Sierra Engineering & Software, Inc.

ANALYSIS REPORT	NUMBER: 2019-001b DATE: 18 June 2019
SUBJECT: Exhaust Plume Calculations for SpaceX Raptor Booster Engine	PAGE 1 OF 10 NO. OF APPEN. 0
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1.0 SUMMARY

Calculations were performed to estimate the far-field exhaust constituents of the SpaceX Raptor liquid oxygen-liquid methane (LOX-LCH4) booster rocket engine firing under sea-level conditions. Although the exit-plane exhaust is fuel-rich and contains high concentrations of carbon monoxide (CO), subsequent entrainment of ambient air results in nearly complete conversion of the CO into carbon dioxide (CO_2). A small amount of thermal nitrous oxides (NOx) is formed, all as NO. The CO and NO emissions are predicted to be less than 0.024 lb_m/s each, per engine under nominal power (100%) operation. No soot is predicted to be generated by this engine cycle. The CO and NO emission rates for the Super Heavy has been estimated to be no more 0.788 lb_m/s each. The predicted sea-level CO and NO emission rate for the Starship upper stage are estimated to be no more than 0.168 lb_m/s each.

2.0 ENGINE DESCRIPTION

The subject engine is the baseline booster engine for the SpaceX Super Heavy launch vehicle. The baseline Super Heavy stage includes 31 Raptor engines. The propellants are liquid oxygen (LOX) and liquid methane (LCH4). The subject engine uses a closed power cycle with a 34.34:1 regeneratively-cooled thrust chamber nozzle. As a simplification needed to address the problem with the existing axisymmetric analysis tools, the computational nozzle exit plane. Characteristic dimensions of the thrust chamber nozzle are included in Table 1.

The nominal operating condition for the Raptor engine is an injector face stagnation pressure (Pc) of 3669.5 psia and a somewhat fuel-rich engine O/F mixture ratio (MR) of 3.60. The current analysis was performed for the 100% nominal engine operating pressure (Pc=3669.5 psia) and an engine MR of 3.60.

Table 1: Raptor Nozzle Characteristics

Throat Radius (in)	4.362
Downstream radius of curvature (in)	1.309
Tangency angle (deg)	32.0
Nozzle lip exit angle (deg)	6.0
Nozzle exit diameter (in)	51.226
Nozzle throat to exit length (in)	60.06

3.0 ANALYSIS APPROACH

A series of simulations were required to estimate the emissions from the Raptor engine. The PERCORP analysis model[1] was used to estimate the O/F mixture ratio variations that exist within the Raptor thrust chamber. The VIPER parabolized Navier-Stokes model[2] was used to kinetically expand the thrust chamber exhaust to the nozzle exit plane. The VIPER results were used to assess the validity of the PERCORP solution, correlating engine thrust, mass flow rate and specific impulse (ISP) to test results. PERCORP input parameters were adjusted until there was good agreement between the VIPER performance predictions and the test results. The SPF code[3] was used to predict the flow structure of the free exhaust plume and the entrainment of ambient air. VIPER solution was used as the starting condition for the SPF. Though the SPF code can handle detailed chemical kinetics within the plume evolving flow field, the strong barrel shock downstream of the nozzle exit produces numerical convergence problems with the version of SPF used. The present SPF simulations were performed without chemical kinetics. The results were air entrainment and gas temperature profiles. The SPF and VIPER results were used as inputs for one-dimensional kinetic modelling of the plume flow field. The kinetic model in the TDK code[4] was used to model chemical reactions within the evolving plume flow field.

TDK modelling of the plume flow field included chemical mechanism that address a) the oxidation of CO to CO_2, b) the complex oxidation of hydrocarbons to H_2O and CO_2, and c) the thermal generation of NOx in a mixture of air and combustion products. Table 2 includes the chemical reactions and rates used in the TDK simulation.

