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March 21, 2017

VIA ELECTRONIC FILING

Ms. Kimberly D. Bose, Secretary
Federal Energy Regulatory Commission
888 First Street, N.E.
Washington, D.C. 20426

Re: Rio Grande LNG, LLC and Rio Bravo Pipeline Company, LLC
Docket Nos. CP16-454-000 and CP16-455-000

Dear Ms. Bose:

Rio Grande LNG, LLC and Rio Bravo Pipeline Company, LLC (collectively "RG Developers") hereby submit for filing in the above-referenced dockets, information supplementing their May 5, 2016 application. The documents filed as part of this submission are as follows:

1. Response to the Federal Energy Regulatory Commission ("FERC") October 27, 2016 Engineering Information Request No. 2 on Rocket Launch Failures Siting Concerns;

2. Response to the FERC October 27, 2016 Engineering Information Request No. 3 on Rocket Launch Failures Siting Concerns; and

3. Response to the FERC October 27, 2016 Engineering Information Request No. 4 on Rocket Launch Failures Siting Concerns.

Pursuant to Rule 388.112 of the Commission's regulations, the RG Developers hereby request confidential treatment for a portion of this response because it contains Critical Energy Infrastructure Information ("CEII").[1] Such information merits CEII treatment as it identifies areas within the Rio Grande LNG Export Terminal site that could be viewed as vulnerabilities and the relative likelihood of debris from a damaged launch vehicle impacting the site. The confidential information is submitted under seal and has been marked "Contains Critical Energy Infrastructure Information – Do Not Release." Questions regarding this request for confidential treatment should be directed to the undersigned.

The transmittal letter is being served on the entities on the Commission's service lists for the relevant dockets. The public portions of the materials filed will be available on the FERC's e-library system once posted.

Should you have any questions about these matters, please feel free to contact the

[1] 18 C.F.R. § 388.112 (2016).

undersigned at (202) 662-4555.

Respectfully submitted,

/s/ Erik J.A. Swenson
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Attorneys for Rio Grande LNG, LLC and
Rio Bravo Pipeline Company, LLC

EJAS/AC
Enclosure

cc: Gertrude Johnson (FERC)
Jennifer McCoy (EDGE Engineering and Science, LLC)

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

FERC October 27, 2016 Engineering Information Request, No. 2 on Rocket Launch Failures Siting Concerns:

As part of the impact analysis from potential future space launch missions, include a quantification of risk (likelihood and consequences) in accordance with 14 CFR Parts 415 and 417. This analysis should account for all future launch vehicle-series including but not limited to Falcon 9, Falcon Heavy, Interplanetary Transport System launch vehicle, and shall address the following:

a. The consequence analysis should include all events that would reach or extend into the LNG plant boundary or LNG shipping channel [*sic*],[1] that could impact personnel or impact the LNG facilities based on the design failure limits of occupied and unoccupied buildings (walls and roofs), tanks (outer walls and roofs), piping, and other equipment. In addition, the following consequences endpoints reaching or extending into the LNG plant boundary or LNG shipping channel should be provided:
    i. Distances to toxic vapors for Acute Exposure Guideline Levels AEGL-1, AEGL-2, and AEGL-3 with uncertainty factors associated with the model and supportive toxic release information/modeling;
    ii. Distances to flammable vapors for the lower flammability limit (LFL) with uncertainty factors associated with the model and supportive flammable release information/modeling;
    iii. Distances to radiant heats—in units of kilowatt per square meter, kW/m^2—for 5 kW/m^2, 10 kW/m^2, and 37.5 kW/m^2 with uncertainty factors associated with the model and supportive fire parameters/modeling;
    iv. Distances to overpressures—in units of pound-force per square inch, psi—for 1 psi, 3 psi, 5 psi with uncertainty factors associated with the model and supportive information on explosion parameters/modeling; and
    v. Distances to projectiles—in units of foot–pound-force, ft-lbf—for 11 ft-lbf, 100 ft-lbf, 1,000 ft-lbf, 10,000 ft-lbf, 100,000 ft-lbf, 1×10^6 ft-lbf, and 3×10^6 ft-lbf with uncertainty factors associated with the model and supportive projectile parameters (mass, velocity, diameter, angle, source, and type) and modeling.
b. The likelihood analysis should include the individual and cumulative equivalent annual frequencies of event(s) that would reach or extend into the LNG plant boundary or LNG shipping channel,[2] that could impact personnel or impact the LNG facilities based on the design failure limits of occupied buildings (walls and roofs), tanks (outer walls and roofs), piping, and other equipment. In addition, events with failure rates of 3×10^{-5} failures per year or higher should be highlighted. Also, include an uncertainty analysis of the frequency data and calculations as well as the source of the frequency data.
c. The risk analysis should be quantified and presented based on individual risk and societal risk and should account for the number of personnel sheltered and in open areas of plant during site preparation, construction, commissioning, normal operations, maintenance, and turnarounds. The number of personnel on LNG ships while in transit and while docked should be accounted for as well.

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[1] The RG Developers note that the "LNG shipping channel" should be referred to as the "Brownsville Shipping Channel"

[2] Ibid

Response:

The RG Developers contracted with ACTA, Inc. ("ACTA") to complete the requested analysis of potential future space launch missions at the Space Exploration Technologies Corporation ("SpaceX") Boca Chica, Texas commercial spaceport launch site ("Spaceport"). ACTA is a recognized subject matter expert in the evaluation of range safety hazards and risks from launch vehicle debris, blast and toxic gases, for the Department of Defense, the Federal Aviation Administration ("FAA"), National Aeronautics and Space Administration ("NASA"), and other international companies and agencies.

The analysis was conducted in accordance with 14 CFR 415 and 417 to:

- Review and select credible launch vehicle-series from the Spaceport launch site;
- Identify potential Spaceport hazards and quantify the consequences distances;
- Screen hazards based on the potential to impact the LNG plant ("Terminal") boundary or the Brownsville Shipping Channel ("BSC"), and include additional likelihood and risk analysis;
- Complete ground safety or flight safety analyses to determine probability and likelihood of a potential impact to the Terminal boundary or the BSC; and
- Assess the risk to the Terminal boundary or the BSC from a SpaceX launch failure.

The results of the ACTA analysis conclude that the risk (including likelihood and consequence) of a potential launch failure leading to an impact to the Terminal boundary or BSC is insignificant. A summary of the key findings from ACTA's Independent Risk Assessment for Space Launch Failures includes:

1. Consequence distances for launch failures leading to toxic vapor dispersion, flammable vapor dispersion, radiant heats, and overpressure do not extend to the Terminal boundary and BSC. These hazards do not pose a risk to the RG LNG Project even in an adverse wind condition (25 to 35 knot range and blowing predominantly to the west or west-northwest).

2. The consequence distances for projectiles show the potential for debris with kinetic energy of 11 ft-lbs (foot–pound-force) or greater could impact the Terminal boundary and BSC. However:
   a. A launch failure leading to the potential for debris impacts to the Terminal boundary and BSC also requires a launch attempted during adverse wind conditions.[3]
   b. The occurrence of the adverse wind conditions at the Spaceport is a low probability event, with the Spaceport having a greater than 97% launch availability for favorable wind conditions.
   c. During favorable wind conditions, there is a remote potential (less than 1 in 100,000,000 per launch) for debris of greater than, or equal to 11 ft-lbs impacting the Terminal boundary.

3. The probability of debris impacting the Terminal boundary and BSC (assuming a launch during adverse wind conditions) is less than FAA risk criteria detailed in 14 CFR 417.[4]

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[3] These adverse wind conditions are likely to be excluded from the permitted launch conditions.

[4] 14 CFR Appendix B to Part 417, B417.13 states:

> Land hazard areas analysis (a) General. A flight hazard area analysis must establish land hazard areas in the vicinity of the launch site and land hazard areas in the vicinity of each land impact location to ensure that the probability of a

a. LNG Terminal Criteria: 1×10^{-6} per launch for each hazard; and
b. LNG Shipping Criteria: 1×10^{-5} per launch for each hazard.

4. Incorporating the anticipated annual launches from the Spaceport does not result in a likelihood of debris impacting the Terminal boundary or BSC (assuming a launch during adverse wind conditions) at the FERC likelihood criteria of greater than 3×10^{-5} per year.

Given the distance of the Terminal location and the BSC to the Spaceport, and the fact that the ACTA analysis illustrates a risk less than the FAA risk criteria and FERC likelihood criteria, there is no additional action required from the RG Developers in response to FERC's siting concerns. As part of the Waterway Suitability Assessment ("WSA") process, the RG Developers will continue to work with the United States Coast Guard ("USCG") to define the appropriate safety and security measures for LNG vessels transiting the BSC and define the extent of open sea (Gulf of Mexico) exclusion area, downrange from the launch-pad for (general and LNG) shipping around the actual time of launch.

To account for all potential future launch vehicle-series, the RG Developers reviewed available public information to identify and screen the full range of vehicles to be included in an analysis by ACTA.

The Falcon 9, Falcon Heavy, and Falcon 9 related sub-orbital launch vehicles qualify under the screening process for inclusion in an impact analysis, as these launch vehicles meet the threshold criteria for realness and relevance (as determined by evaluating the level of development, operating area and timing for each launch vehicle considered). Falcon 9 related sub-orbital launch vehicles were determined to be able to be conservatively modeled by the Falcon 9 based upon launch vehicle size, amount of propellant used, and the number of anticipated debris. Thus, all conclusions made about the Falcon 9 and Falcon Heavy are applicable to the sub-orbital launch vehicles.

The screening determined that the Interplanetary Transport System ("ITS") does not qualify for inclusion in an impact analysis for three reasons. First, the ITS remains a very early stage concept. Second, the ITS development has not been funded in any significant way and there is no fiscal commitment to see it through on a definite time frame. Third, SpaceX has not proposed or sought launch licensing required to operate the ITS out of the Spaceport.

The screening process also eliminated all other launch vehicles because SpaceX has not proposed to launch any other existing or planned launch vehicles from the Spaceport.

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member of the public being struck by debris satisfies the probability threshold of 1×10^{-6} required by §417.107(b) and to determine exclusion areas that may require entry control and surveillance prior to initiation of flight. The analysis must establish a land impact hazard area that accounts for the effects of impacting debris resulting from normal and malfunctioning launch vehicle flight, except for toxic effects, and accounts for potential impact locations of all debris fragments. The land hazard area must encompass all individual casualty contours and the near-launchpoint blast hazard area calculated as required by paragraph (c) of this section. A launch operator may initiate flight only if no member of the public is present within the land hazard area. B417.11 Ship hazard areas analysis (a) General. A flight hazard area analysis must establish ship hazard areas bound by the 1×10^{-5} ship impact contour in the vicinity of the launch site and the vehicle's three-sigma dispersion limit plus a 5nm buffer in the vicinity of a planned, downrange impact location.

Attachment A describes in further detail the RG Developers' launch vehicle screening criteria and the application of such criteria to existing and future launch vehicles.

a. A consequence analysis was performed by ACTA and includes a quantitative modeling analysis to determine if the hazards from the Spaceport could reach or extend into the Terminal boundary or BSC (see Figure EIR 2-1 for relative distances). Hazard zones impacting the Terminal boundary and BSC could potentially impact personnel or impact the Terminal facilities based on the design failure limits of occupied and unoccupied buildings (walls and roofs), tanks (outer walls and roofs), piping, and other equipment. The results of this consequence analysis are contained herein as Attachment B, with specific results summarized below.

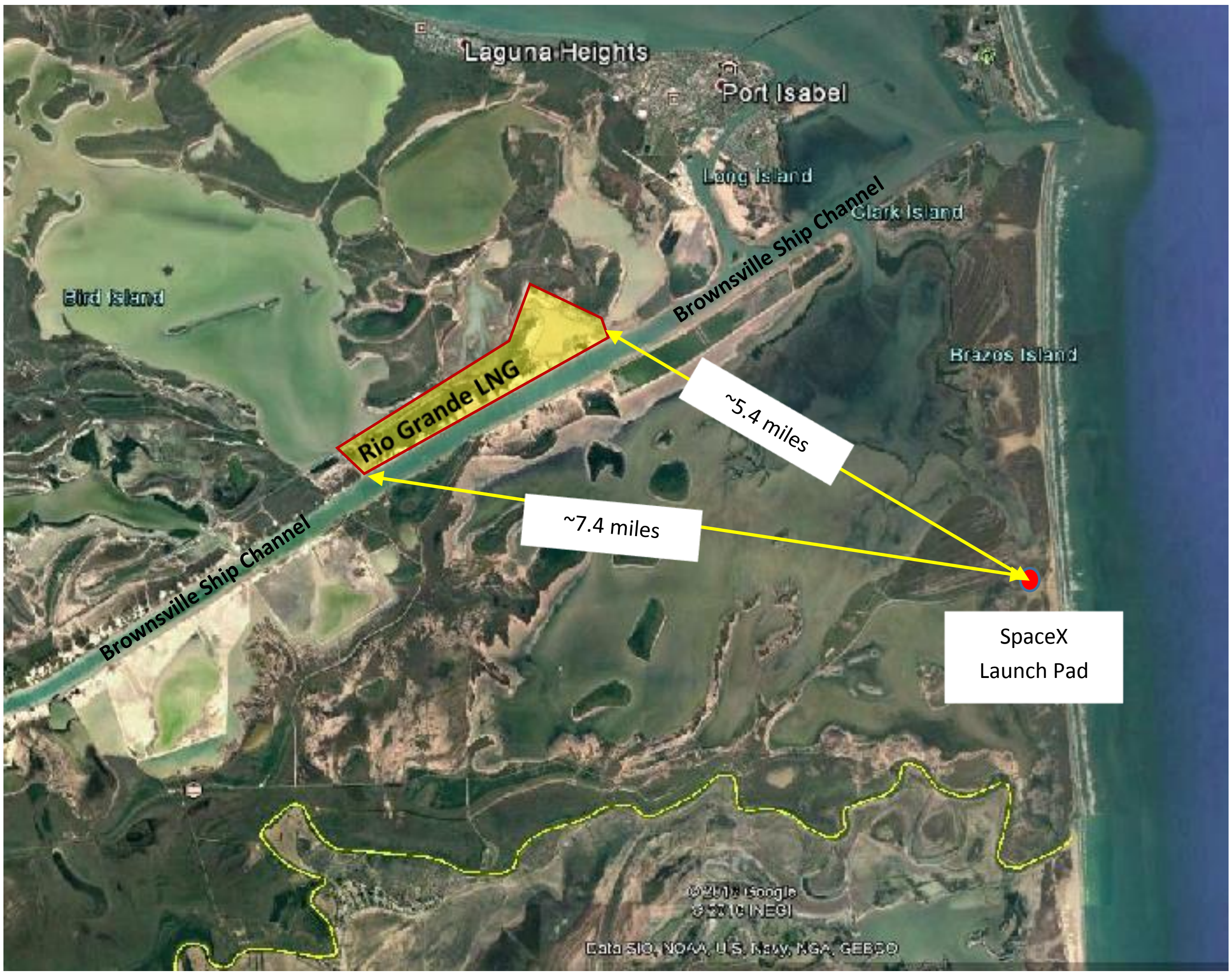

Figure EIR 2-1 Relative Distances between the Spaceport and the Terminal, and the BSC

As the Falcon Heavy represents the most conservative approach to the requested analysis in terms of propellant volume and the number of predicted debris, the RG Developers are presenting the results of the on-ground analysis on the Falcon Heavy launch vehicle for items i. through iv. Due to the differences in the thrust to weight ratio between the Falcon 9 and the Falcon Heavy causing some of the predicted results for the Falcon 9 to present a higher dispersed projectile fall-out risk to the Terminal and the identified critical areas, the in-flight analysis for both the Falcon 9 and Falcon Heavy is captured in item v. The following items are in response to the specifically requested information:

i. The toxic vapor distances were calculated for a worst case instantaneous spill of the entire contents of a stage-1 rocket-grade kerosene ("RP-1") propellant tank. This spill scenario will result in an evaporating pool, with toxic vapors dispersing downwind. ACTA modeled this scenario using the Launch Area Toxic Risk Assessment-3D computer code ("LATRA3D"). The distance to the FERC requested, Acute Exposure Guideline Levels ("AEGL") concentration, is predicted to be (with a 50% uncertainty factor included):
   1. AEGL-1 (42 ppm) at 20,080 feet;
   2. AEGL-2 (161 ppm) at 7,800 feet; and
   3. AEGL-3 was not evaluated, as the AEGL committee has made no recommendation on this exposure threshold, but it is expected to be retained within a close proximity to the launch pad.

