = mass flow rate, kg / s

C = discharge coefficient (dimensionless, usually about 0.72)

A = discharge hole area, m^2

k = c_p/c_v of the gas = the isentropic expansion coefficient
= (specific heat at constant pressure) / (specific heat at constant volume)

ρ = real gas density, kg / m^3 at P and T

P = absolute source or upstream pressure, Pa

P_A = absolute ambient or downstream pressure, Pa

M = gas molecular weight

R = the Universal Gas Law Constant = 8314.5 (Pa · m^3) / (kgmol · °K)

T = gas temperature, °K

Z = the gas compressibility factor at P and T (dimensionless)

The above equations calculate the initial instantaneous mass flow rate for the pressure and temperature existing in the source vessel when a release first occurs. The initial instantaneous flow rate from a leak in a pressurized gas system or vessel is much higher than the average flow rate during the overall release period because the pressure and flow rate decrease with time as the system or vessel empties. Calculating the flow rate versus time since the initiation of the leak is much more complicated, but more accurate. This more accurate calculation was not attempted because the initial flow rate provides an upper bound on release and is therefore, most conservative in terms of estimating maximum airborne concentrations.

The value for Q is used to determine the air concentration. Treating the airplane as a well-mixed zone provides an estimate of the average concentration within the plane. In practice, concentrations will be higher immediately adjacent to the leak location for a brief period of time. In airplanes there is a high rate of air exchange to help maintain pressure within the plane which will enhance the mixing. For these simulations, it is assumed that the air changes are conducted with ‘fresh’ air meaning that all of the BF_3 is removed by the air exchange process. In a plane, much of the air is recirculated. This implies that the filters used in the air recirculation system effectively remove the BF_3. This is a reasonable assumption as the BF_3 will immediately form an aerosol hydrate after contacting with water vapor. If there is outside air brought in to the system as part of the air handling system it will be free from BF_3.

The fundamental equation for the concentration of BF_3 in the airplane is:

$$\frac{dC_{BF3}}{dt} = -AchC_{BF3} + Q(t)/V \qquad (5)$$

Where: C_{BF3} is the concentration of BF3 in g/m^3

Ach is the number of air exchanges per unit time (1/s)

Q (t) is the source term (g/s)

V is the volume of the plane.

Solving for C_{BF3} with the initial condition that C_{BF3} (0) = 0 yields:

$$C_{BF3} = e^{-Ach*t} \int_0^t \frac{Q(t)}{V} e^{Ach*t} \qquad (6)$$

Solving for the case when Q (t) is constant gives:

$$C_{BF3}(t) = C_{BF3}(t = 0)e^{-Ach*t} + \frac{Q}{AV}\left(1 - e^{-Ach*t}\right) \qquad (7)$$

Three cases will be considered. The first assumes that pressure losses are insignificant and Q is constant with $C_{BF3}(0) = 0$. It will be shown that the total mass in the detector available for release would be complete within a few minutes in this case for typical values of the parameters relating to the volume of the plane air exchange rate. The second case assumes that all of the mass is released instantly at t=0 and therefore, Q = 0 and $C_{BF3}(0) = M/V$ where M is mass available to be released. The third case integrates equation 6 numerically to examine the impacts on predicted concentration of the release rate which depends on the pressure difference between the BF_3 container and the outside and the area of the leak.

The mass available for release is limited by the ratio of internal and external pressures. Once the pressures equilibrate the release rate will be limited to diffusion out of the pinhole leak and will be very slow. For example, if the internal pressure is 100 kPa and the external pressure is 70 kPa only 30% of the mass may be released.

$$M = M_t * \left(1 - \frac{Pa}{P}\right) \qquad (8)$$

Where M_t is the total mass in the canister and other variables have been previously defined.

Material Properties and Model Parameters

The isentropic expansion factor is the ratio of the specific heat at constant pressure, C_p, to the specific heat at constant volume, C_v. It is often called the specific heat ratio or heat capacity ratio. While the parameter C_p is typically available, the parameter C_v is more difficult to find in the literature. In fact, a search did not find any values of the isentropic expansion factor or C_v for BF_3. A range of isentropic expansion factors is presented in Table 1. This range is used in calculating release rates. For an ideal gas, the greater the number of molecules in the gas, the lower the isentropic expansion factor. For this reason, the isentropic expansion factor is expected to be on the low end of this range for BF_3 and that ammonia (NH_3), with an isentropic expansion factor of 1.31 at 15°C, is the closest analogue for BF_3 with data available.