Table 2: Kinetic Reactions Included in One Dimensional Chemistry Simulations*

	A	N	B
H + H + m = H2 + m†	6.4E17	1.0	0.0
H + OH + m = H2O + m	8.4E21	2.0	0.0
O + O + m = O2 + m	1.9E13	0.0	-1.79
CO + O + m = CO2 + m	1.0E14	0.0	0.0
O + H + m = OH + m	3.62E18	1.0	0.0
CH4 + m = CH3 + H + m	1.259E17	0	88.4
HCO + m = CO + H + m	5.012E14	0	19.0
C2H3 + m = C2H2 + H + m	7.943E14	0	31.5
N+NO = N2+O	2.700E13	0	0.355
N+O2 = NO+O	9.000E9	-1.0	6.5
N+OH = NO+H	3.360E13	0	0.385
HO2+NO = NO2+OH	2.110E12	0	-0.480
NO2+O = NO+O2	3.900E12	0	-0.240
NO2+H = NO+OH	1.320E14	0	0.360
O2 + H = O + OH	2.2E14	0.0	16.8
H2 + O = H + OH	1.8E10	-1.	8.9
H2 + OH = H2O + H	2.2E13	0.0	5.15
OH + OH = H2O + O	6.3E12	0.0	1.09
CO + OH = CO2 + H	1.5E7	-1.3	-.765
CO + O = CO2	2.5E6	0.0	3.18
CO2 + O = CO + O2	1.7E13	0.0	52.7
CH4+ OH = CH3 + H2O	3.162E13	0	6.0
H + CH4 = CH3 + H2	6.310E14	0	15.1
O + CH4 = CH3 + OH	3.981E14	0	14.0
CH3 + O = CH2O + H	1.259E14	0	2.0
CH3 + OH = CH2O + H2	3.981E12	0	0
C2H2 + OH = C2H + H2O	6.310E12	0	7.0
H + CH2O = HCO + H2	3.162E14	0	10.5
O + CH2O = HCO + OH	1.995E13	0	3.1

* TDK reaction format is k=AT**(-N)*EXP(-1000B/RT) [cc-Kcal-K-mole-s]

† m is any molecule for a third body reaction

Table 2: Kinetic Reactions Included in One Dimensional Chemistry Simulations (ctd)

	A	N	B
OH + CH2O = HCO + H2O	7.943E12	0	0.2
H + HCO = CO + H2	1.995E14	0	0
OH + HCO = CO + H2O	1.000E14	0	0
H + C2H2 = C2H + H2	1.995E14	0	19.0
O + C2H2 = CH2 + CO	5.012E13	0	3.7
C2H + O2 = HCO + CO	1.000E13	0	7.0
CH2 + O2 = HCO + OH	1.000E14	0	3.7
H + C2H4 = C2H3 + H2	1.000E14	0	8.5
C2H2 + H = C2H3	5.500E12	0	2.39
H + C3H6 = C2H4 + CH3	3.981E12	0	0

4.0 ANALYSIS RESULTS

The PERCORP modelling of the Raptor thrust chamber included 1.2% of the total engine flow (13.89 lb/s) as film coolant. Fuel-rich gas, used fuel film coolant, is injected through three slots located in the converging section of the thrust chamber. The PERCORP code is not currently capable of treating three discreet injection slots; however, since the slots are all within just a 0.71-inch axial length, the total film cooling effect on the exhaust plume can be reasonably approximated using just a single. The PERCORP solution for the nominal 349. 6 lbf-s/lb_m engine specific impulse includes a 2.3% core mixing loss, yielding a characteristic velocity (C*) efficiency of 98.6%. The PERCORP results included initial boundary conditions for the VIPER nozzle flow field simulation. The predicted thrust chamber nozzle exit species mass fractions from VIPER are listed in Table 3.

The SPF modelling stepped to 100 nozzle exit radii (Rexit = 25.613 inches, 2.134 ft). Predicted plume contours for temperature and mass fractions of N_2 and CO are presented in Figure 1 through Figure 3. Since there plume entrainment and mixing field is simulated for chemically frozen flow, the N_2 contours are representative of the air entrainment, while the CO contour indicates a key product of incomplete combustion.