   RP-1 vapor concentrations to the AEGL levels do not reach the Terminal boundary or the BSC. Please note, toxic hydrogen chloride gases from combustion of the propellant were not considered since the launch vehicles do not utilize solid propellant stages.

ii. The distance for flammable RP-1 vapor dispersion was evaluated for the same scenario as the toxic hazard (e.g., instantaneous spill of the entire contents of a stage-1 rocket-grade kerosene (RP-1) propellant tank). ACTA modeled this scenario using the LATRA3D. The distance to the FERC requested "LFL" and ½ LFL concentrations, is predicted to be (with a 50% uncertainty factor included):
   1. 1 LFL (6,000 ppm) 195 feet; and
   2. ½ LFL (3,000 ppm) 790 feet.

   Flammable RP-1 gaseous concentrations do not reach the Terminal boundary or the BSC. It is noted that the potential for ignition of the flammable cloud and potential for vapor cloud explosion was considered; however, the potential to generate a significant overpressure is negligible due to vaporization rate and limited confinement and congestion.

iii. The distance to radiant heats levels were calculated for a fireball from the full propellant quantity. ACTA modeled a fireball from 2,720,000 pounds of liquid oxygen & RP-1 using the LATRA3D. The distance to the FERC requested thermal radiation levels, is predicted to be:
   1. 5kW/m^2 at 7,230 feet;
   2. 10kW/m^2 at 5,170 feet; and
   3. 37.5kW/m^2 at 2,670 feet.

   Radiant heat levels at any material or critical level do not reach the Terminal boundary or the BCS.

iv. The distances to overpressures were calculated for an on-pad vehicle explosion. ACTA modeled the explosion using the Hazardous Explosion software. The distances to the FERC requested overpressure levels, are predicted to be:
   1. 1 psi at 3,700 feet;
   2. 3 psi at 1,400 feet; and
   3. 5 psi at 950 feet.

Overpressure levels at any material or critical level do not reach the Terminal boundary or the BSC.

v. The distances to projectiles from an on-pad vehicle explosion are predicted by ACTA to be contained within an arc of 4,800 feet (with 99% confidence) from the launch pad. No fragments from an on-pad explosion are expected to reach the Terminal boundary or the BSC.

Analyses were also performed by ACTA for the first 100 seconds of flight of the Falcon 9 and the Falcon Heavy vehicles in order to simulate failures up to a point in flight where the vehicles are well above the jet stream and have established a significant downrange eastward velocity (1,130 ft/s for the Falcon 9 and 1,990 ft/s for the Falcon Heavy).

Given the large area identified within the Terminal boundary, and the dependency of an impact with the distance to the launch pad, it was desirable to determine critical equipment and personnel areas within the Terminal boundary. During this determination, the RG Developers arrived at the conclusion that the process trains and utility areas have "good" proxies within the five identified Terminal critical areas. ACTA then generated impact probabilities for the 5 Terminal critical areas which account for all 1,332 Falcon 9 and all 2,505 Falcon Heavy vehicle debris pieces, and then further filtered to partition the impact probabilities into the requested 7 kinetic energy classifications:

1. 11 ft-lb or greater;
2. 100 ft-lb or greater;
3. 1,000 ft-lb or greater;
4. 10,000 ft-lb or greater;
5. 100,000 ft-lb or greater;
6. 1,000,000 ft-lb or greater; or
7. 3,000,000 ft-lb or greater.

The ACTA analysis showed that there is potential for debris to impact within the Terminal boundary. Therefore, the probability and likelihood of debris impacting the five identified Terminal critical assets for the seven FERC requested kinetic energy classifications is discussed further below in response to b.

b. The probability (per launch basis) and frequency (per year basis) of a launch failure, and subsequent debris, that would extend into the Terminal boundary or the BSC were evaluated taking into account both a non-adverse wind condition launch window, which occurs approximately 97.3% of the year, and an adverse wind condition launch window, which occurs approximately 2.7% of the time. The probability of impacting the Terminal critical assets for a launch occurring during the non-adverse wind condition launch windows is at least 1 to 2 orders of magnitude less than that of an adverse wind condition (less than a 1 in 5,000,000 occurrence per launch). This will result in a probability of impacting the Terminal critical assets with less than a 1 in 100,000,000 occurrence per launch. Additionally, the probability of an individual event that would reach or extend into the Terminal boundary, cumulatively impacting the Terminal assets, or the BSC does not exceed the FAA criteria of 1×10^{-6} per launch (14 CFR 417).

For a launch under an adverse wind condition, the probability of an individual event that would reach or extend into the LNG plant boundary will not exceed the FAA criteria of 1 X 10^{-6} per launch for the LNG Terminal boundary. Specifically, the Table EIR 2-1 summarizes the combination of the seven requested kinetic energy classifications for the LNG Terminal boundary and the Terminal critical areas for a Falcon 9, with Table EIR 2-2 summarizing the same for the Falcon Heavy. Tables EIR 2-1 and EIR 2-2 are contained herein as Attachment C.

The impact probabilities of an individual event in the BSC are predicted to be one order of magnitude greater (i.e. higher by a factor of 10) than the results presented for the Terminal boundary due to BSC's approximate area being ½ the size of the area within the overall Terminal boundary and the closer proximity of the BSC to the SpaceX Spaceport. For a launch under an adverse wind condition, the probability of an individual event that would reach or extend into the BSC will not exceed the FAA criteria of 1 X 10^{-5} per launch for the BSC.

The RG Developers note from the SpaceX Spaceport Final Environmental Impact Statement, that the control systems and personnel for a launch are located between the Terminal and the launch pad (approximately two miles from the launch pad), and SpaceX may elect not to launch during adverse wind conditions for the safety of their personnel, given the extremely low frequency of these conditions occurring. It is highly probable that SpaceX will self-impose a day-of-launch weather constraint to reduce the risk to their own facilities and nearby general public area.

Incorporating the expected launches per year for the Falcon 9 and Falcon Heavy, the probabilities in Tables EIR 2-1 and EIR 2-2 can be expanded from a per launch basis to an annual basis. The cumulative annual frequency of launch events that would impact Terminal critical assets, or the BSC will not exceed the FERC frequency criteria of 3 X 10^{-5} per year. Tables EIR 2-3, 2-4 and 2-5 enumerate the cumulative annual frequencies assuming 12 launches of the Falcon 9, 11 launches of the Falcon 9 and 1 launch of the Falcon Heavy, and 10 launches of the Falcon 9 and 2 launches of the Falcon Heavy, respectively. Tables EIR 2-3, EIR 2-4 and EIR 2-5 are contained herein as Attachment C.

c. Based on the results of the ACTA analysis, which illustrates that the risk to the Terminal critical assets and BSC are lower than the FAA risk criteria (per launch basis), and the FERC likelihood criteria, the societal and individual risks are concluded to be insignificant and adequately controlled for personnel sheltered and in open areas of the plant during site preparation, construction, commissioning, normal operations, maintenance, and turnarounds, or on LNG ships while docked.

While the ACTA analysis shows that there is a remote potential for debris impacting the BSC during an adverse wind condition launch window, the actual potential for debris impacting an LNG vessel in transit will be reduced by a factor of almost 100 to a less than 1 in 5,000,000 occurrence. This is based upon an anticipated 312 shipments per year at full build-out of all 6 trains and a one-hour transit time in the channel for ingress and egress resulting in a rate of an LNG vessel occurrence of 0.07. Further, as part of the WSA process the RG Developers will continue to work with the USCG to define any safety and security measures for LNG vessels and other vessels associated with the Rio Grande LNG project that may be appropriate to operating within the BSC.

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

List of Responders

Response to FERC's October 27, 2016 Engineering Information Request No. 2

Item	Author	Title	Contact Information
Response	Nick Verell, PE	Project Engineer NextDecade, LLC	(832) 426-1553
Attachment A	Erik Swenson	Regulatory Counsel Norton Rose Fulbright	(202) 662-0200
	Nick Verell, PE	Project Engineer NextDecade, LLC	(832) 426-1553
Attachment B	Randy Nyman	Operations Manager ACTA, Inc.	(360) 732-0021
Attachment C	Nick Verell, PE	Project Engineer NextDecade, LLC	(832) 426-1553

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

Attachment A – Detailed Screening of All Potential Future Launch Vehicle Series

ATTACHMENT A

SELECTION OF LAUNCH VEHICLES FOR ANALYSIS

Overview

In conducting this screening, the RG Developers employed boundary conditions analogous to those previously used by the Federal Energy Regulatory Commission ("FERC") in performing LNG terminal safety reviews. This screening determined that the Falcon 9, Falcon Heavy, and Falcon 9 related sub-orbital launch vehicles qualify for inclusion in an impact analysis, as these launch vehicles meet the threshold criteria for realness and relevance (as determined by evaluating the level of development, operating area and timing for each launch vehicle considered).

Other existing or future launch vehicles did not qualify for inclusion in the impact analysis for a variety of reasons. The Interplanetary Transport System ("ITS") did not qualify for inclusion in an impact analysis based on the very early stage of the concept, the lack of fiscal commitment to see it through on a definite time frame, and the fact that SpaceX has not proposed or sought launch licensing required to operate the ITS out of the South Texas launch facility ("SpaceX TX Facility"). Other launch vehicles were excluded based on the lack of any indication that they will operate out of the SpaceX TX Facility.

Screening Criteria

As noted above, only launch vehicles that were deemed to be sufficiently real and relevant to the SpaceX TX Facility were included in the analysis. With respect to the realness criteria, when considering transportation sector safety and reliability impacts on LNG terminals, FERC generally emphasizes vehicles currently in service.[1] Because the current Engineering Information Request requests that future launch vehicles also be considered, this analysis has been extended to include launch vehicles not yet in operation. However, the scope of this review was limited to future vehicles for which there exists (1) a reasonable expectation of future operation of such vehicles, and (2) design information sufficiently detailed and final to meaningfully analyze – concepts that follow the reasonably foreseeable threshold approach used to determine the elements to be included in a National Environmental Policy Act review.[2]

With regard to the relevance criteria, to warrant engineering review of a specific launch vehicle there must be an expectation of such launch vehicle operating: (1) in sufficient proximity to the Rio Grande LNG Project to potentially affect safety, and (2) over a time frame that overlaps with the expected life of the Rio Grande LNG Project.

In the case of the Rio Grande LNG Project site, only launch vehicles operating out of the proposed SpaceX TX Facility would come sufficiently close to the proposed Rio Grande LNG Project site to warrant study. Further, only launch vehicles operating between the time the Rio Grande LNG Project enters the construction phase (currently scheduled for 2018) through the end of the project's expected useful life (approximately 2047) would be relevant.

Screening of Specific Launch Vehicles

Falcon 9

Level of Development - The Falcon 9 is an existing, fully operational launch vehicle of known design. While the Federal Aviation Administration currently licenses individual missions, the Falcon 9 so far has received all necessary regulatory approvals and flown more than 30 missions to date. A small number of mission failures provides information useful to a risk analysis for the Rio Grande LNG Project.

Operating Area - The Final Environmental Impact Statement for the proposed SpaceX TX Facility ("SpaceX FEIS") contemplates launches of the Falcon 9 at the site. See Final Environmental Impact Statement - SpaceX Texas Launch Site, Volume I, Executive Summary and Chapters 1-14 (May 2014) at ES-1. The SpaceX website also expresses SpaceX's intention to launch Falcon 9 vehicles from this site. See http://www.spacex.com/about/capabilities.

Timing - The SpaceX FEIS covers operations through 2025, which overlaps with the proposed construction and operation of the Rio Grande LNG Project. Further, as of February 24, 2017, there were 35 additional future Falcon 9 missions reflected on the SpaceX mission manifest suggesting that this vehicle is likely be operated contemporaneously with the Rio Grande LNG Project.

Falcon Heavy

Level of Development - The Falcon Heavy is not yet operational. However, it represents a largely designed and reasonable evolution of the Falcon 9, incorporating a first stage composed of three Falcon 9 nine-engine cores, and a second stage identical to the Falcon 9 second stage. See http://www.spacex.com/falcon-heavy.

Operating Area - The SpaceX FEIS contemplates up to two launches per year of the Falcon Heavy at the proposed SpaceX TX Facility. See Final Environmental Impact Statement - SpaceX Texas Launch Site, Volume I, Executive Summary and Chapters 1-14 (May 2014) at ES-1. The SpaceX website also expresses SpaceX's intention to launch Falcon Heavy vehicles from this site. See http://www.spacex.com/about/capabilities.

Timing - The first Falcon Heavy is projected to launch in 2017. Further, the SpaceX FEIS covers operations through 2025, which overlaps with the proposed construction and operation of the Rio Grande LNG Project. In addition, as of February 24, 2017, there were six Falcon Heavy missions listed on the SpaceX mission manifest suggesting that this vehicle is likely be operated contemporaneously with the Rio Grande LNG Project.

Falcon 9 related Sub-Orbital Launch Vehicles

Level of Development – SpaceX has designed and operated multiple sub-orbital launch vehicles, including the Grasshopper, and the Falcon 9 Reusable Development Vehicles. To date, these have been test vehicles leading to the Falcon 9 design. SpaceX may develop additional sub-orbital vehicles. The RG Developers anticipate that the risk of such vehicles either: (1) will be treated as less than or equal to that associated with the Falcon 9 and Falcon Heavy vehicles because they are close relatives of the Falcon 9 employing shared technologies but carrying less propellant; or (2) cannot be meaningfully analyzed from a safety standpoint at this time, because the vehicles to be used have yet to be designed. In this regard, we note that the SpaceX FEIS expressly covers "smaller" sub-orbital vehicles. SpaceX FEIS at ES-3.

The sub-orbital vehicles specifically considered in the SpaceX FEIS would use the same propellant/oxidizer combination as the Falcon 9 and Falcon Heavy, but carry only 6,900 gallons of propellant and oxidizers, versus 124,000 gallons for the Falcon 9 and 550,000 for the Falcon Heavy. See SpaceX FEIS Table 4.9-1, at 4-78. Any future sub-orbital launch vehicles would be subject to Federal Aviation Administration licensing requirements and operation of those vehicles would need to take into consideration the Rio Grande LNG Project before the vehicle could be approved.

