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MEMO TO : Air Quality Staff

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RE : Model Input Parameters for Flares

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Most refined air quality models, including AERMOD and ISC-Prime, do not provide for direct modeling of flares. Therefore, the treatment of plume rise from flares is not straightforward, because traditional input values of stack temperature, diameter, and exit velocity have no physical significance once combustion has occurred at the top of the stack. To properly model flare plume rise, therefore, virtual values of stack temperature, diameter, and exit velocity must be developed which allow the model to calculate a buoyancy representative of conditions above the flare. In addition, a virtual (effective) stack height may be calculated which accounts for the length of the flame. These virtual values are then entered for traditional model input.

The North Dakota Department of Health (NDDH) recommends a new approach for flare stack plume rise which is based on the method used in the EPA SCREEN3 model. This new approach supersedes the method previously used by the NDDH as outlined in the *North Dakota Guideline for Air Quality Modeling Analyses* (1990). To be more consistent with the SCREEN3 methodology, the new approach assumes a different entrainment heat loss (55% vs. 25%), and adds the provision to revise (increase) stack height by calculated flame length.

A primary component of plume rise calculations in air quality models is the buoyancy flux parameter. Necessary virtual stack parameters for flare modeling can be established by equating two versions of the buoyancy flux parameter. The buoyancy flux parameter incorporated in the ISC-Prime and AERMOD models (Briggs) is defined:

$$F = \frac{gV_S}{\pi} \cdot \frac{(T_S - T_a)}{T_S} \qquad (1)$$

where

F is the buoyancy flux parameter (m^4/sec^3),
g is acceleration of gravity (9.8 m/sec^2),
V_S is volume flow rate of stack gases at stack conditions (m^3/sec),
T_a is ambient air temperature (K), and
T_S is stack gas temperature (K).

For calculating plume rise from flare stacks, SCREEN3 uses the following equivalent form of the buoyancy flux parameter:

$$F = \frac{gQ}{\pi C_p \rho T_a} \tag{2}$$

where

Q is the net heat release from combustion of gas stream (calories/sec),
C_p is the specific heat of air (0.24 calories/gram-K), and
ρ is the density of air (1205 gram/m^3).

Setting Equation 1 equal to Equation 2, and solving for V_S provides:

$$V_S = \frac{Q}{C_p \rho T_a} \cdot \frac{T_S}{(T_S - T_a)} \tag{3}$$

or

$$D_S = \left[\frac{Q}{C_p \rho T_a} \cdot \frac{T_S}{(T_S - T_a)} \cdot \frac{4}{\pi W_S}\right]^{0.5} \tag{4}$$

where

D_S is the stack diameter (m) and
W_S is the stack exit velocity (m/sec).

Therefore, if the heat release is known and ambient temperature is assumed, arbitrary virtual values of stack velocity, diameter, and temperature can now be established which satisfy this equation, and ensures that the model correctly calculates the buoyancy flux parameter for flares. The formulation of Equation 4 is consistent with the treatment in SCREEN3, which solves for stack diameter in terms of set values for stack velocity and temperature.

In its policy for flare plume rise, the NDDH now recommends the use of Equation 4 with set values of 293 K for ambient temperature, 1000 K for stack temperature, and 40 m/sec for stack exit velocity. The use of 293 K for ambient temperature is consistent with SCREEN3 and other screening methods. The use of a relatively large value for stack temperature minimizes sensitivity of the equation to variations in ambient temperature. Finally, the use of 40 m/sec for stack exit velocity is intended as a compromise to ensure the value is not too low to trigger inappropriate stack-tip downwash, or too high to trigger inappropriate assumption of momentum dominated plume rise in refined models.

Substituting standard values for C_p and ρ, (as noted above), and assuming fixed values of ambient temperature, stack gas temperature, and stack exit velocity, as discussed above, Equation 4 reduces to:

$$D_S = 7.29 \times 10^{-4}(Q)^{0.5} \quad (5)$$

for calculating virtual stack diameter. Note that Q is specified as the *net* heat release from the flare. Consistent with SCREEN3, the NDDH assumes that 55 percent of the total heat released is lost due to entrainment of ambient air. Therefore, the net heat release, Q, equals 45 percent of the total calculated heat release (calories/sec) for the combusted gas stream.

As in SCREEN3, effective stack height is calculated by adding flame length on to the physical stack height:

$$h_{se} = h_s + h_f \quad (6)$$

and

$$h_f = 4.56 \times 10^{-3}(Q_t)^{0.478} \quad (6')$$

where

h_{se} is the effective stack height for model input (m),
h_s is the physical stack height (m),
h_f is the flame length (m) (Beychok, 1979), and
Q_t is the *total* heat release from the flare (calories/sec).

In summary, the following procedure is now used to develop model input parameters for flares.

1) Set stack exit velocity to 40 m/sec and stack gas temperature to 1000 K.

2) Obtain the total flare heat release (calories/sec) by summing the heat of combustion of the individual flared gas components, based on the volume flared in one second. Volumetric heating values for natural gas stream components are provided in the attached table (one Btu = 252 calories). Alternatively, a total of 1200 Btu/ft^3 (302,400 calories/ft^3) can be assumed for typical sweet gas streams in western North Dakota.

3) Obtain the net heat release, Q, by multiplying the value obtained in Step 2 by 0.45 (accounts for 55 percent heat loss due to entrainment of ambient air).

4) Calculate the virtual stack diameter using Equation 5.

5) Calculate the effective (model input) stack height using Equation 6.

Heat of Combustion*

Substance	Formula	Molecular Weight	Cubic Ft per Lb	Btu per Cubic Ft	Btu per Lb
Hydrogen	H_2	2.016	187.723	275.0	51,623
Carbon Monoxide	CO	28.010	13.506	321.8	4,347
Methane	CH_4	16.041	23.565	913.1	21,520
Ethane	C_2H_6	30.067	12.455	1641.0	20,432
Propane	C_3H_8	44.092	8.365	2385.0	19,944
Butane	C_4H_{10}	58.118	6.321	3113.0	19,680
Pentane	C_5H_{12}	72.144	5.252	3709.0	19,517
Benzene	C_6H_6	78.107	4.852	3601.0	17,480
Toluene	C_7H_8	92.132	4.113	4284.0	17,620
Xylene	C_8H_{10}	106.158	3.567	4980.0	17,760
Acetylene	C_2H_2	26.036	14.344	1448.0	20,776
Napthalene	$C_{10}H_8$	128.162	2.955	5654.0	16,708
Methyl Alcohol	CH_3OH	32.041	11.820	768.0	9,078
Ethyl Alcohol	C_2H_5OH	46.067	8.221	1450.5	11,929
Ammonia	NH_3	17.031	21.914	365.1	8,001
Hydrogen Sulfide	H_2S	34.076	10.979	596.0	6,545

*From American Gas Association

SFW:saj