Table 3: Thrust Chamber Nozzle Exit Species Mass Fraction from VIPER Simulation

Species	Mass Fraction
CO2	0.39950
H2O	0.41333
CO	0.12071
O2	0.054752
H2	0.007462
OH	0.0035882
O	5.3558E-04
CH4	7.286E-05
H	5.207E-05

Figure 1: Plume Temperature Contours (degrees K)
R is radius normalized by Rexit, X is axial distance from nozzle exit normalized by Rexit

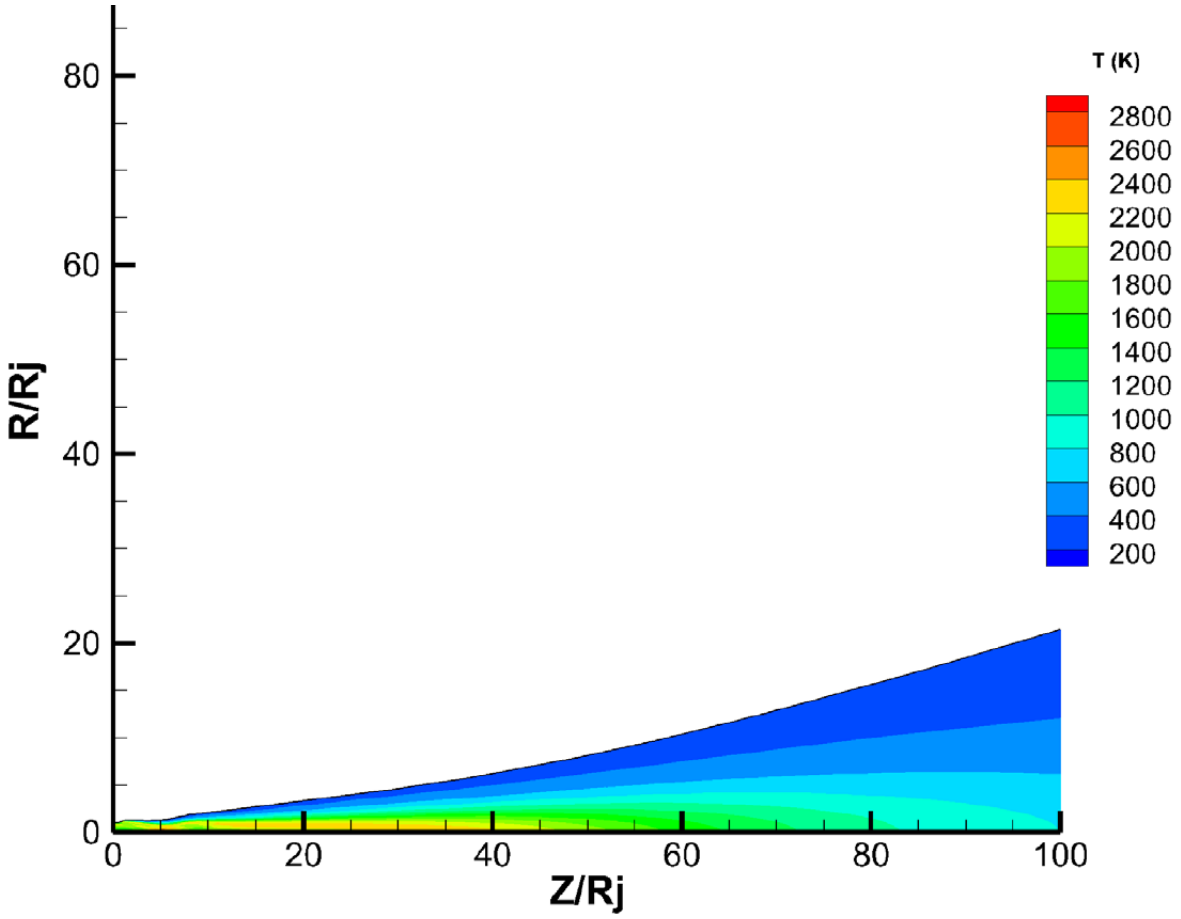


Figure 2: Plume N_2 Mass Fraction Contours
R is radius normalized by Rexit, X is axial distance from nozzle exit normalized by Rexit