Table 2 Isentropic Expansion Factors for various gases at 20°C*

Gas	Cp/Cv		Gas	Cp/Cv
H_2	1.41		Dry Air	1.40
He	1.66		CO_2	1.30
N_2	1.404		NH_3	1.31
Cl_2	1.34		CO	1.40
Ar	1.67		O_2	1.40
CH_4	1.32			

* N_2 and NH_3 at 15°C

Table 3 Model Parameters for the base case

Parameter	Definition	Value	Comment
C	Discharge coefficient	0.72 (dimensionless)	Literature value
A	Hole area	$2\ 10^{-7}$ m^2	0.5 mm diameter circular hole. LND recommended value.
k	Isentropic Expansion Factor	1.31 (dimensionless)	Based on NH_3 in Table 2.
ρ	Real gas density	3.07 kg/m^3	Honeywell, 2006.
P	Container pressure	105000 Pa ($kg/m/s^2$)	
P_a	Ambient pressure in the plane	80500 Pa ($kg/m/s^2$)	
T	Temperature	20 (°C)	Leads to the highest pressure difference
M	BF_3 mass in detector	12.8 g	LND recommended value.
V	Cargo volume	600 m^3	Cargo volume for a medium sized plane (Boeing 747F)
Ach	Air changes per hour	15 h^{-1}	

Model Results

The first calculations determined whether the flow is choked or not using the isentropic expansion factor and the criteria described above. Flow is not choked due to the low pressure differential between the interior and exterior of the detector. Equation (3) was used to obtain the initial mass flow rate from the 0.25 mm radius hole as 0.047 g/s. The mass available for release in the base case was 3 grams based on the initial mass in the detector (12.8 g) and the ratio of external to internal pressure (80.5/105). Thus, the release at this rate would be complete after 64 seconds at this initial rate. For this reason, the instantaneous release model was used to estimate concentrations for a 3 gram release. The concentrations over time are provided in Table 4 and Figure 1.

Table 4 Predicted concentration of BF_3 for instantaneous release of 3 g.

Time (min)	BF_3 Concentration (3 g release) mg/m^3
0	4.98E+00
1	3.88E+00
2	3.02E+00
3	2.35E+00
4	1.83E+00
5	1.43E+00
6	1.11E+00
7	8.65E-01

8	6.74E-01
9	5.25E-01
10	4.09E-01
11	3.18E-01
12	2.48E-01
13	1.93E-01
14	1.50E-01
15	1.17E-01
16	9.12E-02
17	7.10E-02
18	5.53E-02
19	4.31E-02
20	3.35E-02
30	2.75E-03
40	2.26E-04
50	1.86E-05
60	1.52E-06