Operating Area - The SpaceX FEIS contemplates that SpaceX may launch sub-orbital vehicles from the South Texas launch facility.

Timing – The SpaceX FEIS contemplates that SpaceX may launch sub-orbital vehicles during the construction period and operating life of the Rio Grande LNG Export Project.

Interplanetary Transport System (a.k.a. the BFR or Mars Rocket)

Consequently, to perform an impact analysis of the ITS, ACTA would be forced to make assumptions about numerous essential attributes about the ITS. If the ITS were simply a refinement or expansion of the Falcon 9 (e.g., akin to the Falcon Heavy), conducting such an exercise might produce a useful approximation of the consequences of an ITS launch failure. However, it would not be appropriate to simply scale up the Falcon 9 and Falcon Heavy designs as "good" proxies for the ITS because if the ITS ever reaches fruition, its design will represent a true leap in technology.

Level of Development – The ITS represents a visionary concept, but has yet to be developed with sufficient specificity or finality to meet the threshold criteria for realness and relevance.[3]. In describing the ITS, SpaceX's Chief Executive Office, Elon Musk's statements make it clear that some key drivers are not yet determined and much of the technology remains to be developed.[4] Among other things, the payload to be carried is described as "100 people thereabouts" with an undetermined amount of supplies and luggage. Yet, payload is a critical driver of the other details of the ITS. The construction of the ITS's booster would require the first time use of an advanced form of carbon fiber representing, in Mr. Musk's words, "a significant technical challenge." The engine technology also requires a leap forward in order to achieve the highest chamber pressure engine ever built.[5]

The RG Developers' asked their consultant ACTA to review knowns and unknowns about the ITS. To the best of ACTA's knowledge, no vehicle the size of the proposed ITS has ever been assessed by the range safety community and, therefore, no existing debris lists are comparable. Further, because the ITS has not progressed beyond conceptual design, the Center of Gravity and Moment of Inertia of the ITS are not known.[6] In addition, the explosive safety community has not resolved siting requirements for liquefied oxygen in combination with liquefied methane propellants.

Finally, there is no clear funding path for the massive engineering and technological effort required to bring the ITS to fruition. SpaceX's website describes the lack of a funding path going forward and notes Mr. Musk's emphasis on embracing the larger goal before funding can be obtained.[7] Understandably, SpaceX has yet to formally pursue licensing of the ITS.

Operating Area - During the video described above, the ITS is depicted as launching from Cape Canaveral's launch pad 39A in Florida. Mr. Musk mentions that there is the possibility of adding the SpaceX TX Facility to the operating area of the ITS at some unspecified point in the future. However, there is no formal proposal or published plan to do so. Moreover, the SpaceX FEIS makes no provision for operating the ITS out of South Texas. The SpaceX FEIS also does not include consideration of methane as a rocket fuel, which would be essential to operating the ITS there. See SpaceX FEIS Table 4.9-1, at 4-78.[8]

The expected characteristics of the ITS (3.5 times the liftoff weight, 3.6 times the lift-off thrust, 1.1 times the height and 1.2 times the diameter of the Saturn V used for the U.S.'s manned lunar missions) impose constraints on where it can be launched. The SpaceX animation depicts the ITS launching from Cape Canaveral's launch pad 39A, presumably because this site was the formerly used to launch the Saturn V and is the only existing or planned SpaceX facility with the capacity to service a vehicle of this size.

Timing – As noted above, by SpaceX's own estimation, the timing for the ITS is fuzzy. While SpaceX aims to develop the ITS during the Rio Grande LNG Project's operating life, the ITS is clearly speculative at this time, and it is difficult to reliably predict if the ITS or any similar manned Mars rocket will be operated in our lifetimes.

Other Launch Vehicles

While other known launch vehicles exist (see, e.g., https://en.wikipedia.org/wiki/List_of_orbital_launch_systems) and would be susceptible to detailed engineering analysis, all such vehicles can be eliminated from the risk analysis on the basis that none are proposed for operations out the SpaceX TX Facility.

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[1] The February 2017 version of the FERC's *Guidance Manual for Environmental Report Preparation for Applications Filed under the Natural Gas Act, Volume II, Liquefied Natural Gas Project Resources Reports 11 & 13 Supplemental Guidance* states in relevant parts (underscoring added for emphasis):

> "13.G.3 Waterway Safety and Reliability Impact Studies
>
> PROVIDE an analysis that addresses potential safety and reliability impacts of proposed LNG vessels (i.e., LNG carriers, LNG barges, etc.) loaded or unloaded at the project facilities and from <u>current commercial and recreational waterway traffic</u> with reference to other Resource Reports (e.g. Resource Report 8).
>
> 13.G.4 Road Safety and Reliability Impact studies [sic]
>
> PROVIDE an analysis that addresses potential safety and reliability impacts from proposed tanker trucks loaded or unloaded at the project facilities and from <u>commercial and recreational roadway traffic</u> with reference to other Resource Reports (e.g. Resource Report 8). The safety and reliability analysis should include studies that take into account visibility, day/night conditions, passing vehicle direction, passing vehicle contents, sizes, and speeds, and tanker truck contents, sizes, and speeds.
>
> 13.G.5 Rail Safety and Reliability Impact Studies
>
> PROVIDE an analysis that addresses potential safety and reliability impacts from proposed rail cars loaded or unloaded at the project facilities and from <u>current commercial and passenger rail traffic</u> with reference to other Resource Reports (e.g. Resource Report 8). The safety and reliability analysis should include studies that take into account visibility, day/night conditions, frequency, passing rail car direction, contents, sizes, and speeds.
>
> 13.G.6 Air Safety and Reliability Impact studies [sic]
>
> PROVIDE an analysis that addresses potential safety and reliability impacts from <u>current commercial, military, and recreational air traffic</u> near the facility and along the LNG vessel route. with reference to other Resource Reports (e.g. Resource Report 8). The safety and reliability analysis should include studies that take into account visibility, day/night conditions, flight paths, and aircraft sizes and speeds."

Underscoring added for clarity.

[2] The U.S. Coast Guard's Waterway Suitability Assessment ("WSA") is a useful model for comparison against the screening processing used here. In the WSA, the RG Developers included anticipated waterway traffic created by the proposed Annova LNG, LLC ("Annova") and TX LNG Brownsville LLC ("TX LNG") export terminal projects, even though those projects have yet to be constructed, because both Annova and TX LNG have: (1) obtained at least one necessary authorization (i.e., authorizations from the Department of Energy's Office of Fossil Energy ("DOE/FE") to export LNG to countries with free trade agreements requiring national treatment for trade in natural gas ("FTA Authorizations")); (2) have formally applied for multiple additional key approvals or authorizations (e.g., to the FERC for authorization to construct, own and operate the proposed natural gas liquefaction facilities/export terminals, and to the DOE/FE for authorization to export LNG to countries lacking free trade agreements requiring national treatment for trade in natural gas); (3) made public their plans in sufficient detail to make reasonable projections of future waterway traffic impacts attributable to their proposed projects; and (4) are actively pursuing completion of those projects in accordance with published schedules. In contrast, the RG Developers have excluded from its WSA analysis, three additional projects that have been proposed for sites along the Brownsville Ship Channel – Barca LNG, LLC; Gulf Coast LNG Export, LLC; and EOS, LLC. While these three projects have obtained their FTA Authorizations, which may provide information from which hypothetical ship traffic projections

could be inferred, none of the projects have filed the considerably more detailed applications required to obtain approval from FERC. Further, to the RG Developers knowledge, detailed design work for these projects has not been done and the projects are not being actively pursued in a manner consistent with any credible plan to actually implement the projects. In short, these projects were properly excluded from the WSA analysis because none of them are sufficiently real to merit inclusion in a detailed analysis. Similarly, launch vehicles must be screened to separate those that are more imagined than real from those sufficiently developed to support and justify meaningful analysis.

[3] While both the Falcon 9 and Falcon Heavy are discussed on web pages accessible directly from the SpaceX home page, the ITS is not. See http://www.spacex.com/. To find any SpaceX hosted information about the ITS on the internet, it is necessary to go directly to: http://www.spacex.com/mars. The ITS-related site contains two videos with animations of the ITS. The first video is about an hour long and consists of a presentation by SpaceX's Chief Executive Officer Elon Musk. The second video is only a few minutes long and consists of an animation of an imagined ITS mission to Mars. All the information provided by the second video is also provided by the first and not discussed separately here. The only other ITS specific information on the ITS-related site is a link to the slides presented by Elon Musk during the first video. http://www.spacex.com/sites/spacex/files/mars_presentation.pdf. In the video, Mr. Musk explains his rationale for humans becoming interplanetary, identifies hurdles that must be overcome to make travel to the planets practicable, and outlines his approach to solving key hurdles, which involves development of the ITS. The video does not provide a complete description of the ITS. As Mr. Musk notes, his purpose is to make Mars travel "seem possible … something that we could do in our lifetimes." He concedes that "right now [we] are just trying to keep the ball moving forward", the effort is subject to a "very constrained budget", and there is a "good chance we don't succeed."

[4] *See* video at http://www.spacex.com/mars.

[5] Consequently, the ITS will not rely on the Merlin engines used in the Falcon 9, rather the ITS will depend on new, never before used, Raptor engines. The Raptor engine is expected to use methane as fuel, rather than a conventional rocket fuel -- such as the RP-1 (essentially highly refined Kerosene) that propels the Falcon 9 and that will propel the Falcon Heavy. Mr. Musk describes the Raptor as "a lot trickier than the Merlin." It is an essential trick that must be mastered before a Mars venture can succeed because (1) the higher thrust to weight ratio (by about a factor of three compared to the Merlin engine) is crucial; and (2) methane fuel needs to be utilized in order to refuel on Mars. Not only are the Raptor engines still in development, they will be used in an array of 42 engines for the booster – an approach intended to increase reliability, but one that remains untested. Id.

[6] Such details are used to make turn rate calculations, which are an important component of analysis vehicle behavior for risk analysis purposes.

[7] "Musk stated that it's possible that the first spaceship would be ready for tests in four years, with the booster ready a few years after that, but he shied away from exact schedules in his presentation. 'We're kind of being intentionally fuzzy about the timeline,' he said. 'We're going to try and make as much progress as we can with a very constrained budget.' Musk said that the funding could come from several sources, including SpaceX's own cash flow, proposals floated by Musk since last year to develop a satellite constellation, private investments, and his own assets. He also suggested government funding could play a role. 'Ultimately, this is going to be a huge public private partnership,' he said. At the press conference, though, he said that while he has already briefed NASA senior management about his plans, he did not necessarily expect agency funding to help develop it. 'In the future, there may be a NASA contract, there may not be. I don't know,' he said. 'If there is, that's a good thing. If there's not, it's obviously not a good thing.' Musk, though, dismissed questions about the share of funding for the system coming from public or private sources as 'pedestrian' compared to the bigger issues that are driving

the development of the transport system. 'There are larger issues at stake,' he said. 'Are we going to be a multiplanetary species or not?'"
http://spacenews.com/spacex-unveils-mars-mission-plans/

[8] The following additional relevant information appears on the SpaceX website:

"Florida
CAPE CANAVERAL AIR FORCE STATION, SPACE LAUNCH COMPLEX 40
The site's location on the southeast coast of the US provides access to a wide range of low and medium inclination orbits frequently used by communications and Earth-observing satellites and by supply missions to the International Space Station. The site also allows access to geostationary orbits, as well as departures to the Moon and interplanetary destinations. Situated on Cape Canaveral Air Force Station, with Patrick Air Force Base to the south and NASA's Kennedy Space Center to the north, SLC-40 benefits from many support services in the region, including security and launch range control, weather monitoring, ground support infrastructure, payload processing facilities, and long-range tracking cameras capable of observing launches from liftoff through stage separation and second-stage ignition out over the Atlantic.
....
Texas
SPACEX SOUTH TEXAS LAUNCH SITE
SpaceX is building the world's first commercial launch site designed for orbital missions in the Boca Chica area of South Texas. The site's southern, coastal location is uniquely optimized for orbital space launches from the continental United States – it is as close to the equator as possible, while remaining distanced from populated areas. SpaceX South Texas will be optimized for commercial launches, and will support launches of the Falcon 9 and Falcon Heavy to low-Earth orbit, geostationary orbit, and beyond."

http://www.spacex.com/about/capabilities. Underscoring added for clarity.

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

Attachment B - Rio Grande LNG Facility Consequence and Likelihood Analysis Due to Launch Vehicle Failures at the SpaceX Boca Chica Texas Spaceport

Attachment B contains Critical Energy Infrastructure Information.

Those portions of the document that contain confidential information are being submitted under separate cover pursuant to 18 CFR § 388.112.

ACTA Technical Report No. 17-1008/1-02

Rio Grande LNG Facility Hazard Predictions Due to Launch Vehicle Failures at the SpaceX Boca Chica Texas Spaceport

Under Contract to:
Rio Grande LNG, LLC

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March 2017

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1. EXECUTIVE SUMMARY

ACTA Inc., at the direction of Rio Grande LNG, LLC (RG LNG), has conducted consequence and likelihood analyses that evaluated the potential impact of future space launch missions that the Space Exploration Technologies Corporation (SpaceX) has proposed to launch from their Boca Chica commercial spaceport launch site. The launch pad for these vehicles is approximately 5.93 miles to the east-southeast (ESE) of the proposed Rio Grande LNG liquefaction facility and export terminal site (Terminal) located along the northern shore of the Brownsville Ship Channel (BSC). The launch pad is also located approximately 5 miles ESE from the BSC.

To account for all potential credible future launch vehicle-series, RG LNG reviewed available public information to identify and screen the full range of vehicles to be included in an analysis by ACTA. This screening included a review of available public information on the Falcon 9 V1.1, the Falcon Heavy, the Interplanetary Transport System (ITS), sub-orbital launch vehicles, and other potential future launch vehicles.

Following an evaluation of the level of development, operating area and timing of the potential launch vehicle series by RG LNG, only the Falcon 9 V1.1, Falcon Heavy and sub-orbital launch vehicles were qualified for inclusion in these analyses. Given the size and payload capabilities of the sub-orbital launch vehicles as compared to the Falcon 9 V1.1, an analysis of the Falcon 9 V1.1 is more than adequate to account for an analysis of the sub-orbital launch vehicle. Thus, all conclusions made about the Falcon 9 and Falcon Heavy are applicable to the sub-orbital launch vehicles.

In this report, ACTA presents the consequence and likelihood analyses derived from candidate launch vehicle data and application of a suite of range safety analysis computer programs developed by ACTA and used at many of the United States Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) space launch ranges.

Launch vehicle failures pose potential debris impact, blast overpressure, distant focused overpressure, thermal, toxic and flammable plume hazards to the Terminal and the BSC. For any space launch operation, containment of debris hazards and minimization of risk from debris impacts both in the launch area and downrange is one of the most important safety requirements.

The design and implementation of a range safety system is the most critical factor in controlling risk and containing hazards within a launch range, such as the SpaceX Boca Chica spaceport. SpaceX has proposed to use an autonomous flight safety system (AFSS) to detect and prevent vehicles on a malfunction trajectory from exiting a "safe area", but if a violation occurs then the vehicle thrust will be terminated. SpaceX will likely terminate thrust by shutting down the engines and venting propellant by opening valves. Under these conditions the vehicle acceleration is stopped and the vehicle projected impact position stops moving. After thrust termination the vehicle, which is aerodynamically unstable, will begin to tumble and is subject to aerodynamic breakup if the structural load conditions are exceeded. An aerodynamic breakup may lead to an explosive event as the propellant tanks buckle and rupture. In this case debris may be thrown from a different location and at a lower altitude.