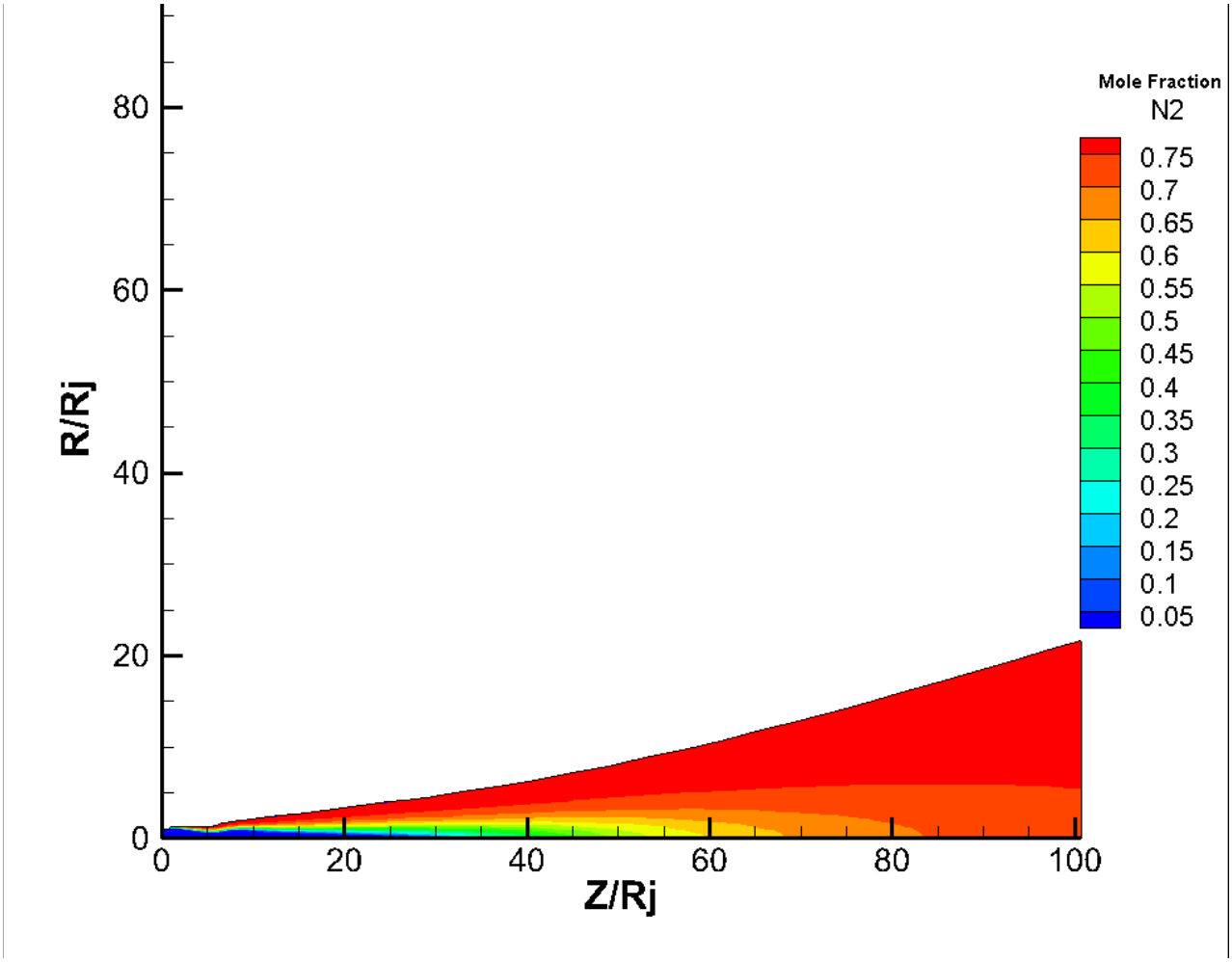