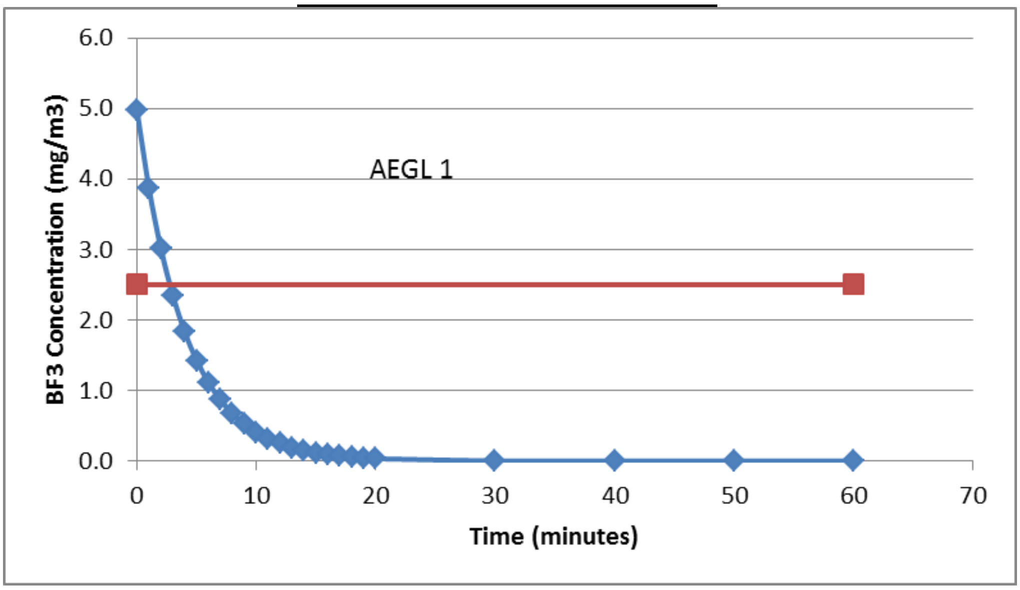

Figure 1 Predicted BF3 concentration for a pulse release of 3 g into a cargo volume of 600 m^3.

The table and figure show that AEGL 1 will be exceeded for a little more than 2 minutes in this case. The BF_3 concentration decreases quickly due to the high rate of air exchange in this simulation. The initial concentration is determined by the mass released and the volume of the plane. Thus, for the base case volume of 700 m^3, the release would have to be limited to less than 1.75 grams.

The fact that the release would take over a minute and the air exchange rate is 15 per hour or one every 4 minutes suggests that the peak concentrations will be slightly overestimated by assuming a pulse release. To evaluate this effect the calculations were repeated using the time-dependent release rate for non-choked flow, Eqn (3), and integrating Eqn (6) numerically. In this case, the peak concentration was reduced from 5.0 mg/m^3 to 4.5 mg/m^3

for a 0.25 mm radius hole, which is still greater than the AEGL I. In both cases, the average concentration exceeded the AEGL for approximately 3 minutes. The peak concentration also exceeded the NIOSH ceiling value of 3 mg/m^3.

Sensitivity Analysis

The key parameters in determining the concentrations are the leak rate, volume of the cargo space, and the air exchange rate. The key parameters and the values used in the study are as follows:

- Hole Area: The evaluation showed that the release rate from a 0.25 mm radius hole is sufficiently fast to release all of the available mass within 2 minutes. A larger hole would make this time even faster. A substantially smaller hole would slow the release down and reduce peak concentrations. Simulations were performed for a 0.125 mm radius. This reduces the area and therefore flow rate by a factor of 4 from the base case (0.25 mm radius hole).
- Ambient Pressure: The ambient pressure influences the rate of release and the total amount of mass that can be released. Lower ambient pressures lead to faster mass release rates and greater total mass release. Simulations were performed with an ambient pressure of 70.5 kPa to complement the base case value of 80.5 kPa.
- Volume: The peak concentration decreases with increasing volume. Literature values of cargo volumes for planes range from approximately 25 - 50 m^3 on passenger planes to 1300 m^3 on the Antonov AN-225, the world’s largest cargo plane. It is assumed that the detectors would be shipped on Cargo planes and the following volumes were analyzed 100 m^3 (small cargo plane), 600 m^3 (Boeing 747F), 1000 m^3 (Airbus) and 1300 m^3 (Antonov AN-225).
- Air Changes per hour: The time the concentration exceeds the AEGL is a function of the number of air changes per hour. A range in values between 5 and 20 air changes per hour was evaluated.
- Temperature: The effects of temperature were only evaluated at 20°C. Lower temperatures would reduce the internal pressure in the BF_3 detector and lead to lower predicted release rates and concentrations.

The peak concentration results of the sensitivity analysis are presented in Tables 5 -8. Table 5 and 6 present the results for a 0.25 mm radius hole and an ambient pressure of 80.5 kPa and 70.5 kPa for various volumes and air change rates. The maximum concentration for the pulse release provides an upper bound on concentration and is also provided. Tables 7 and 8 present similar information for a 0.125 mm radius hole. Areas shaded in light blue in Tables 5 – 8 have peak concentrations less than the AEGL I. The concentrations for the pulse release are the mass released divided by the plane volume. For the ACH dependent release equation 6 was evaluated as a function of time and the peak concentration is reported. Depending on the ACH and volume of the plane the peak concentration was not reached for 30 to 150 seconds.

