APPENDIX 1:

ISFAHAN AND NATANZ GAUSSIAN PLUME CALCULATIONS

Basic chemical reactions for the production of UF6

Mass balance for UF6 production assuming ideal (100% efficient or stoichiometric) reactions is obtained as follows:

Inserting molecular weights and solving for masses of each compound used to produce 1 kg (2.2 lbs) of UF6 gives

1 kg UF6 => 0.797 kg (U3O8) + 0.004 kg (H2) + 0.227 kg (HF) + 0.108 kg (F2) - 0.136 kg (H2O) (1)

On a mass basis to produce 1000 kg (2,200 lbs) of UF6, the following input masses are required for equation (1)

1000 kg (UF6) = 797 kg (U3O8) + 4 kg (H2) + 227 kg (HF) + 108 kg (F2) - 136 kg (H2O) (2)

Observe that the reaction in equation (2) generates 136 kg (299 lbs) of H2O.

As stated in the methodology and assumptions section, for the purposes of calculating travel distances and exposed areas we are utilizing IDLH for toxicity values. The IDLH values for UF6, UO2F2, HF, F2 and other fluoride compounds as very similar and within a narrow range of values. So a combined, mean IDLH value is assumed as follows since the accurate estimation of the various mass components of the possible fluoride products is not possible in the event of an attack on Iran's nuclear fuel facilities.

IDLH for fluoride products released to the atmosphere is

25 ppm or 38.8 mg (F2)/m3 (air) (3)

The airborne dispersion and deposition of the toxic materials that could be released from an attack upon an Iranian nuclear site with UF6, HF, or F2 can be modeled using the standard Gaussian plume atmospheric dispersion and transport model (Refs 3 and 5). The atmospheric dispersion concentration is quantified in terms of the standard X /Q dispersion factors where

X (grams of toxic material/m3) liberated into the atmosphere

Q (grams of toxic material/s) released from the source.

The Gaussian plume model equation uses the following simplified equation

$X / Q = Pd / [\, 2^{1/2} \pi \, Sx \, Sy \, Sz \,]$ (4)

Where

Pd = time duration of the toxic release(s)

$\pi = 3.1415$

Sx, Sy, Sz = dispersion coefficients for travel in (x), horizontal (y), vertical (z) directions (m)

The objective for this analysis is to provide an estimate of the distance x(m) that a toxic plume can travel from the release point to the point at which the plume exhibits as concentration equal to the IDLH value for the toxic material. The ground distance that the plume will travel until this concentration occurs is x. The value of x is contained in the dispersion coefficients as follows for distances greater than about 5 km (3.1 miles).

$Sx = Sy = 0.13 \, x^{0.9}$ (5)

$Sz = 0.57 \, x^{0.58}$ (6)

These experimental numerical values shown in equations (5) and (6) assume atmospheric stability Class D that are typical worldwide values used for ambient meteorological conditions prevalent about 2/3 of time for average weather conditions and wind speeds of about 3.1 m/s.

Solving equation (4) for x by substituting equations (5) and (6) gives

$x^{2.38} = 13.2 \, Pd \, (Q / X)$ (7)

or

$x \, (m) = 2.96 \, [Pd \, (Q / X)]^{0.42}$ (8)

Equation (8) may now be used to estimate the travel distance along the ground that this toxic plume will move as a hemisphere. The toxic materials inventory estimated at Isfahan and Natanz will be used to determine the travel distance x from equation (8) as follows for each site.

The toxic material inventory at Isfahan and Natanz is estimated at 371 metric tons. Since it is not evident how this inventory is distributed between these two sites, we have assumed a range of releases of 1 to 50% percent of total inventory at each site. (Table 9)

If the military attack upon the UF6 storage and processing sites is highly successful, then the release of 50% of the UF6 that might be dispersed on the ground and into the atmosphere is shown in the following calculation.