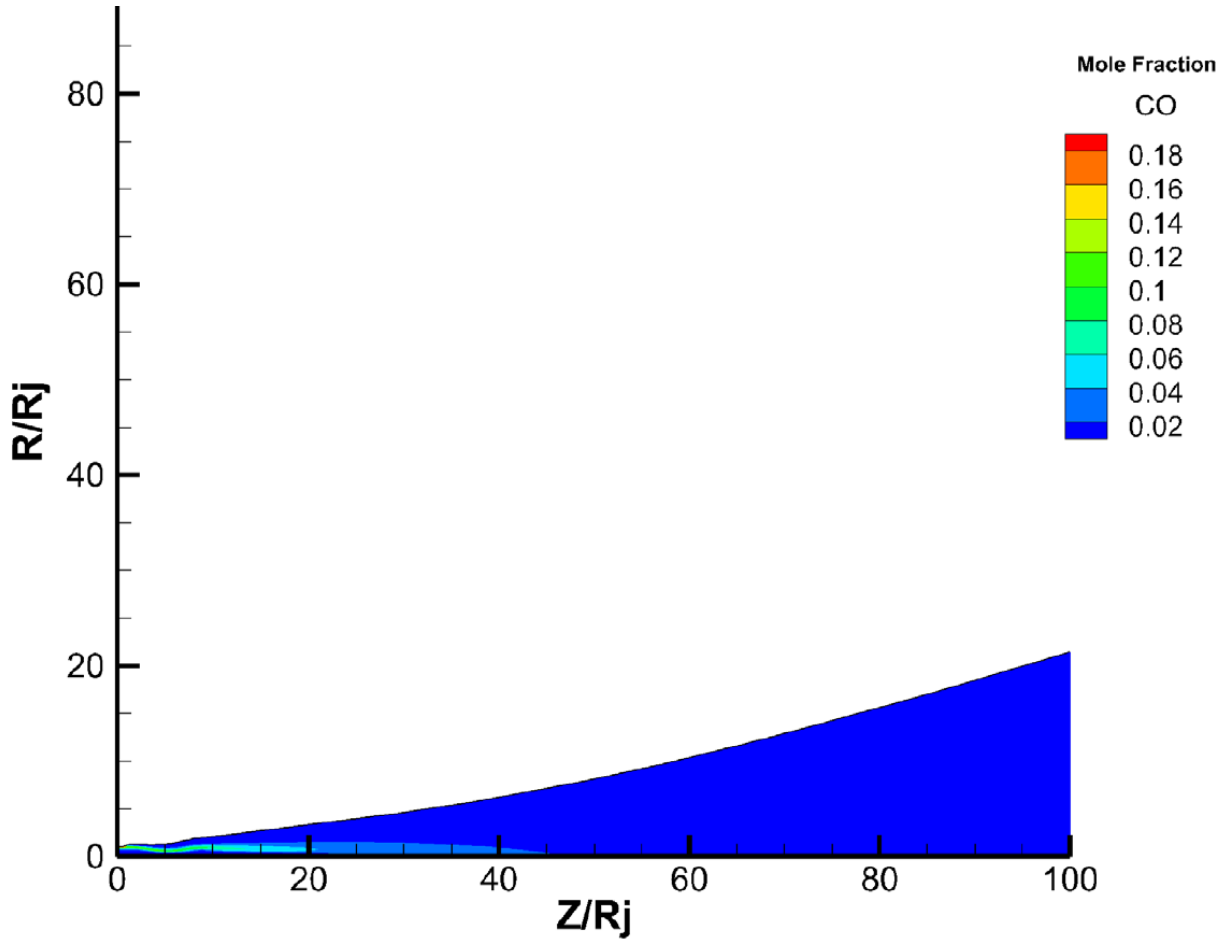