This launch vehicle failure analysis report addresses the distances to toxic, flammability, thermal, overpressure (blast and distant focused), and projectile (debris) impacts as specifically requested of RG LNG by the Federal Energy Regulatory Commission (FERC).

As the Falcon Heavy represents the most conservative approach to the requested analysis in terms of propellant volume and the number of predicted debris, ACTA is presenting the results of the on-ground analysis on the Falcon Heavy launch vehicle. Due to the differences in the thrust to weight ratio between the Falcon 9 and the Falcon Heavy causing some of the predicted results for the Falcon 9 to present a higher risk to the Terminal and the identified critical areas, the in-flight analysis and likelihood includes both the Falcon 9 and Falcon Heavy.

- Distances to Toxic Vapors

  Toxic hazard corridor distances associated with rocket grade kerosene (RP-1) Acute Exposure Guidance Levels (AEGL)-1 42 parts per million (ppm) and AEGL-2 161 ppm limits were predicted for an instantaneous spill of the entire contents of a stage-1 RP-1propellant tank. There is no AEGL-3 concentration defined for RP-1, as the Environmental Protection Agency (EPA) AEGL Committee has not made a recommendation on this exposure threshold. The spill scenario produces a very large evaporating pool that defines the worst case toxic plume hazard zone. The AEGL-1 42 ppm hazard corridor downwind distance is predicted to be 20,080 feet with a 50% uncertainty factor (1.5 times the predicted downwind distance) included.

  RP-1 vapor concentrations to AEGL-1 do not reach the Terminal or BSC from an accidental release at the SpaceX spaceport. Emission of toxic hydrogen chloride gases from combustion of the propellant are eliminated due to the absence of solid propellant stages.

- Distances to Flammable Vapors

  Flammable RP-1 plumes or clouds from launch vehicle spill accidents and explosions were evaluated and found to be small for the evaporating pool scenario. The flammable plume downwind length defined by ½ lower flammability limit (LFL), i.e. 3,000 ppm, was predicted to be 790 feet under a stable atmospheric stability condition, a low 1 m/s wind speed, and a 50% uncertainty factor included (1.5 times the predicted downwind distance). The flammable plume downwind length defined by LFL, i.e. 6,000 ppm, was predicted to be 195 feet under a stable atmospheric stability condition, a low 1 m/s wind speed, and a 50% uncertainty factor included (1.5 times the predicted downwind distance).

  The explosive launch vehicle failure event at ground level was predicted to produce vaporized RP-1 that would result in an approximately spherical cloud that could disperse as far as 3,280 feet downwind under high wind conditions before diluting below the LFL.

  No flammable RP-1 gaseous concentrations from spaceport Falcon Heavy accident scenarios are predicted to reach the Terminal or BSC perimeter.

- Distances to Radiant Heats

Thermal radiation from a large liquid oxygen (LOX) + RP-1 fireball involving 2,720,000 pounds of propellant is predicted to generate radiant energy heat flux of: 5kW/m^2 at 7,230 feet from the fireball; 10kW/m^2 at 5,170 feet from the fireball; and 37.5kW/m^2 at 2,670 feet from the fireball [9]. However, the total predicted duration over which there is any significant radiant energy transfer from the fireball is estimated to be approximately 15.1 seconds. ACTA estimates that the potential intact Falcon Heavy vehicle impact location nearest to the Terminal has a separation distance of approximately 22,000 feet, therefore the radiant energy flux of 5kW/m^2 are not predicted to reach the Terminal or the BSC.

- Distances to Overpressures

  The largest propellant quantities will drive the maximum overpressure distances, and therefore, ACTA focused on the Falcon Heavy vehicle (having the largest amount of propellant) to perform this portion of the analysis. The Falcon Heavy when fully fueled contains 2,720,000 pounds of RP-1 and LOX. ACTA applied DoD Standard 6055.9 to determine the TNT explosive equivalent for this type and quantity of propellant. For launch pad operations, the 6055.9 Standard dictates using 20% of the first 500,000 pounds of propellant and 10% of the residual mass to compute the TNT equivalency. Applying this formula to the 2,720,000 pounds of propellant gives 322,200 pounds of TNT equivalent.

  - Air blast incident overpressure of 1 psi, given a Falcon Heavy full propellant load detonation at the launch pad, is predicted to extend to approximately 3,700 feet from the pad and does not impact the Terminal or the BSC.
  - Fragments thrown from an on-pad vehicle explosion are predicted to be contained with 99% confidence within an arc distance of 4,800 feet from the launch pad. No fragments from an on-pad explosion are predicted to reach the Terminal or the BSC perimeter.

- Distances to Projectiles

  - Wind Data Processing

    Adverse wind conditions could result in the greatest debris impact probability at the Terminal and BSC, however, when an adverse wind condition (i.e. where the average wind speeds within the vertical profile are in the 25 to 35 knot range and blowing predominately to the west or west-northwest), is not present, the probability of debris impacts near, or within, the Terminal perimeter is reduced by at least an approximate 1 to 2 orders of magnitude (a factor of at least 10 to 100). The estimated probability for an adverse wind condition on the day of launch is 0.027, or 2.7%.

    If launches were allowed to take place under adverse wind conditions, in certain cases there exists a less than 1 in 5,000,000 occurrence per launch for an impact energy greater than, or equal to 11 ft-lbf may impact the Terminal perimeter. However, launches under these adverse wind conditions are not expected as the Federal Aviation Administration (FAA) flight safety protocols require SpaceX to meet acceptable risk thresholds expressed in terms of human serious injury casualty expectations.

    In particular, while the FAAdoes not dictate to SpaceX, or any other launch operator, what wind conditions are permissible, it does limit the permissible risk associated with a launch taking into account the actual wind conditions at the time of the launch. Appendix B to Part 417 – Flight Hazard Area Analysis for Aircraft and Ship Protection – of the Code of Federal Regulations states, in relevant part:

> "A flight hazard area analysis must establish land hazard areas in the vicinity of the launch site and land hazard areas in the vicinity of each land impact location to ensure that the probability of a member of the public being struck by debris satisfies the probability threshold of 1×10^{-6} …. A launch operator may initiate flight only if no member of the public is present within the land hazard area. … [T]he analysis must account for trajectory and breakup dispersions, variations in debris class characteristics, and debris dispersion due to any wind condition under which a launch would be attempted."

Absent SpaceX identifying other mitigations measures that successfully mitigate the risk, SpaceX may elect to constrain their launch attempts to exclude cases with high surface winds, buffeting or excessive wind speed and direction shears aloft. Given that these possible self-imposed constraints are unknown at this time, the modeling for the consequence and likelihood analyses takes into account the frequency of occurrence of adverse wind conditions, thus yielding conservative estimates of actual debris impact calculations near, or within, the Terminal site.

- Debris Dispersion Analyses

The impact probabilities described below have been adjusted to take into account the rate of occurrence of an adverse wind condition on the day of the launch.

ACTA's findings regarding these hazards are summarized as follows:

- The impact probabilities on a per-launch basis in the BSC are anticipated to be one order of magnitude (i.e. a factor of 10) higher than the following results presented for the Terminal due solely to the closer proximity of the BSC to the launch pad.

- Falcon 9 V1.1 vehicle impact probabilities on a per-launch basis (in order of decreasing probability):
  - There is approximately less than, or equal to, a $1.81 \text{ X } 10^{-7}$ probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal perimeter.
  - There is approximately less than, or equal to, a $9.98 \text{ X } 10^{-9}$ probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG storage tank area.
  - There is approximately less than, or equal to, a $7.99 \text{ X } 10^{-9}$ probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG vessel loading area.
  - There is approximately less than, or equal to, a $7.46 \text{ X } 10^{-9}$ probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal normally occupied building area.

  - There is approximately less than, or equal to, a 5.30 X 10^{-9} probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG truck loading area.
  - There is approximately less than, or equal to, a 3.26 X 10^{-9} probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG rundown line area.
- Falcon Heavy vehicle impact probabilities on a per-launch basis (in order of decreasing probability):
  - There is approximately less than, or equal to, a 1.42 X 10^{-7} probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal perimeter.
  - There is approximately less than, or equal to, a 6.44 X 10^{-9} probability per launch of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal normally occupied building area.
  - There is approximately less than, or equal to, a 5.82 X 10^{-9} probability of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG storage tank area.
  - There is approximately less than, or equal to, a 4.87 X 10^{-9} probability per launch of getting debris impacts of greater than, or equal to, a 11 ft-lb in in the Terminal LNG vessel loading area.
  - There is approximately less than, or equal to, a 3.50 X 10^{-10} probability per launch of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG rundown line area.
  - There is approximately less than, or equal to, a 2.76 X 10^{-9} probability per launch of getting debris impacts of greater than, or equal to, a 11 ft-lb in the Terminal LNG truck loading area.

2. ABBREVIATIONS & TERMS

AEGL	Acute Exposure Guideline Levels
AFB	Air Force Base
AFS	Air Force Station
AFSS	Autonomous Flight Safety system
AFTOX	Air Force Toxics (computer program)
BSC	Brownsville Shipping Channel
BVEC	Breakup State Vectors
COT	Catastrophic On-Trajectory (vehicle failure)
CG	Center of Gravity
cm	centimeter
CRISE	Cloud Rise (computer program)
CFR	Code of Federal Regulations
CSWG	Common Standards Working Group
DDESB	Department of Defense Explosive Safety Board
DoD	Department of Defense
EPA	Environmental Protection Agency
ESE	east-southeast
FAA	Federal Aviation Administration
FERC	Federal Energy Regulatory Commission
ft/s	Feet Per Second
$ft\text{-}lb_f$	Foot-Pounds Force
FTS	Flight Termination System
HAZX	Hazardous Explosion (computer program)
HFDD	Hazardous Fragment Density Distance
IIP	Instantaneous Impact Point
IV&V	Independent Verification and Validation
KE	Kinetic Energy
kW/m^2	Kilowatts per Square Meter

LATRA3D	Launch Area Toxic Risk Analysis 3-Dimensional (computer program)
LFL	Lower Flammability Limit
LNG	Liquefied Natural Gas
LOT	Loss of Thrust (vehicle failure)
LOX	Liquid Oxygen
lb_m	Pound Mass
lb_m/min	pounds-mass per minute
MFT	Malfunction Turn (vehicle failure)
m/s	meters per second
mg/m^3	milligrams per cubic meter
MFCO	Missile Flight Control Officer
MI	Moment of Inertia
MMH	Monomethyl Hydrazine (spacecraft fuel)
NASA	National Aeronautics and Space Administration
ppm	parts per million
P_f	Probability of Failure
P_i	Probability of Impact
psf	Pounds Per Square- Foot
psi	Pounds Per Square Inch
RA	Random Attitude (vehicle failure)
RG LNG	Rio Grande LNG, LLC
RP-1	Rocket Propellant-1 (kerosene)
RRAT	Range Risk Analysis Tool
RSO	Range Safety Officer
SpaceX	Space Exploration Technology Corporation
Terminal	RG LNG’s Natural Gas Liquefaction Facility And LNG Export Terminal
TTK	Trajectory Toolkit
UFL	Upper Flammability Limit

3. CAPTURE MATRIX

Item 2 a. The consequence analysis should include all events that would reach or extend into the LNG plant boundary or LNG shipping channel, that could impact personnel or impact the LNG facilities based on the design failure limits of occupied and unoccupied buildings (walls and roofs), tanks (outer walls and roofs), piping, and other equipment. In addition, the following consequences endpoints reaching or extending into the LNG plant boundary or LNG shipping channel should be provided:	
i. Distances to toxic vapors for Acute Exposure Guideline Levels AEGL-1, AEGL-2, and AEGL-3 with uncertainty factors associated with the model and supportive toxic release information/modeling;	Section 8.1
ii. Distances to flammable vapors for the lower flammability limit (LFL) with uncertainty factors associated with the model and supportive flammable release information/modeling;	Section 8.2
iii. Distances to radiant heats—in units of kilowatt per square meter, kW/m2—for 5 kW/m2, 10 kW/m2, and 37.5 kW/m2 with uncertainty factors associated with the model and supportive fire parameters/modeling;	Section 8.3
iv. Distances to overpressures—in units of pound-force per square inch, psi—for 1 psi, 3 psi, 5 psi with uncertainty factors associated with the model and supportive information on explosion parameters/modeling; and	Section 8.4
v. Distances to projectiles—in units of foot–pound-force, ft-lbf—for 11 ft-lbf, 100 ft-lbf, 1,000 ft-lbf, 10,000 ft-lbf, 100,000 ft-lbf,, 1 × 106 ft-lbf, and 3 × 106 ft-lbf with uncertainty factors associated with the model and supportive projectile parameters (mass, velocity, diameter, angle, source, and type) and modeling.	Section 9
Item 2 b. The likelihood analysis should include the individual and cumulative equivalent annual frequencies of event(s) that would reach or extend into the LNG plant boundary or LNG shipping channel, that could impact personnel or impact the LNG facilities based on the design failure limits of occupied buildings (walls and roofs), tanks (outer walls and roofs), piping, and other equipment. In addition, events with failure rates of 3 × 10-5 failures per year or higher should be highlighted. Also, include an uncertainty analysis of the frequency data and calculations as well as the source of the frequency data.	Section 9

Item 2 c. The risk analysis should be quantified and presented based on individual risk and societal risk and should account for the number of personnel sheltered and in open areas of plant during site preparation, construction, commissioning, normal operations, maintenance, and turnarounds. The number of personnel on LNG ships while in transit and while docked should be accounted for as well.	Section 10

4. INTRODUCTION

Rio Grande LNG, LLC (RG LNG) has proposed to construct and operate a natural gas liquefaction facility and liquefied natural gas (LNG) export terminal (Terminal) along the northern shore of the Brownsville Ship Channel (BSC). The Terminal boundary facing the proposed Space Exploration Technology Corporation (SpaceX) commercial spaceport located near Boca Chica, Texas ranges between 5.4 and 7.4 miles from the launch pad location as depicted in Figure 4-1. The LNG vessel loading area at the proposed Terminal site is located approximately 5.93 miles from the launch pad.

Figure 4-1 Terminal Location Relative to the SpaceX Boca Chica Spaceport.

SpaceX has published plans indicating that the Boca Chica spaceport will involve launches of the Falcon 9 V1.1 variants, the Falcon Heavy, and sub-orbital vehicles (the only known types being smaller variants on the Falcon 9). The Interplanetary Transport System (ITS) is not currently included in the published plans for the Boca Chica spaceport. Each of these vehicles uses only liquid propellants consisting of liquid oxygen (LOX) and rocket grade kerosene (RP-1).

Figure 4-2 SpaceX Falcon 9 and **Falcon Heavy [1]**

Absence of solid propellant stages eliminates two classes of hazards:

1) explosive impacts of large solid propellant fragments or intact solid propellant motors; and
2) emission of toxic hydrogen chloride gases from combustion of the propellant.

Use of hydrocarbon based fuels and LOX further eliminates hazards associated with liquid hypergolic fuels and oxidizers, which are all significantly toxic. Small quantities of hypergols, such as monomethyl hydrazine (MMH) may be used on payloads on these vehicles and these could pose a toxic hazard in the immediate launch pad area or over several hundred feet around a satellite impact following a launch vehicle failure, but are not anticipated to impact the Terminal perimeter or the BSC.