The results in Table 5 and 6 contrast the maximum concentration as a function of area of release (hole size). At this ambient pressure there is not enough mass released to exceed the AEGL I of 2.5 mg/m^3 for the largest volume. At the smallest volume, the peak concentration exceeds the AEGL I by approximately a factor of 10 for all simulated air exchange rates. The effect of air exchange rate on peak concentration is to reduce the peak value by approximately 33% in going from an instantaneous release to 20 air changes per hour for all volumes for the 0.25 mm radius hole. This is because the release occurs so quickly that air exchange rates have only a minor influence.

Table 5 Peak BF_3 concentrations (mg/m^3) as a function of cargo volume and air change rate at 20°C, ambient pressure of 80.5 kPa and hole radius of 0.25 mm. (AEGL I = 2.5 mg/m^3)

Air changes per hour	Volume (m^3)			
	100	600	1000	1300
	BF_3 Concentration (mg/m^3)			
Pulse release	29.9	5.0	3.0	2.3
5	27.1	4.5	2.7	2.1
10	24.8	4.1	2.5	1.9
15	22.9	3.8	2.3	1.8
20	21.3	3.5	2.1	1.6

For the 0.125 mm radius hole (Table 6), the air exchange rate is much more important. The peak concentration was reduced by approximately 67% in going from the pulse release simulation to 20 air changes per hour with release limited by the hole size and pressure difference. For this pressure difference, the two largest simulated volumes had peak concentrations below AEGL I for air exchange ratios above 5 and the 600 m3 volume was below the AEGL I for air exchange rates greater than 15. The small volume always had a peak concentration in excess of the AEGL I.

Table 6 Peak BF_3 concentrations (mg/m^3) as a function of cargo volume and air change rate at 20°C, ambient pressure of 80.5 kPa and hole radius of 0.125 mm. (AEGL I = 2.5 mg/m^3)

Air changes per hour	Volume (m^3)			
	100	600	1000	1300
	BF_3 Concentration (mg/m^3)			
Pulse release	29.9	5.0	3.0	2.3
5	21.5	3.6	2.1	1.7
10	16.8	2.8	1.7	1.3
15	13.9	2.3	1.4	1.1
20	11.8	2.0	1.2	0.91

Tables 7 and 8 examined the peak concentrations for a larger pressure difference than the base case. In this case, the ambient pressure was approximately 30% lower than the container pressure. Even the largest volume simulated had a peak concentration in excess of the AEGL I limit for the pulse release and air exchange rates below 15. The results in Tables 7 and 8 show results similar to the previous example (Tables 5 and 6). The major difference is the mass release rate is approximately 30% higher and therefore the concentrations are 30% higher.

Table 7 Peak BF_3 concentrations (mg/m^3) as a function of cargo volume and air change rate at 20°C, ambient pressure of 70.5 kPa and hole radius of 0.25 mm. (AEGL I = 2.5 mg/m^3)

Air changes per hour	Volume (m^3)			
	100	600	1000	1300
	BF_3 Concentration (mg/m^3)			
Pulse release	42.1	7.0	4.2	3.2
5	37.2	6.2	3.7	2.9
10	33.7	5.6	3.4	2.6
15	30.8	5.1	3.1	2.4
20	28.3	4.7	2.8	2.2

Table 8 Peak BF_3 concentrations (mg/m^3) as a function of cargo volume and air change rate at 20°C, ambient pressure of 70.5 kPa and hole radius of 0.125 mm. (AEGL I = 2.5 mg/m^3)

Air changes per hour	Volume (m^3)			
	100	600	1000	1300
	BF_3 Concentration (mg/m^3)			
Pulse release	42.1	7.0	4.2	3.2
5	28.5	4.7	2.8	2.2
10	21.5	3.6	2.2	1.7
15	17.3	2.9	1.7	1.3
20	14.5	2.4	1.5	1.1

Figures 2 and 3 are provided to illustrate the time-dependent concentration for the 100 m^3 volume simulation at two different air exchange rates (5 and 20 h^{-1}). At the low air exchange rate, the peak value is 27.3 mg/m^3 and the concentration remains above the AEGL for 30 minutes. At the higher flow rate, the peak concentration is 21.3 mg/m^3 and remains above the AEGL for slightly longer than 8 minutes. Both peak around 100 seconds after the start of release due to the reduction in release rate as the internal pressure equilibrates. The ACH = 5 case, Figure 2, peaks at 103 seconds and the ACH 20, Figure 3, case peaks at 91 seconds.