Figure 3: Plume CO Mass Fraction
R is radius normalized by Rexit, X is axial distance from nozzle exit normalized by Rexit



The reactive plume was defined to include all flow that had a CO concentration greater than 1,000 ppm. Integration of the SPF data indicates that 23,079 lb/s air is entrained by the end of the simulation (Figure 4). It is estimated that the 215 foot entrainment end point is reached 179 msec after the plume flow exits the nozzle.

The subsequent TDK simulation of the plume chemistry required an approximate fit of the air entrainment rate. The SPF air entrainment profile was fit to an "availability profile" for the TDK simulations, whereby ambient air is mixed into the plume flow. Figure 5 shows that the approximate TDK air addition agrees well with the entrainment rate predicted by SPF.

Figure 4: Axial Air Entrainment Estimates from SPF.

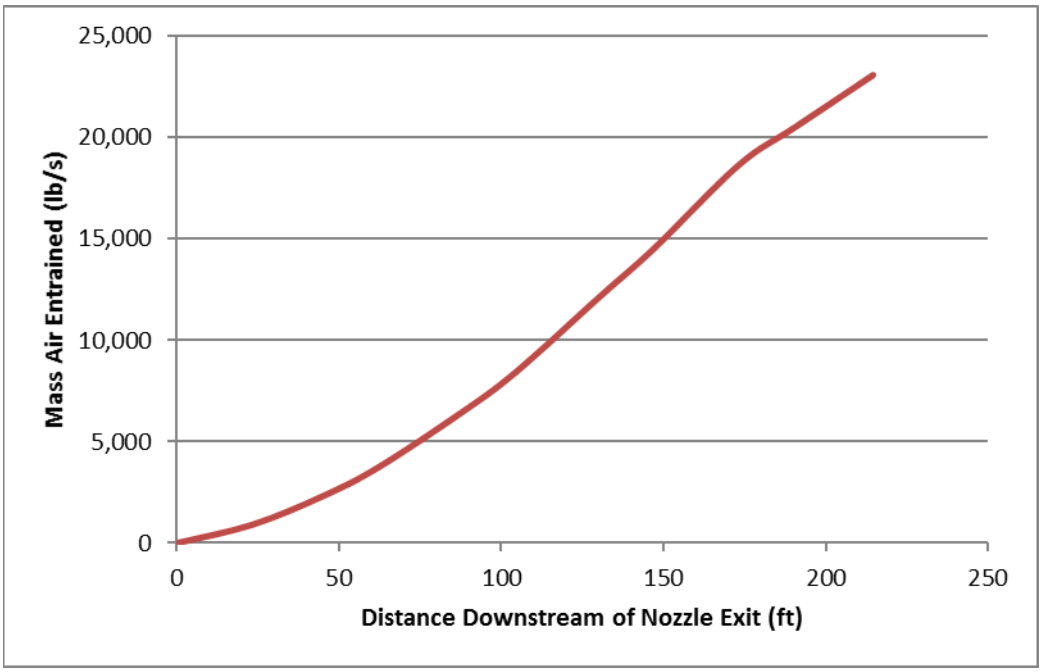
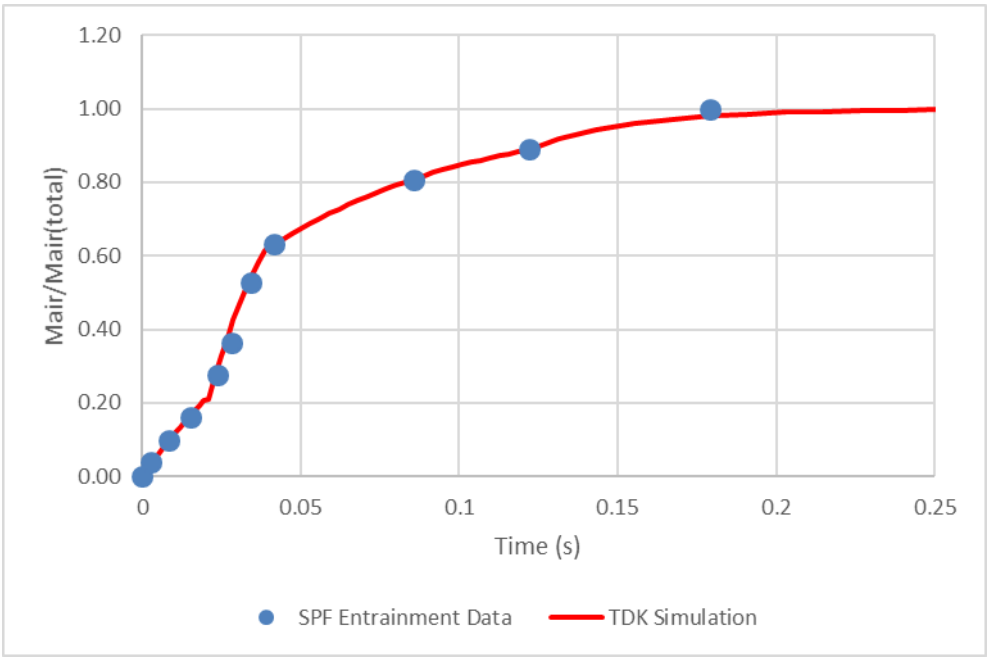
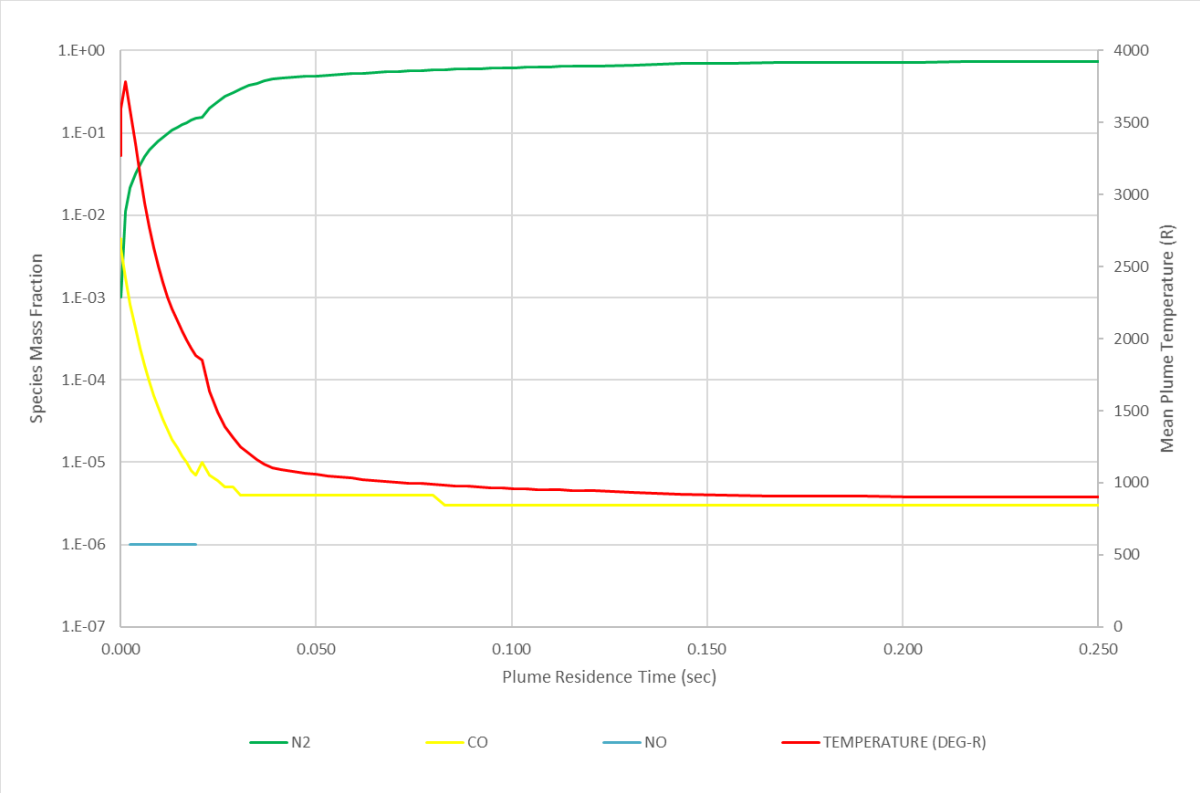