Pd(s) Q(g/s) = 6.01×10^{7} g of toxic fluorine materials

X= 0.0388 g/m^3 average IDLH for these toxic materials

Pd(Q/X) = 1.54×10^{9} m^3

Gaussian Plume Calculations for Military Strikes on Iranian Nuclear Infrastructure							
% 371 (MT) of UF6 Released to Atmosphere	Fluorine in Airborne Compounds (g)	Fluorine at >= 25 ppm		Fluorine at >= 25 ppm		Chlorine at >= 10 ppm	
		Travel distance (km)	Area (=L L/2) (sq km)	Travel distance (miles)	Area (=L L/2) (sq miles)	Travel distance (km)	Area (=L L/2) (sq km)
		IDLH Fluorine		IDLH Fluorine		IDLH Chlorine *	
		X(IDLH) = 25 ppm		X(IDLH) = 25 ppm		X(IDLH) = 10 ppm	
1	1.20E+06	4	8	3	5	5	13
5	6.01E+06	8	32	5	13	9	41
10	1.20E+07	11	61	7	25	12	72
20	2.40E+07	15	113	9	41	16	128
25	3.00E+07	16	128	10	50	18	162
50	6.01E+07	21	221	13	85	24	288

Table 9

And a travel distance from the release point of the toxic materials is

$$x(m) = 2.96\ [Pd(\ Q/X)]^{0.42} = 21 \text{ km (13 miles)}$$

Notes:
1: IDLH - Immediately Dangerous to Life and Health (U.S. NIOSH)
*Since Chlorine use is widespread compared to Fluorine and toxic health effects are similar, the IDLH effective distance and area data for Chlorine are also presented for comparison

Consequences of Radiation Exposures from UF6

The UF6 materials used in the Iranian Nuclear Program Iran pose both chemical toxicity and radiological risks to humans. The chemical toxicity effects are evident immediately upon release of fluorine compounds into the environment. The radiological effects appear over long periods of time associated with the radioactive decay properties of the radioactive materials. The long-term radiological risk to humans from the uranium in the UF6 after fluorine in the UF6 has dissipated and uranium compounds are now dispersed within the environment. Uranium is a very long-lived alpha emitter (half-life of U-235 is 704 million years and U-238 is 4.5 billion years) with long sequences of other radioactive daughters that pose significant health hazards. These radioactive products associated with U are deposited within the body through breathing and ingestion poses both long-term cancer risks.

The risk associated with the deposition of U and its radioactive daughters on soil can be estimated from the total inventory of UF6 reported. A RESRAD (Ref 4) analysis shows that 8.4 grams of uranium deposited per square meter of land surface area poses a radiation exposure of about 1 milliSievert/year (or 100 millirem/year) from all pathways producing human radiation exposure. This level is generally considered the maximum allowable additional dose to the public from surface-deposited radiation above natural background radiation exposures. The land area that could be contaminated at this level from the eventual release to the environment of 371 Metric Tons is given by

$$371 \times 10^6 \text{ g UF6} \times (0.676 \text{ g U/g UF6})/[8.4 \text{ g U/(sq m land area)}] = 30 \text{ sq km (11.6 sq. miles)} \quad (9)$$

About 30 sq km (11.6 sq. miles) of land could be contaminated for centuries from this deposition of uranium on adjacent land. This contaminated land must either be abandoned for human use or extensive cleanup performed including removal of all surface materials (soil, water, etc.) at very large economic expenditures.

References:

1. "Implementation of NPT Safeguards Agreement and relevant provisions of Security Council resolutions," IAEA Report to the Board of Governors, 18 February 2010: 6.
2. IDLH values provided in the CDC-NIOSH Pocket Guide to Chemical Hazards, 18 Nov 2010, www.cdc.gov/niosh/npg/. IDLH is an acronym for "Immediately Dangerous to Life or Health," and is defined by U.S. National Institute for Occupational Safety and Health (NIOSH) as exposure to airborne contaminants likely to cause death or immediate or delayed permanent adverse health effects. NIOSH is the United States federal agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness. NIOSH is part of the Centers for Disease Control and Prevention (CDC) within the U.S. Department of Health and Human Services.
3. "Airborne Release Fraction/Rates and Respirable Fractions for Nonreactor Nuclear Facilities," DOE Handbook, DOE-HDBK-3010-94, December 1994.
4. RESRAD is a computer code developed by U.S. Department of Energy to evaluate human health and ecological risks resulting

from residual radioactive and chemical contamination. The RESRAD code has been widely used in the United States and abroad for assessing environmental radiation risks.

5. "Development of a Computer Model for Calculation of Radioactive Materials into the Atmosphere after an Accident," UCRL-CR-129075, November 1997.

6. Deichmann, W. and H. Gerarde, "Hydrofluoric Acid," Toxicology of Drugs and Chemicals, Academic Press, NY, NY, pg. 317-318, 1969.