These complex launch vehicles have a history of failures resulting in release of highly energetic and potentially explosive propellants. To minimize risk to the general public, space launch facilities have traditionally been constructed in remote areas with a downrange flight path over broad ocean areas that avoid overflight of densely populated areas.

In this risk evaluation, ACTA has applied industry accepted range safety analysis methods and software tools to assess the probability of exposing the Terminal and the BSC to the common hazards associated with launch vehicle failures. The principle hazards associated with space launch operations can be generally categorized into the following classes, which are ranked approximately in order of hazard concern:

- Explosive and inert debris impacts from errant vehicle flight failures.
- Air blast effects from launch vehicle explosions (both pre-launch ground processing operations and early flight failures).
- Airborne transport and dispersions of toxic propellants or combustion products (typically from combustion of solid propellants or incomplete combustion of hypergolic propellants).

In this report, ACTA provides an overview of remaining debris, air blast, and thermal radiation hazards expressed in terms of threshold values and probability of occurrence based on the results from analyses of the Falcon 9 V1.1 and Falcon Heavy launch vehicles.

5. OVERVIEW OF VEHICLE DATA DEVELOPMENT

ACTA developed vehicle flight trajectories and vehicle breakup debris lists for application to Falcon 9 V1.1 and Falcon Heavy hazard and risk analyses. The assumptions and methodologies applied by ACTA in development of vehicle trajectories and debris lists used in this study are consistent with practices applied to similar data development performed by ACTA in support of space launch vehicle safety assessments performed since 1989 at Vandenberg Air Force Base (AFB), Cape Canaveral Air Force Site (AFS), other DoD launch ranges and, more recently, the Federal Aviation Administration (FAA) office of commercial space transportation.

5.1. Nominal Trajectories

Launches from the Boca Chica spaceport will be constrained to fly within a narrow launch corridor between approximately 93 and 95 degrees azimuth relative to true north [4]. This permits the downrange instantaneous impact point (IIP) to pass through the gap between the southern tip of Florida and Cuba, therefore avoiding densely populated areas in this region. Safety analyses performed in this study assumed that initial stage Stage 1 flight for rockets leaving the Boca Chica spaceport shall fly an azimuth of approximately 94 degees taking the IIP trace nearly due east over the Carribean Sea.

Nominal and 3-σ (sigma) trajectories developed for a historical Vandenberg AFB Falcon 9 V1.1 mission were applied to the Boca Chica spaceport to support the hazard and risk simulations for Falcon 9 V1.1 launches. These trajectories are fairly lofted trajectories, where the vehicle pitch to down range occurs at a higher altitude or the pitch rate to begin moving the vehicle in the down range direction is slower, which ACTA deems to be conservative for application to the Terminal risk assessment. A lofted trajectory will cause debris impact dispersion ground impact uncertainty ellipses to stay in the launch pad area longer, and spread up range and cross range towards the Terminal more than a non-lofted trajcetory.

SpaceX has not released detailed trajectory information for the Falcon Heavy, therefore ACTA generated a trajectory for the Falcon Heavy using published data on the initial thrust and total mass of the Falcon Heavy carrying a maximum payload weight. ACTA applied the pitch rate from the Falcon 9 V1.1 to the Falcon Heavy therefore the loft of the trajectories are the same. The Falcon Heavy, however has a significantly higher thrust-to-weight ratio than the Falcon 9 V1.1 giving the Falcon Heavy a quicker rate of acceleration, which affects the dispersion of the debris and the duration of flight where debris is impacting land in the launch area. The reduction in flight duration where debris is a potential hazard reduces the time integrated impact probability.

5.2. Inert Debris Data Development

ACTA used existing debris lists applied to Falcon 9 V1.1 launches at Cape Canaveral AFS and Vandenberg AFB to evaluate V1.1 debris hazards at the Boca Chica spaceport. The Falcon 9 V1.1 debris list had the following general attributes:

- 1,332 total fragment count
- Fragment mass range = 3,300 to 0.02 lbm
- Explosion induced velocity range = 2000 to 8.5 ft/s

The vehicle explodes upon breakup due to presence of igntion sources, and the mixing of the fuel and oxidizer. Explosion induced fragment velocities are predicted to be highest for light weight pieces nearest the postulated centers of explosion, which for Stage 1 were the aft thrust section and the common internal propellant tank dome that separates the fuel and oxidizer. Although empirical data from past liquid propellant only launch vehicle explosions is limited, the predicted data is within the family of observed data and therefore believed to be credible for this application, and consistent with other analyeses conducted by ACTA.

ACTA generated debris lists for the Falcon Heavy launches based upon vehicle Stage 1 and Stage 2 similarites between the Falcon 9 V1.1 and the Falcon Heavy. The Falcon Heavy essentially uses three of the Stage 1 assemblies with some additional structural hardware to mate the three assemblies together. The Falcon Heavy also has a different payload adapter suited for the larger payload capability. The Falcon Heavy debris list had the following general attributes:

- 2,505 total fragment count
- Fragment mass range = 7,753 to 0.02 lbm
- Intact payload mass = 119,000 lbm
- Explosion induced velocity range = 950 to 12 ft/s

5.3. Vehicle Center of Gravity and Moments of Inertia Data

Center of gravity (CG) and moment of intertia (MI) data is used to predict the vehicle turn rate given a thrust vector offset failure event. In this study ACTA used CG and MI data to support the simulation of 'random attitude' failure modes. A random attitude failure mode represents a rocket guidance and control system failure wherein the launch vehicle flight computer program logic determines that the vehicle current flight path is erroneous and that the vehicle should be flying in a different direction, and then commands the vehicle to go into a maximum turn capability mode to steer onto the new course. If the vehicle survives the aerodynamic loads during the turn to the new heading, it realigns the thrust vector with the long axis of the vehicle and continues stable flight.

The CG and MI data along with a maximum thrust vector deflection angle are used to solve the turn rate equations. For the Falcon 9 V1.1, ACTA used previous mission support CG and MI data applied for a Vandenberg AFB Falcon 9 V1.1 launch. ACTA applied solid cylinder moments of inertia formulas along with stage diameters, lengths, weights and propellant burn rate data to approximate time dependent CG and MI data for the Falcon Heavy vehicle. This method has been applied to new vehicles in past analyses as a substitute when the vendor has not yet generated such data based on full mass properties. ACTA has compared this approach against vendor data for several historical launch vehicles and found that using solid cylinder formulas with inherent uniform mass distribution assumptions provides a reasonable fit to the "real" data.

5.4. Vehicle Failure Modes and Probabilities

One of the objectives of this study is to assign probability of occurrence to hazardous outcomes that could affect the Terminal. A key factor in allocating final hazard probabilities is defining the expected launch vehicle failure probability along with a set of conditional probabilities allocated to possible failure modes. In this study the Falcon 9 V1.1 vehicle is credited with a higher reliability because it has a launch history of 2 stage Stage 1 flight failures out of 30 mission attempts. ACTA has histroically applied a Bayesian update method to derive stage dependent failure probabilities for the Falcon 9 V1.1 launch vehicle.

For the new Falcon Heavy launch vehicle, ACTA applied the methods recommended by the Common Standards Working Group (CSWG). The CSWG consisted of members from the FAA and all the major federal ranges, and undertook a charter to define accepted methods for assigning vehicle failure probabilities. ACTA applied the following Stage 1 flight failure probabilities:

- Falcon 9 V1.1 0.035
- Falcon Heavy 0.083 (0.02 to 0.22 90% confidence)

ACTA assumed that failures of either of the 2 types of SpaceX vehicles at the Boca Chica spaceport could be reasonably approximated by the following 4 classic expendable launch vehicle failure modes [3] with assigned relative probabilities of occurrence [4]:

- Catastrophic on trajectory failure (COT) $P_f = 0.180$
- Loss of thrust failure (LOT) $P_f = 0.205$
- Malfunction turn failure (MFT) $P_f = 0.564$
- Random attitude failure (RA) $P_f = 0.051$

The relative failure probabilites assigned to the failure modes are the same as those estimated for the Falcon 9 V1.1 vehicle and used at Vandenberg AFB.

The federal ranges tend to run risk analyses that do not directly consider uncertainty in the launch vehicle failure probability and instead run risk analyses with discrete P_f inputs. In this study, P_f uncertainty was not considered (in fact the range risk analysis tool (RRAT) is not currently designed to include uncertainty sampling of P_f). However, the failure probability rates are direct linear scale factors on the computed impact probabilites provided the following two conditions apply, and both of which are trye in this study:

- the failure rates are allocted uniformly over the analysis time range
- the relative probabilites of the failure modes are not altered

Therefore if a change to the failure probability of the Falcon 9 V1.1 needed to be considered (e.g. from 0.035 to 0.05), the impact probabilty values reported in this document would all be scaled by a factor (i.e. 0.05/0.035 =1.4286).

5.5. Vehicle Structural Load Capabilities

Structural load capability is an important vehicle attribute that factors into how far from the nominal trajectory track errant launch vehicle debris may reach. Launch vehicles minimize structural weight to improve payload lift capability and reduce needed propellant loads, but do so at the expense of weakening the vehicle. The aerodynamic load limit is typically defined as a "Q-sin(α)" value where "Q" is the dynamic pressure that is based on vehicle velocity and surrounding air density and "α (alpha)" is the angle of attack of the launch vehicle. The sine of the α angle gives the component of the dynamic pressure force that acts laterally on the vehicle and incudes a bending moment that will tend to buckle the the vehicle. These two terms are multipled together and expressed in pounds per square-foot (psf).

Based on historical data for Q-sin(α) values previously computed for the Falcon 9 V1.1 vehicle, ACTA asumed a Q-sin(α) value of 130 psf at a 1 degree angle of attack reference point for both the Falcon 9 V1.1 and the Falcon Heavy vehicles. ACTA has seen Q-sin(α) values for other launch vehicles as low as 52 psf and typical values in the 87 psf range. Therefore, the 130 psf value is understood to be conservative for the purposes of this study as a higher Q-sin(α) value allows the vehicle to sustain a turn longer and get debris farther off the noninal trajectory path than a lower Q-sin(α) would permit.

6. RANGE SAFETY SYSTEM ASSUMPTIONS

The most critical factor in controlling risk and containing hazards within a safe launch area is the design and implementation of a range safety system. Traditionally, this involved a range safety officer (RSO) or missile flight control officer (MFCO) who acted as a "man in the loop" monitoring flight radar tracking and telemetry data and using this information to makes decisions on when to send destruct commands to an erratic launch vehicle. In more recent years, there have been 2 significant trends regarding the role of a MFCO:

- There has been a move away from placing destruct charges on launch vehicles that blow up the vehicle and disperse propellants when the MFCO sends destruct commands. Instead of destroying the vehicle, a simpler system that shuts down thrust of liquid engines is less costly and preferred by launch vendors.
- On-board autonomous flight safety systems (AFSS) are being programmed into multiple redundant flight computers and the range safety system is simplified by removing the ground tracking and associated range safety command and control systems entirely. The flight computer on the launch vehicle tests the current positon and velocity and computes IIP values comparing them against what is acceptable for the mission and if a violation of AFSS rules occurs, the vehicle thrust is terminated.

SpaceX proposes to use an AFSS type approach[1] to detect and prevent vehicles flying on a malfunction trajectory from exiting a "safe area". If a violation occurs, then vehicle thrust is terminated. There are several key considerations to be made regarding risk analysis assumptions to be applied to an AFSS approach:

- ACTA assumed the following basic rules as being loaded into the AFSS:
  - Fixed impact limit lines such that if a propagated vacuum IIP exceeds the limit line then thrust is terminated.
  - If the vehicle net velocity vector is headed toward the ground and the vehicle drops below a threshold altitude of 5000 feet, then thrust is terminated.

ACTA assigned an IIP termination line surrounding the proposed Boca Chica launch pad with the intent that such a fixed termination line would protect people and assets up-range and cross-range from the launch pad and still allow errant random attitude vehicle flight of up to 7 seconds to avoid possibilities of destroying a "good" vehicle. The IIP lines open in the downrange direction allowing a "safe" flight corridor in the direction of the intended nominal and 3-σ trajectories.

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[1] On February 19, 2017 SpaceX launched the first United States vehicle, a Falcon 9, to use an AFSS rather than a MFCO to provide range safety functions. The SpaceX AFSS was previously flown in "shadow mode" on 13 prior flights. The Air Force has developed ground support systems to test and load flight rule data sets to the launch vehicle AFSS.

To provide a conservative estimate of the time delay between when an IIP line violation occurs and when the AFSS takes the action to terminate, ACTA assumed a MFCO delay model with the following setting:

- 5 second minimum failure duration (time allowed to detect and verify that a failure event has occurred)
- Latency = 1 second (delay time between confirmation of a termination condition and when thrust can actually be terminated)
- System response uncertainty = 0.5 seconds (equals one standard deviation applied to a normal distribution)

The MFCO delay model attributes listed above are considered by ACTA to be quite conservative when applied to an AFSS termination system because an autonomous system will not have delays associated with human response and time to transmit termination signals from a ground tracking system to the launch vehicle. Applying these rules to simulated random attitude failure mode trajectories of the Falcon 9 V1.1 and the Falcon Heavy vehicles resulted in the debris IIP containment areas shown in Figure 6-1.

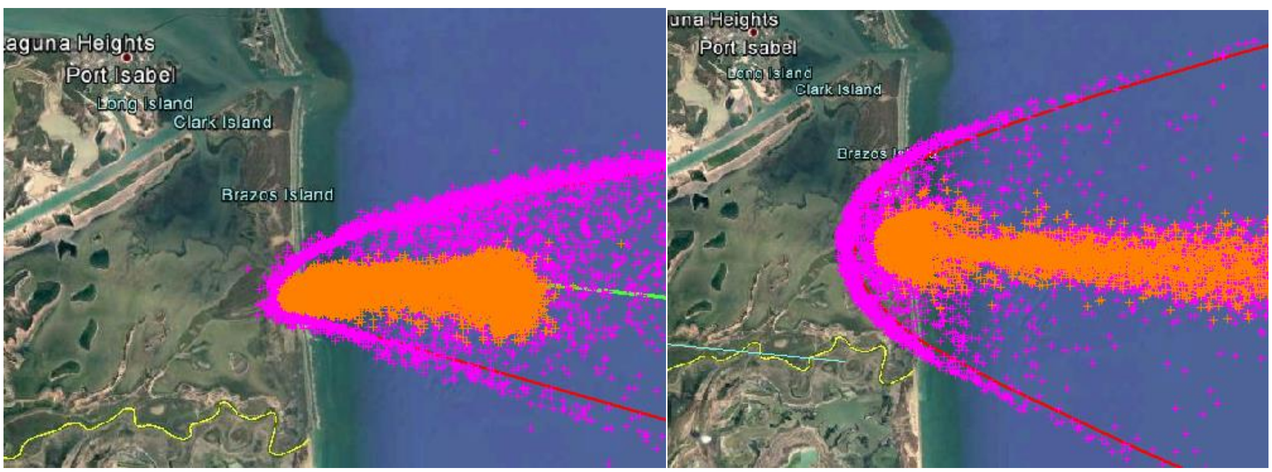


Figure 6-1. Present Position of Vehicle at time of Thrust Termination (Orange + Marks) and IIP Points (Pink + Marks) for Falcon 9 V1.1 (left) and Falcon Heavy (right)

The FAA will require that SpaceX launches from Boca Chica to have a range safety system reliability of 0.999 at 95% confidence. The FAA guidelines indicate that when modeling the consequences of a Flight Termination System (FTS) failure a probability of failure of 0.002 should be applied. In this study effort, ACTA **did not** set up trajectory simulations without range safety constraints.