Figure 5: Approximate Air Entrainment Profile used in TDK Simulations



The one-dimensional kinetics modeling of the after-burning characteristics of the exhaust plume was performed assuming a piecemeal constant pressure (13.3-14.7 psia) and entrainment of ambient temperature air. The small concentration of unburnt methane is rapidly oxidized, surviving less than 1 msec. The model predicted that nearly complete CO oxidation occurs, with concentrations reduced to 3 ppm within 100 msec. The plume exit concentration is approximately 1 ppm. There is no significant thermal NO formation, with just 1 ppm formed during the early part of the entrainment process. The NO mass fraction at the end of the 215 ft long plume entrainment is less than 1 ppm. Given the total mixed plume mass flow rate of 24,227 lb/s, this corresponds to CO and NO mass flow rates of no more than 0.024 lb/s for each. Figure 6 shows the predicted temperature and pollutant species mass fraction profiles. The pollutant flow rates were calculated in terms of lb_m generated per second of steady engine operation.

Figure 6: Predicted Profile of Bulk Plume Temperature and Species Mass Fraction



Due to the complexity of how the 31 engines are integrated into the base of the Super Heavy vehicle, there is not a simplified method to directly predict the air entrainment and exhaust burnout chemistry for the installed engines. An extensive computational fluid dynamics (CFD) analysis would likely be needed to fully address the entrainment process. However, engineering judgement can be used bound the problem. The outermost 24 engines will entrain air like the single engine for the outboard portion of their flow (about 50%), but the inboard portion of the flow will interact with the exhaust from the inner engines, delaying the time and distance before

the plume flow field interacts with ambient air. The centermost 7 engines will likely entrain rocket exhaust plume for a significant amount of time before air entrainment begins. The effluent from the rocket nozzle exhaust only contains significant amounts of CO as an unburned combustion product, and there is no propellant nitrogen included in the rocket nozzle exhaust. It is likely that the hot interior CO will oxidize as soon as air is available (entrained) and the only NO is formed as a result of the small time window when the exhaust is hot and there is air introduced into the plume. With this description of the global flow field generated by the Super Heavy, it is likely that the exhaust plume length is 3-4 times longer than predicted for a single engine (645-860 ft), but that the CO and NO emission for the Super Heavy are no more than 31 times the single engine level (0.744 lb_m/s for each).

The same Raptor engine is used on the upper stage Starship. Starship uses a cluster of 7-engines (6 around 1). Using the same logic as above, the plume flow field for the Starship configuration should be 2-3 times longer than predicted for a single stand-alone engine (430-645 ft), with total CO and NO emission rate no more than 0.168 lb_m/s each.

5.0 REFERENCES

[1] *Performance Correlation Program (PERCORP 2006) Reference and User's Manual, Version 2.0*, Sierra Engineering Inc., Carson City, NV, June 2009

[2] *Viscous Interaction Performance Evaluation Routine For Two-Phase Nozzle Flows With Finite Rate Chemistry, VIPER 4.5*, Software and Engineering Associates, Carson City, NV, 2018

[3] Taylor, M.W. and Pergament, H.S.; *Standardized Plume Flowfield Model SPF-III, Version 4.2 Program User's Manual*, PST TR-51, Propulsion Science and Technology, Inc. East Windsor, NJ, June 2000

[4] Nickerson, G. R., Dunn, S.S., Coats, D.E. and Berker, D.R.; *Two-Dimensional Kinetics (TDK) Nozzle Performance Computer Program User's Manual*, Software and Engineering Associates, Carson City, NV, Jan 1999