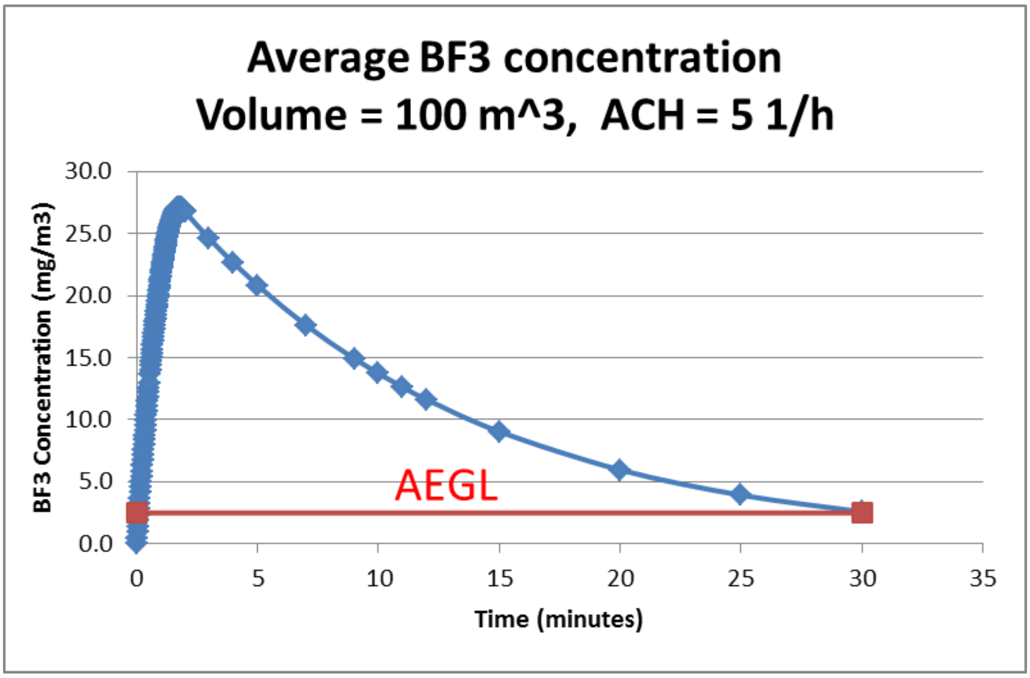

Figure 2 BF_3 concentration time history for ambient pressure of 80.5 kPa with a 0.25 mm radius hole.