7. RANGE SAFETY ANALYSIS TOOL OVERVIEW

ACTA performed hazard and risk analyses for this study using software tools and methods that are widely accepted in the range safety community. Each of the software tools has been peer reviewed by an Independent Verification and Validation subject matter expert. The following software tools were applied:

TTK [5][6]	Supports debris hazard and risk analyses
RRAT [7][8]	Supports debris hazard and risk analyses
LATRA3D[9][10]	Supports hazard and risk analyses
HAZX [11][12]	Support ground air blast and fragmentation hazard and risk analyses

The United States Air Force and Army major test ranges (Cape Canaveral AFS, Vandenberg AFB and Reagan Test Site) have been the primary sponsors of the development of TTK, RRAT and LATRA3D, which are applied to hazards associated with the powered phase of flight of rockets. The U.S. Army via the DoD Explosive Safety Board (DDESB) has been the primary sponsor of the HAZX ground safety code. ACTA is the principal developer of each of these computer programs. The ACTA flight safety analysis codes are actively maintained and improved as needs arise. These codes are used by trained government analysts to perform pre-launch mission planning studies and day of launch risk analyses at NASA, Air Force, Navy and Army ranges and by the FAA Office of Commercial Space Transportation. ACTA provides user training, software configuration control, and software maintenance to government agencies for each of these programs.

7.1. Debris Impact Hazard and Risk Analysis Programs

TTK is a pre-processor program that generates mission specific data inputs for RRAT and LATRA3D. The code uses launch vehicle data and drag corrected trajectory algorithms to simulate many randomly generated powered flight failures at short time steps along the nominal trajectory. Examples of malfunction turn failure trajectories, real and simulated, are shown in Figure 7-1. Examples of random attitude trajectories where a guidance system error steers the vehicle to a new, but incorrect, heading are shown in Figure 7-2.

Figure 7-1. Malfunction Turn Trajectory Simulation

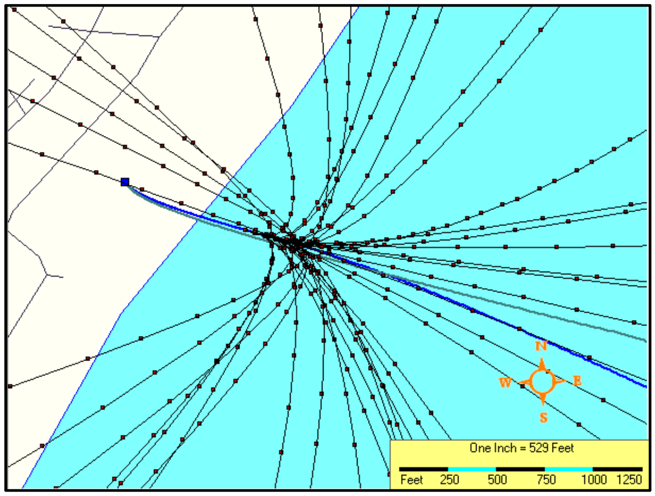


Figure 7-2. Example of Random Attitude Failure Trajectories

The failure trajectories are tracked and tested to determine when the launch vehicle will achieve one of the following end conditions:

- The IIP or present position violates a range safety rule and powered flight is terminated
- The vehicle impacts the ground and explodes within the permissible flight corridor
- The vehicle breaks up aerodynamically before reaching a range safety rule violation
- The vehicle achieves orbital velocity

TTK saves thousands of sampled time, position and velocity state conditions, called Breakup State Vectors (BVECs), that are passed to RRAT for debris dispersion calculations. One effect that range safety termination limits have is that breakup state vectors can become concentrated along the flight termination limit lines as illustrated in Figure 7-3, which is a plot of impact points propagated from breakup state vectors associated with a launch from the Cape Canaveral AFS. The accumulation of breakup states at the termination lines occurs very early in flight when the vehicle velocity is low or significantly later in flight when the vehicle velocity is high but the atmospheric density is low. The intermediate phase of flight where the vehicle velocity and the atmospheric density are both relatively high favors aerodynamic breakup before a limit line is reached.

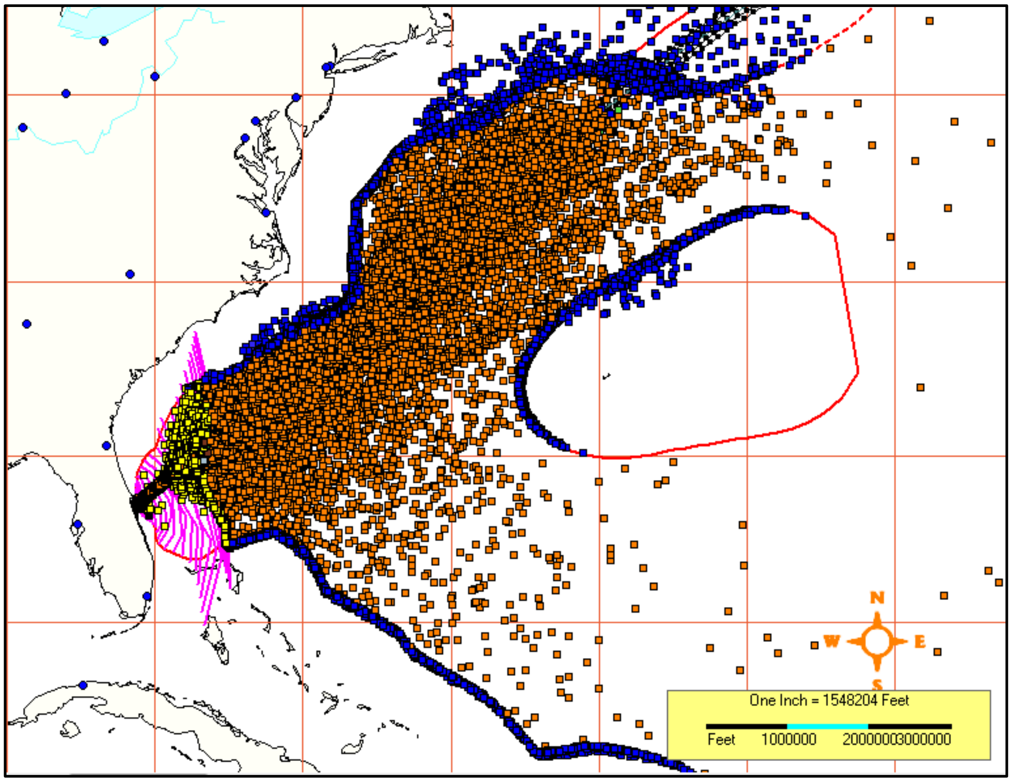


Figure 7-3. Example of Debris Impact Points Associated with Breakup State Vectors and Range Safety Flight Termination Lines for a Cape Canaveral Launch.

The RRAT tool takes the BVEC data generated by TTK failure trajectory simulations and applies a vehicle breakup debris list appropriate to the type of vehicle failure (typically intact vehicle impact, explosive breakup, aerodynamic breakup). RRAT is also where the probability of vehicle failure is assigned and population data is defined as needed to support impact probability calculations. RRAT accounts for uncertainty in the parameters that affect the dispersion of the debris at ground impact as illustrated in Figure 7-4.

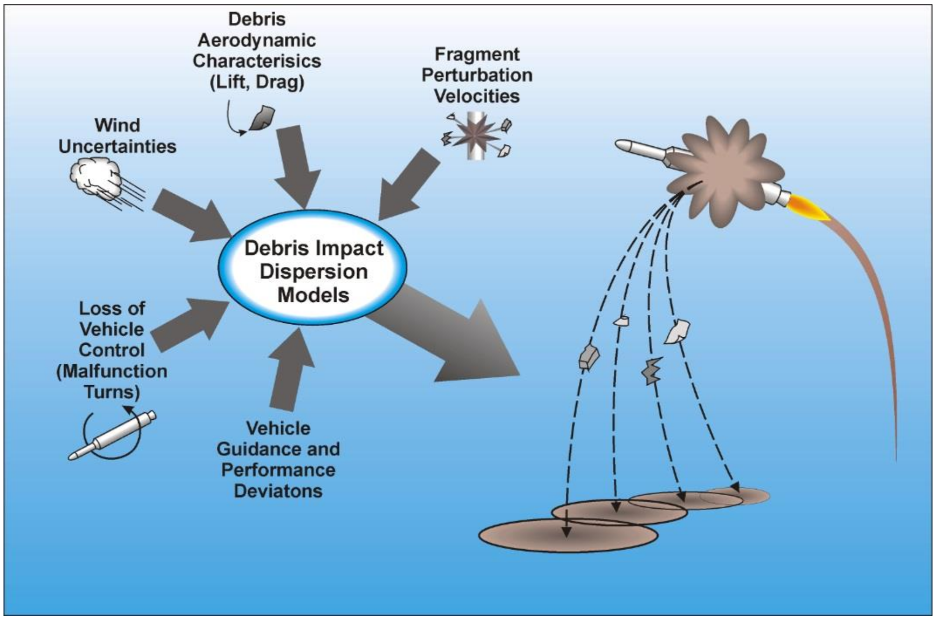


Figure 7-4. Illustration of Uncertainty Factors Applied in RRAT that Affect Debris Impact Dispersions

When the debris impact uncertainties are randomly selected from hundreds to thousands of samples, the resulting debris impact dispersion tends toward a bivariate normal probability distribution (Central Limit Theorem).

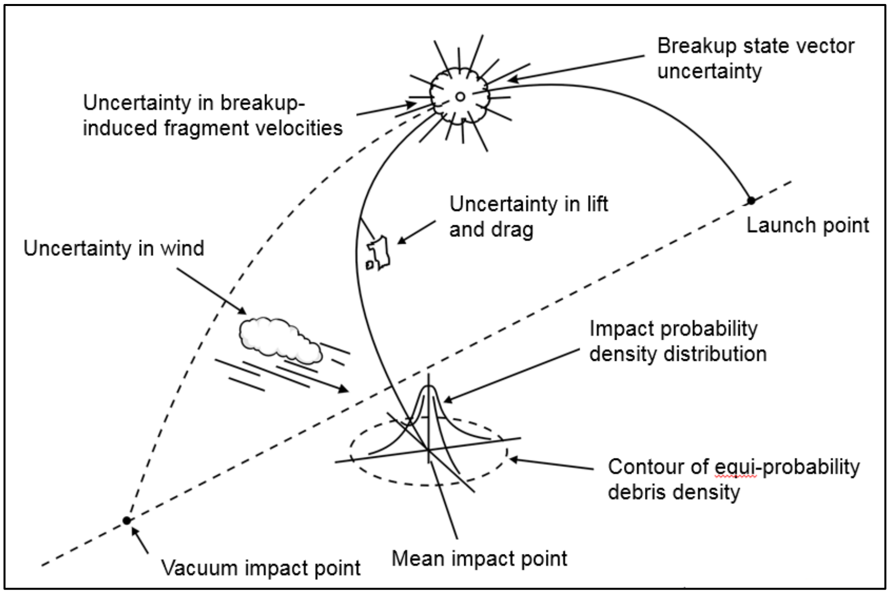
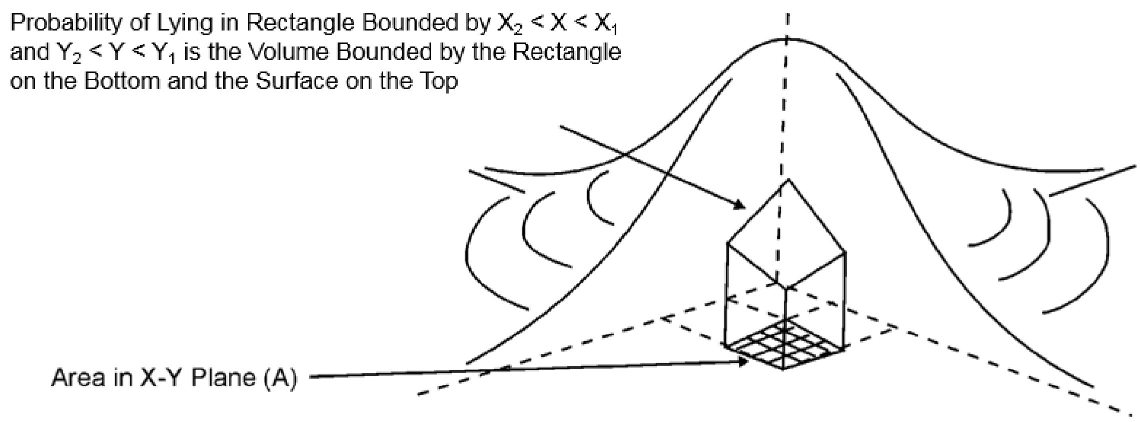


Figure 7-5. Combined Effect of Multiple Debris Impact Uncertainties Results in a Bivariate Normal Impact Probability Distribution.

RRAT is used to generate debris impact dispersion statistics for each debris class defined in the input debris data for all simulated failure times. Impact probability for each debris class is calculated for each Terminal area defined in the RRAT input population area by integrating the volume under the bivariate normal impact probability distribution that corresponds to the Terminal critical asset area. This concept is illustrated in Figure 7-6.



$$P_I(A) = \frac{1}{\sqrt{2\pi}\sigma_x} \int_{x_2}^{x_1} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2}} dx \cdot \frac{1}{\sqrt{2\pi}\sigma_y} \int_{y_2}^{y_1} e^{-\frac{(y-\mu_y)^2}{2\sigma_y^2}} dy$$

$P_I(A)$ becomes the impact probability if the density function is for an impact distribution

Figure 7-6. Method Used to Calculate Debris Impact Probability on a Given Area.

7.2.<u>Toxic Dispersion Hazard and Risk Programs</u>

ACTA applied the LATRA3D model to predict toxic cloud formation and dispersion and LFL plume sizes for Falcon Heavy propellant release scenarios. LATRA3D is a Gaussian Puff type of dispersion model that is conceptually similar to a number of EPA sanctioned models such as CALPUFF and SCIPUFF. LATRA3D is unique in that it has significant internal support features that are designed to model the source formation from rockets in normal flight mode, catastrophic liquid propellant explosions and rupture of solid rocket motors that eject burning propellant fragments that emit toxic combustion products. The same drag corrected impact predictor that is used in the RRAT and TTK codes is also applied n LATRA3D. LATRA3D includes a full NASA developed chemical combustion model to solve for the thermodynamic state and chemical composition of propellant mixtures that result in catastrophic failure of a launch vehicle. LATRA3D also includes the evaporating pool algorithms originally developed by the Air Force and applied in the AFTOX (Air Force Toxics) code. All chemical release sources are modeled in LATRA3D as a series of time dependent overlapping “puffs” that are assumed to have a mass distribution that is normally distributed across the puff dimensions. This assumption allows the partial differential atmospheric turbulent dispersion equation to be solved in closed form resulting in a computer program that runs fast enough to be used during day of launch applications where new weather balloons are provided on an hourly basis. Gaussian plume and puff models are widely used and well accepted in the atmospheric dispersion modeling community as a means to predict average concentrations at receptors downwind of potential release sites.