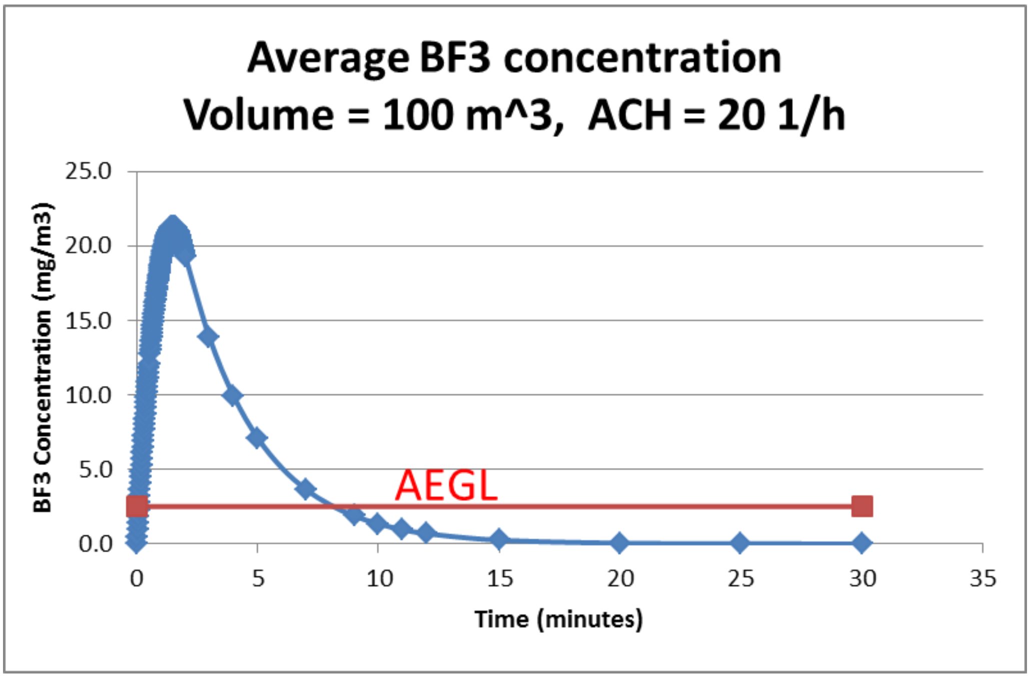

Figure 3 BF_3 concentration time history for ambient pressure of 80.5 kPa with a 0.25 mm radius hole.

Figures 3 and 4 show the effect of hole size on the time to peak concentration and the peak concentration in the high air exchange case (ACH = 20) for the 100 m^3 plane volume.

Figure 3 is based on the results from a 0.25 mm radius hole and Figure 4 is based on a 0.125 mm radius hole. The smaller hole size limits the mass release rate and allows for more mixing due to the

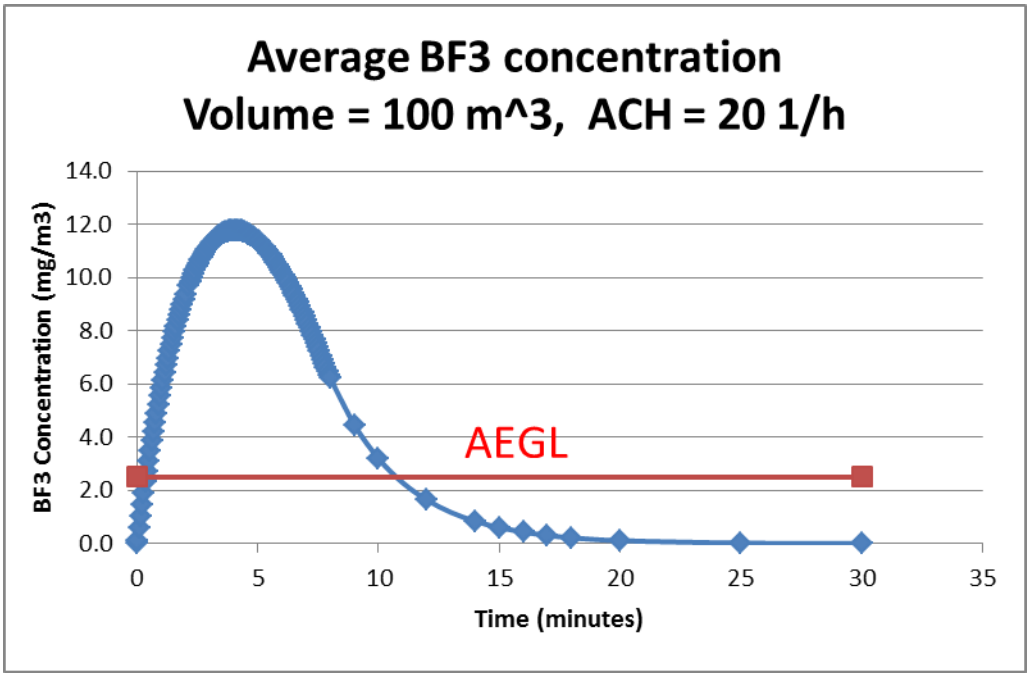

Figure 4 Figure 5 BF$_3$ concentration time history for ambient pressure of 80.5 kPa with a 0.125 mm radius hole.

high air exchange rate. The peak concentration is much lower for the 0.125 mm radius hole than for the 0.25 mm radius hole (11.8 versus 21.3 mg/m^3). The peak concentration occurs after 4 minutes for the 0.125 mm radius hole simulation as compared to 1.5 minutes for the 0.25 mm radius hole simulation.