LATRA3D, when executed for rocket explosion or launch scenarios, requires a full weather balloon data set to compute buoyant cloud rise. Rocket exhaust plumes and fireballs are highly buoyant sources that typically rise hundreds to thousands of feet above ground level and the transport and dispersion occur at elevations where surface wind tower data is not applicable and traditional Pasquill-Gifford dispersion coefficients (turbulence parameterizations) do not directly apply. LATRA3D applies specialized algorithms to predict upper air turbulence growth rates for elevated sources.

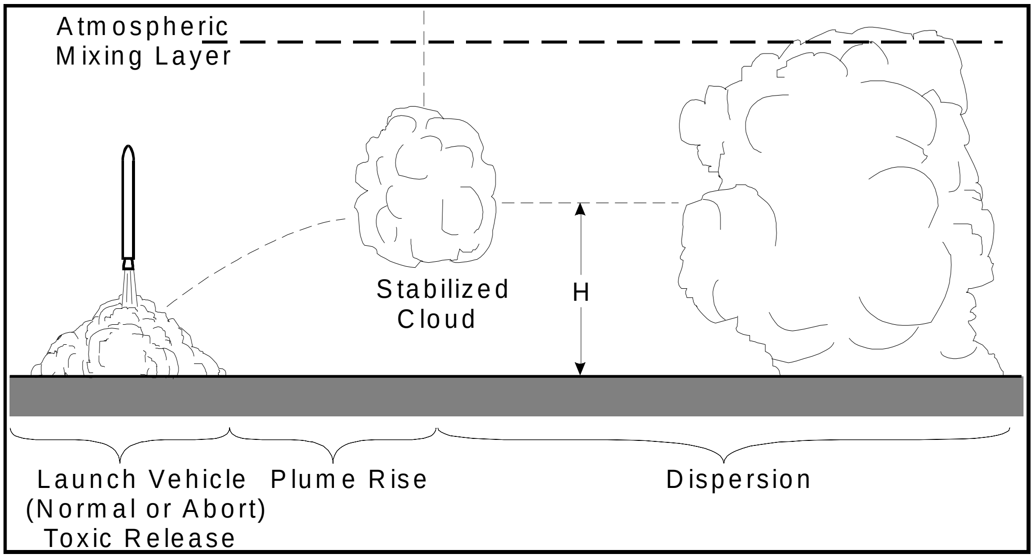


Figure 7-7. Illustration of Buoyant Cloud Rise and Dispersion Applied to Rocket Propellant Release Events

When executed for non-buoyant ground releases, LATRA3D can either be executed using a surface wind conditions or a full weather balloon sounding. Surface conditions include setting a single wind speed and direction, surface roughness, air and ground temperature, time of day, latitude and longitude of the release point, cloud cover and cloud ceiling. The code determines an atmospheric stability category based on a combination of a wind speed index and a solar radiation index. LATRA3D assigns the equivalent of a Pasquill stability class F to clear sky nighttime conditions with wind speed less than 2 m/s.

LATRA3D was reviewed and critiqued by Hanna Consultants via an Independent Verification and Validation (IV&V) process [9]. The IV&V team made several recommendations for improvements to the code, of which the most significant were incorporated. The IV&V team determined that LATRA3D was suitable for application to rocket exhaust emissions and the code is routinely used by the Air Force at Cape Canaveral AFS and Vandenberg AFB for launch risk assessment. When need arises the Navy and Army have requested LATRA3D analysis support during launch operations.

7.3. Ground Explosive Safety Hazard and Risk Programs

ACTA, under Army sponsorship, has developed the HAZX computer program that supports rapid assessment of hazards associated with the siting of explosive materials. HAZX is a multitiered analysis tool that at the simplest level performs the equivalent of table lookup distances from the appropriate DoD standard 6055.9 [13]. At a Tier 2 level, HAZX implements the procedures and methodologies set forth in DDESB Technical Paper No. 14 [14].

8. OVERVIEW OF HAZARD ANALYSIS RESULTS

8.1. Distances to Toxic Vapors for Acute Exposure Guideline Levels

The Falcon Heavy and Falcon 9 use RP-1 and LOX as propellants on all stages of the vehicles. LOX is a cryogenic liquid that is hazardous because of the cold temperatures and the enhanced flammability of combustible materials that may come in contact with pure oxygen. LOX is not considered to be a toxic chemical. RP-1 is a highly-refined kerosene fuel that is a blend of approximately 39% paraffin and 58% naphthene hydrocarbons with carbon molecule sizes in the C-6 to C-16 range. Rocket propulsion calculations assign a chemical formula of $C_{12}H_{23.4}$ to RP-1, which equates to a molecular weight of 167.4. RP-1 is very similar to modern jet fuels, and is formulated to have a low vapor pressure (0.8 pounds per square inch (psi) or less) at ambient temperatures. The low vapor pressure means that a spill of liquid will evaporate slowly and this reduces the likelihood of ignition in the event of a spill. The Environmental Protection Agency (EPA) has evaluated the toxicity of kerosene jet fuels as part of the Acute Exposure Guideline Levels (AEGL) for Airborne Chemicals (AEGL) program and has published the final guidelines presented in Table 8-1.

Table 8-1 EPA AEGL Exposure Thresholds Applicable to RP-1 Releases

Jet Fuels (JP-5 and JP-8) Results - AEGL Program

Jet Fuels (JP-5 and JP-8) 8008-20-6 and 70892-10-3 (Final)

	10 min	**30 min**	**60 min**	**4 hr**	**8 hr**
[mg/m³]					
AEGL 1	290 mg/m³	290 mg/m³	290 mg/m³	290 mg/m³	290 mg/m³
AEGL 2	1,100 mg/m³	1,100 mg/m³	1,100 mg/m³	1,100 mg/m³	1,100 mg/m³
AEGL 3	NR	NR	NR	NR	NR

NOTE THAT VALUES ARE IN **mg/m³**, NOT ppm.

The expected health severity effects associated with exposure at the three AEGL thresholds are defined as:

AEGL-1 *= Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.*

AEGL-2 *= Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.*

AEGL-3 *= Life-threatening health effects or death.*

The concentrations in the AEGL table are presented in milligrams per cubic meter (mg/m^3) units because releases of heavier hydrocarbons can be dispersed as atomized droplets rather than single molecules. In the event that the chemical is fully vaporized, then part per million (ppm) concentrations are appropriate. At standard temperature (25 C) and pressure (1 atm.), the AEGL-1 limit equates to 42 ppm and the AEGL-2 limit equates to 161 ppm. The AEGL committee made "No Recommendation" for AEGL-3 exposure thresholds. ACTA used these AEGL values to assess the size of downwind toxic hazard zones associated with accidental releases of RP-1 from a Falcon Heavy accident.

Toxic vapors from an accidental release of RP-1 rocket fuel could occur under two types of scenarios:

- Incomplete combustion of RP-1 with a percentage of the propellant assumed to be vaporized as part of an explosive breakup of the launch vehicle, either on the pad or in flight.
- An RP-1 liquid propellant spill at the launch pad resulting in an evaporating pool of RP-1 without a fire or explosion.

ACTA analyzed both release types using the Launch Area Toxic Risk Analysis 3-Dimensional (LATRA3D) toxic dispersion model. This computer program is used by the Air Force, NASA and the FAA to evaluate toxic emissions from rocket launches and catastrophic failures. The Falcon Heavy was selected as the candidate vehicle because it contains the most RP-1 propellant.

8.1.1. Incomplete RP-1 Combustion

During the mid-1990's the Air Force investigated RP-1 and LOX propellant explosions as part of a study to improve toxic dispersion model simulations applied to Titan IV and Delta II launch vehicles at Vandenberg AFB and Cape Canaveral AFS [15]. The recommendation from that study was to assume that 14% of the RP-1 propellant load of a Delta II first stage would be vaporized and not consumed in combustion reactions. ACTA applied the same liquid propellant fireball mixing and reaction assumptions to the Falcon Heavy as have been used by the Air Force range safety offices for other launch vehicles using RP-1/LOX propellant stages. The Falcon Heavy propellant load of RP-1 when fully fueled is approximately 811,600 pounds. Assuming 14% of this mass is vaporized by heat from an explosion and secondary burning fireball, approximately 113,624 pounds of RP-1 would be converted from liquid to vapor state and mixed with the cooler portions of the fireball exhaust cloud. This post combustion source cloud remains highly buoyant and will rise, entrain ambient air and reach a stabilization altitude where the cloud density equals that of the surrounding air and cloud rise stops. Prevailing winds transport the stabilized cloud downwind and atmospheric turbulence increases the cloud dimensions and dilutes the chemical concentration of the propellant chemical species, including the vaporized RP-1. Atmospheric mixing brings the exhaust cloud chemicals back down to ground level at some distance downwind from the point of cloud rise stabilization. The distance downwind where cloud material makes contact with the ground depends on the cloud stabilization height and the intensity of atmospheric mixing (turbulence).

To comply with toxic dispersion assessments under the equivalent of a Pasquill-Gifford atmospheric stability class F and low wind speed condition (in accordance with 49 Code of Federal Regulations (CFR) 193), ACTA generated a modified Brownsville weather balloon sounding and set the wind speeds to 1 m/s and set the wind directions with small variations centered on a path that would take the emission cloud toward the Terminal area. Relative humidity was set to 50%. This modified weather balloon sounding was input to an Air Force range safety Launch Area Toxic Dispersion Model 3-Dimensional (LATRA3D) toxic dispersion simulation of a Falcon Heavy catastrophic on-pad explosion and calculated the downwind concentrations of vaporized RP-1 at both ground level and at the stabilized cloud height level. The center of the stabilized cloud height was predicted to be at 1,157 meters above the ground with a cloud diameter of 1500 meters. The initial concentration of vaporized RP-1 in the cloud at the time of formation (before cloud rise) is predicted to be 4.18% of the cloud mass. At cloud stabilization, the predicted concentration of RP-1 had dropped to approximately 12 ppm due to significant dilution by entrained air during the cloud rise phase. The RP-1 concentration versus distance predictions from the LATRA3D on-pad explosion simulation are presented in Table 8-2.

The concentrations versus distance values are derived from a grid of concentration receptor points laid out in an alongwind-crosswind pattern. Starting from the source location and moving downwind, LATRA3D scans each crosswind grid row to locate the maximum concentration point and computes the downwind distance from the toxic release source location to that point. The direction that the wind is transporting the toxic source cloud is computed as a bearing relative to the source point of origin (e.g. if the bearing is computed to be 90 degrees then the toxic cloud is moving to the east. Rocket emission clouds associated with normal launch or catastrophic abort are formed over a matter of seconds. Consequently, the toxic source takes the form of a 3-dimensional “cloud” that is modeled in LATRA3D as one or more overlapping “puffs” where each puff represents a packet of toxic gases that are assumed to have a Gaussian mass distribution of the toxic chemical species. At each downwind distance, increment LATRA3D tests the position and size of each puff and determines when the leading edge of the first puff arrives at a receptor point and when the trailing edge of the last puff departs the receptor point. LATRA3D reports in the concentration versus distance table for the “arrival” and “departure” times of the toxic cloud. This information is used in calculating risk mitigation achieved by sheltering people indoors while the toxic cloud passes. It also helps emergency responders know when and for how long a toxic cloud will be present at a given location.

Table 8-2. Predicted RP-1 Concentration vs. Distances at Cloud Stabilization Altitude

MAXIMUM CROSSWIND CONCENTRATION LOCATIONS

ALONG WIND NODE	DOWN WIND RANGE [m]	BEAR [deg]	CONC [ppm]	PUFF TIME (MIN) ARR	PUFF TIME (MIN) DEP
36	960.	123.	7.05E-02	3	4
35	660.	123.	7.63E-01	3	9
34	360.	123.	3.98E+00	3	14
33	60.	120.	9.99E+00	3	19
32	240.	305.	1.24E+01	3	24
31	540.	304.	1.17E+01	3	30
30	840.	304.	1.13E+01	3	35
29	1140.	304.	1.08E+01	3	40
28	1440.	304.	1.03E+01	3	44
27	1740.	304.	9.88E+00	10	50
26	2040.	304.	9.49E+00	15	55
25	2340.	304.	9.08E+00	20	60
24	2640.	304.	8.72E+00	25	65
23	2940.	304.	8.39E+00	30	71
22	3240.	304.	8.04E+00	35	75
21	3540.	304.	7.71E+00	40	80
20	3840.	304.	7.43E+00	46	85
19	4140.	304.	7.14E+00	51	90
18	4440.	304.	6.86E+00	56	95
17	4740.	304.	6.64E+00	61	100
16	5040.	304.	6.38E+00	66	104
15	5340.	304.	6.13E+00	71	109
14	5640.	304.	5.89E+00	77	114
13	5940.	304.	5.65E+00	82	119
12	6240.	304.	4.86E+00	87	124
11	6540.	304.	3.88E+00	92	128
10	6841.	305.	3.65E+00	97	131
9	7140.	304.	3.45E+00	104	136
8	7440.	304.	3.21E+00	110	140
7	7740.	304.	2.87E+00	115	145
6	8040.	303.	2.18E+00	120	149
5	8340.	304.	1.18E+00	125	153
4	8640.	304.	9.99E-01	133	157
3	8941.	305.	8.70E-01	139	160
2	9241.	305.	7.88E-01	145	160
1	9541.	304.	4.13E-01	151	159
0	9841.	305.	1.64E-01	158	162

MAXIMUM RP1(G) CONC 1.24E+01 AT RANGE 240. M, BEARING 305. DEG
PUFF ARRIVAL AT 3, DEPARTURE AT 24 MIN

The ground level concentrations of RP-1 vapors associated with the on-pad explosion scenario were predicted to be less than 1 ppm with the peak concentration occurring approximately 90 meters downwind from the launch pad source. These explosion scenario events that vaporize a portion of the RP-1 are not expected to result in any detectable toxic exposure at the Terminal site or the BSC.

8.1.2. RP-1 Pool Evaporation

As a worst-case release scenario, it was assumed that the entire contents of a first stage RP-1 tank (251,000 pounds) was spilled instantaneously to the ground producing a pool 1 centimeter (cm) deep with a radius of 60.2 meters. ACTA ran a LATRA3D simulation of a Falcon Heavy RP-1 spill event using dispersion conditions similar to the LNG terminal siting requirements (49 CFR 193). Pasquill-Gifford atmospheric stability class F in combination with selected weather balloon sounding with a surface wind speed of 1 m/s. The pool temperature was assumed to be equal to the ambient air temperature of 77 F. Under these conditions the predicted pool evaporation rate was 2,308 pounds-mass per minute (lbm/min). The resulting downwind ground level plume was predicted to have RP-1 concentrations as listed in Table 8-3. Concentration values are computed at 0.5 meters above the ground. Surface roughness was set at 3 cm.