Discussion

The calculations documented in this report treat the cargo space as a single well-mixed zone and provide an estimate of the average concentration in the zone. In practice, it will take several minutes to achieve this mixing depending on the air exchange rate. This suggests that actual concentrations will be higher near the release location than the predicted average value. A detailed numerical evaluation of the concentration could be obtained using computational fluid dynamics techniques. This may be of use in attempting to demonstrate that someone remote from the leak (e.g. the crew) would not be exposed to BF$_3$ concentrations above the AEGL. This would require a case by case analysis due to the need for detailed information on the geometry of the plane, location of the leak, location of the crew, and air handling system.

In practice, the BF$_3$ would form hydrates of aerosol sized particles almost instantly as it contacts water vapor. This would change the transport characteristics depending on the size distribution of aerosol particles. The prediction of the crew's exposure would require accurate modeling of airflow, turbulence, and interactions between aerosol particles and eddies close to indoor surfaces. Deposition of aerosol particles removes them from the air and reduces the airborne concentration. Literature values of deposition of µm size particles (Zhang, 2009, Howard-Reed, 2003) suggest that the deposition process increases the effective air exchange per hour by 0.5 to 5. While this increase is very important in residential studies where the ACH is typically less than 1, it is not as important in airplanes where the ACH is typically greater than 10. The effect of deposition was incorporated by simulating a range of ACH values from 5 – 20. The results showed that the ACH had a pronounced effect on the duration of high concentrations, but had only a minor effect on the peak concentration and timing of the peak.

In an airplane, the air may be recirculated through a filter system. There was no attempt to examine filtration effects. Standard furnace filters were shown to be ineffective in removing 0.3 – 10 µm particles (Howard-Reed, 2003). However, BF_3 aerosols may be more reactive and a standard filter may be effective. Data on HEPA filters were not readily available, but it is expected that they would be more effective than a standard filter.

This study did not address the release of BF_3 in the cargo hold of a passenger plane. Cargo volumes in passenger planes are typically in the range of 20 – 50 m^3. Release in this confined volume would lead to high concentrations in the cargo hold. To examine the concentrations in the passenger cabin would require information on the leakage of air directly from the cargo hold to the passenger cabin (probably minimal due to higher pressure in the passenger cabin) and leakage between the air handling systems for these two areas. It is likely that there will be substantial dilution between the cargo hold and passenger cabin, but this has not been quantified.

The study did not address the reduction in volume in the cargo area due to the cargo. A ninety percent packing efficiency would reduce the available volume for mixing by a factor of 10. Thus, the low volume case (100 m^3) may be more representative of the actual volume available for dilution of the release.

Conclusions

The release of BF_3 from a pinhole leak in a neutron detector into a cargo plane was simulated to obtain the average BF_3 concentration in the cargo area. The volume of the plane was treated as a well-mixed homogenous zone with values ranging from 100 to 1300 m^3. The internal pressure of the detector was set to 105 kPa with an external pressure of 80.5 or 70.5 kPa. Release was limited to the amount of mass required to lower the internal pressure to the external pressure. Simulations were performed for an instantaneous release of the mass (pulse release) and a time-dependent release dependent on the area for release, gas properties, and pressure differential. The time-dependent release was complete within two minutes for a 0.25 mm radius hole and within five minutes for the 0.125 mm radius hole. Peak concentrations were compared to AEGL 1, 2.5 mg/m^3 for BF_3, and found to exceed this limit for pulse release for any volume of cargo space. The larger cargo volumes had conditions where the peak average concentration was predicted to remain below the AEGL. The smallest simulated cargo volume, 100 m^3, always had predicted concentrations in excess of the AEGL.

The analysis shows that for a relatively small hole size (0.25 mm radius) the release is so fast that mixing is limited and predicted peak concentrations are within 67% of the value for instant release for all volumes and air exchange rates. The smaller hole size (0.125 mm radius) restricted release rates to allow for more dilution and lower peak concentrations. To meet the AEGL 1 for the conditions simulated in this study the hole radius would have to be a factor of 3 or 4 lower than the 0.125 mm radius.

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