Table 8-3. Predicted RP-1 Concentration vs. Distance from an Evaporating Pool

MAXIMUM CROSSWIND CONCENTRATION LOCATIONS

ALONG WIND NODE	DOWN WIND RANGE [m]	BEAR [deg]	CONC [ppm]	PUFF TIME (MIN) ARR	PUFF TIME (MIN) DEP
79	19.	166.	8.46E+02	0	111
78	87.	295.	4.58E+03	0	113
77	187.	299.	2.31E+03	1	115
76	286.	301.	1.43E+03	2	117
75	386.	301.	1.01E+03	3	119
74	486.	302.	7.69E+02	5	121
73	586.	302.	6.12E+02	6	123
72	686.	302.	5.03E+02	8	125
71	786.	302.	4.23E+02	9	127
70	886.	303.	3.62E+02	11	128
69	986.	303.	3.14E+02	12	130
68	1086.	303.	2.77E+02	14	132
67	1186.	303.	2.46E+02	15	134
66	1286.	303.	2.20E+02	17	136
65	1386.	303.	1.98E+02	18	138
64	1486.	303.	1.80E+02	20	139
63	1586.	303.	1.64E+02	21	141
62	1686.	303.	1.51E+02	23	143
61	1787.	301.	1.39E+02	24	145
60	1887.	301.	1.29E+02	26	147
59	1987.	302.	1.21E+02	27	148
58	2087.	302.	1.13E+02	29	150
57	2187.	302.	1.06E+02	30	152
56	2287.	302.	9.98E+01	32	154
55	2387.	302.	9.40E+01	33	156
54	2487.	302.	8.87E+01	35	157
53	2587.	302.	8.38E+01	36	159
52	2687.	302.	7.94E+01	38	161
51	2787.	302.	7.53E+01	40	163
50	2887.	302.	7.15E+01	41	164
49	2987.	302.	6.80E+01	43	166
48	3087.	302.	6.47E+01	44	168
47	3187.	302.	6.18E+01	46	170
46	3287.	302.	5.89E+01	47	171
45	3387.	302.	5.63E+01	49	173
44	3487.	302.	5.39E+01	51	175
43	3587.	302.	5.15E+01	52	177
42	3687.	302.	4.94E+01	54	178
41	3787.	302.	4.74E+01	55	180
40	3887.	302.	4.55E+01	57	182
39	3987.	302.	4.37E+01	59	184
38	4087.	303.	4.19E+01	60	185
37	4188.	302.	4.05E+01	62	187

36	4288.	302.	3.91E+01	63	189
35	4388.	302.	3.77E+01	65	190
34	4488.	302.	3.65E+01	67	192
33	4588.	302.	3.53E+01	68	194
32	4688.	302.	3.41E+01	70	196
31	4787.	302.	3.29E+01	71	197
30	4887.	302.	3.19E+01	73	199
29	4987.	302.	3.17E+01	75	201
28	5087.	302.	3.16E+01	76	203
27	5187.	302.	3.15E+01	78	204
26	5287.	303.	3.14E+01	79	206
25	5387.	303.	3.07E+01	81	208
24	5487.	303.	2.97E+01	83	210
23	5586.	303.	2.79E+01	84	211
22	5686.	303.	2.62E+01	86	213
21	5786.	303.	2.49E+01	88	215
20	5886.	303.	2.33E+01	89	217
19	5986.	303.	2.23E+01	94	218
18	6086.	303.	2.17E+01	96	220
17	6186.	303.	2.12E+01	97	222
16	6286.	303.	2.07E+01	99	223
15	6386.	303.	2.02E+01	101	225
14	6486.	303.	1.94E+01	102	226
13	6586.	303.	1.79E+01	104	226
12	6686.	303.	1.74E+01	106	229
11	6786.	303.	1.63E+01	107	231
10	6886.	303.	1.52E+01	109	232
9	6986.	303.	1.41E+01	111	234
8	7086.	303.	1.31E+01	113	235
7	7186.	303.	1.23E+01	114	237
6	7286.	303.	1.07E+01	118	239
5	7386.	303.	1.08E+01	118	240
4	7486.	303.	1.03E+01	120	241
3	7586.	303.	8.97E+00	122	241
2	7686.	303.	7.55E+00	123	241
1	7786.	303.	5.92E+00	125	241
0	7886.	303.	9.47E-01	129	241

MAXIMUM RP-1 CONC 4.58E+03 AT RANGE 87. M, BEARING 295. DEG
PUFF ARRIVAL AT 0, DEPARTURE AT 113 MIN

In the case of the plume from the evaporation pool, the RP-1 vapor is highest right at the pool surface. The peak airborne concentration of 4,580 ppm was predicted at a location just above the pool surface. At a distance of approximately 7,800 meters (25,590 feet) downwind from the evaporating pool the RP-1 concentration dropped below 1 ppm.

An AEGL-2 toxic hazard corridor length of approximately 2,355 meters (7,800 feet) is predicted based on applying a 50% margin of uncertainty on the predicted 1,570-meter distance to the 161-ppm concentration point. An AEGL-1 (mild health effects) toxic hazard corridor length of approximately 6,120 meters (20,080 feet) is predicted based on applying a 50% margin of uncertainty on the predicted 4,080-meter distance to the 42-ppm concentration point.

The toxic corridor lengths will vary with wind speed, pool temperature, ground temperature and vapor pressure uncertainties, however, the AEGL-1 mild effects toxic hazard corridor length associated with vaporized RP-1 is not predicted to reach the Terminal site or the BSC. The case simulated here was a worst-case spill of over 250,000 pounds of RP-1. A much more likely spill scenario would be an accidental release from a ruptured fuel line, rocket umbilical disconnect leak, valve failure or a hole in the tank. These more credible release scenarios would result in much smaller pool sizes and proportionally smaller toxic plume corridors.

8.2.Distances to Flammable Vapors for the Lower Flammability Limit (LFL)

The same types of accident scenarios that produce vaporized RP-1 releases of toxic concern have the potential to produce fuel-air mixtures that fall within the flammability limits of RP-1 (kerosene). If an ignition source is encountered, the portion of the vaporized plume that has RP-1 volume concentrations between 4.9%/vol (Upper Flammability Limit-UFL) and 0.6%/vol (Lower Flammability Limit -LFL) can be rapidly burned in a deflagration type fireball. Such an ignition event would not be expected to produce explosive over pressure shock conditions unless the vapor plume was either confined by several solid surfaces, such as walls and the ground, or was dispersed within a complex structure of pipes, tanks and facility framing. The transition of a deflagration fireball to a detonation requires some assisting mechanism, such as the turbulence induced by complex structure with a confined space, to accelerate the flame front above sonic propagation and trigger a detonation. The flat, open wetlands and partial desert-like terrain combined with a lack of extensive pad structures at the launch site are not expected to offer the confinement or complex structures needed to initiate a detonation event. In addition, the standard evaluation of a ground safety processing event involving explosive reaction of the full propellant load of RP-1 and LOX produces TNT equivalent yields far greater than any detonation of an RP-1 plume gaseous volume resulting from an RP-1 and air reaction.

The same scenarios evaluated for the toxic releases were also evaluated to estimate the size of RP-1 vapor clouds or plume corresponding to the LFL limit. Since the LATRA3D code produces release concentration predictions expressed in ppm units, the LFL threshold of 0.6% by volume is converted from 0.6% to the equivalent 6,000 ppm. The maximum concentration of vaporized RP-1 in a very early flight failure occurring effectively on the launch pad was estimated to be 41,800 ppm at the completion of the initial liquid propellant fireball “burnout” phase. This is below the UFL threshold of 49,000 ppm. The predicted existence of vaporized RP-1 above the lower flammability limit in the presence of a vigorous propellant fireball may seem contradictory. However, the propulsion chemists that evaluated the fireball scenarios for the Air Force [15] assumed that incomplete mixing of the RP-1 and LOX, as the tanks are ruptured, results in some portions of the released cloud of propellants where the RP-1 is extremely fuel rich and is vaporized by radiant heat but lacks the presence of oxidizer (air or vaporized LOX) to sustain a combustion reaction. As the rising exhaust cloud dilutes, it is assumed that ambient air reduces the RP-1 concentration to below the lower flammable limit, but during this cloud rise phase the cloud has cooled enough not to serve as an ignition source. The predicted RP-1 concentration in the propellant exhaust cloud when the cloud reaches stabilization height was predicted to be on the order of 12 ppm, well below the 6,000 ppm LFL. Thus there is a period of time during the active cloud rise phase when the cloud would have an RP-1 concentration between the UFL and LFL. This potentially flammable RP-1 cloud is estimated to be approximately spherical in shape with a radius of approximately 400 meters (1,320 feet) and a downwind displacement from the fireball source of less than 1,000 meters (3,280 feet). The rising fireball cloud is expected to reach this dilution condition in approximately 40 seconds, therefore the downwind transport can be estimated as the prevailing wind speed in the lower 500 meters (1,640 feet) of the atmosphere. A high wind speed case of 25 m/s would transport the cloud downwind 1,000 meters (3,280 feet) when the RP-

1 concentration drops below the LFL. A low wind speed of 1 m/s would only transport the cloud about 40 meters (130 feet) downwind. During active buoyant cloud rise phase where the exhaust products are hot, the air entrainment rate is determined by internal mixing due to strong temperature gradients within the cloud and is relatively independent of the prevailing wind speed.

The dimensions of the flammable plume concentrations are easier to predict and understand for the RP-1 spill scenario in the absence of the complications of a dynamic launch vehicle explosion and fireball. For the evaporating pool of liquid RP-1, LATRA3D predicted that the concentration 0.5 meters (1.6 feet) above the pool is already diluted to a predicted concentration of 4,580 ppm, which is already below the 6,000 ppm LFL of RP-1. To allow for a margin of safety and stochastic uncertainty in plume concentrations, flammability down to 50% of LFL (i.e. 3,000 ppm) is also considered. A flammable plume downwind distance of approximately 160 meters (525 feet) is estimated for the ½ LFL criterion. Applying a 50% LATRA3D modeling and input data uncertainty would extend this to 240 meters (790 feet) downwind from the edge of the evaporating pool. The evaporating pool scenario is predicted to produce a small RP-1 flammable gaseous plume close to the pool boundary and in order to ignite the pool and generate a pool fire an ignition source would need to be within a few hundred meters of the pool itself.

Flammable RP-1 plumes or clouds can exist following a Falcon Heavy accident but the size of these flammable sources is very small compared to the 5.2 mile (8,370 meters) or more separation distance between the Terminal site, or the BSC, and potential RP-1 release locations. No propellant releases are predicted to result in flammable gas volumes within the perimeter of the Terminal or the BSC.

8.3. Distances to Radiant Heats

Catastrophic aborts of liquid propellant launch vehicles invariably result in liquid propellant fireballs that have an active burning phase of several seconds followed by a phase of buoyant cloud rise where the fireball exhaust products cool due to entrainment of ambient air and radiation of thermal energy. Radiant energy can pose a hazard to people and structures if within minimum injury limit levels from the fireball. When considering potential thermal hazards associated with SpaceX launch vehicles, a vehicle utilizing RP-1 impacting the ground will generate an initial fireball involving reaction of LOX and RP-1 followed by a likely secondary burning pool of RP-1 that may last tens of minutes. Both the initial fireball and the pool burn represent thermal radiation sources. The pool burning involves combustion of the low volatility liquid RP-1 with ambient air. When considering the RP-1 vehicles, the Falcon Heavy presents the worst case and the initial fireball will dictate the worst case thermal radiation flux conditions.

To evaluate the radiant energy transfer from a Falcon Heavy vehicle explosion with a full propellant load, ACTA applied a liquid propellant fireball model that has been used for many years as part of the LATRA3D code. ACTA developed this model for range safety applications and incorporated the NASA Lewis Equilibrium Combustion Model to support fireball combustion reaction thermodynamic calculations. The NASA Lewis code has been used widely in the rocket propulsion community to calculate propellant combustion processes and can be applied for both high pressure engine performance calculations as well as ambient pressure propellant mixing reactions. The combustion code is routinely applied to liquid propellant fireballs to solve for the chemical composition, internal energy, enthalpy and flame temperature of liquid propellant fireballs.

In this analysis, ACTA set the combustion conditions to model a stoichiometric mixture ratio of LOX and RP-1 and allowed the code to predict the adiabatic flame temperature under ambient pressure burn conditions. The adiabatic flame temperature is predicted to be 3,068 K but because the differential equations applied in the LATRA3D fireball active burning phase solve for energy losses, incomplete combustion processes involving propellant vaporization and thermal decomposition and some ambient air entrainment during the time dependent evolution of the fireball, the average fireball temperature at "burnout" is predicted to be 2,186 K. At this point the fireball cloud is treated as a large spherical cloud that begins an active buoyant cloud rise phase wherein the cloud spherical radius increases linearly as a function of cloud height above the ground. No further chemical reactions are assumed during the cloud rise phase and the cloud cools as ambient air is entrained and mixed into the hot combustion products cloud. LATRA3D applies empirically derived air entrainment coefficients for the fireball cloud. The cloud rise algorithm predictions were compared with observed rise and growth of 11 large Titan launch vehicle propellant exhaust clouds and the predicted rise, growth and stabilization altitude conditions compared well with the observations.

The LATRA3D cloud rise algorithm calculates the cloud rise in small time increments using an equation set that is solved iteratively at each step to achieve energy and mass balance relationships. At the end of each step a new fireball cloud size, shape (spherical), position and temperature is predicted. By using the cloud surface area, position and temperature at each time step, thermal radiation calculations can be made to an array of "receptor points" arranged around the hot propellant cloud. ACTA incorporated all of the LATRA3D fireball and cloud rise algorithms into a specialized thermal radiation code called CRISE (Cloud Rise). Thermal radiation array calculations are not needed in the LATRA3D toxic dispersion code, so the features needed to perform radiant energy transfer between the cloud and the receptor array, such as shaped factors and grey body energy exchange calculations, are incorporated in the CRISE code. Cloud rise calculations also require a vertical weather balloon profile to provide the ambient air conditions as a function of altitude, which is supported by CRISE. Because thermal radiation heat transfer is proportional to absolute temperature raised to the 4^{th} power, thermal radiation decreases rapidly as the fireball cloud rises and cools. ACTA assumed an emissivity of 0.8[2] for the fireball to calculate radiant energy transmission from the fireball. Distances to radiant heat flux thresholds of interest are listed in Table 8-4.

[2] Based on spectral emissivities of hot CO_2 and water vapor conducted by Richard Tourin where emissivity values ranged from 0.4 to 0.8. See also NASA TM X-53579 where emissivity models are discussed and data is presented on carbon particulate spectral emissivities that are well below blackbody 1.0 over a wide range of the spectrum. An average emissivity of 0.8 is assumed to be conservative in this application. Other reports indicate some rocket plume emissivities as low as 0.1.

Table 8-4 Thermal Radiation Maximum Heat Flux Distances and Durations Predicted for a Falcon Heavy Vehicle Fireball.

Radiant Heat Flux [kW/m^2]	Distance from Fireball [m]	Distance from Fireball [ft]	Duration [sec]
5	2205	7234	7.1
10	1575	5167	7.1
37.5	814	2671	7.1

ACTA estimates that the potential intact Falcon Heavy vehicle impact location nearest to the LNG facility sites has a separation distance of approximately 22,000 feet, therefore the radiant energy flux at the Terminal or BSC are predicted to be below 5 kilowatts per square meter (KW/m^2). The radiant heat flux is expected to drop off rapidly as the fireball begins the cloud rise, expansion and cooling process. After approximately 8 seconds of fireball cloud rise the cloud temperature is predicted to drop below 400 K at which temperature there is negligible radiant energy transfer. When coupled with an estimated 7.1 seconds of active burning, the total predicted duration over which there is any significant radiant energy transfer from the fireball is estimated to be approximately 15.1 seconds.

8.4.Distances to Overpressures

The use of rocket propellant fuels and oxidizers at the launch site mandates compliance with FAA explosive siting requirements. Given that the largest propellant quantities will drive the maximum ground explosion overpressure and fragment throw distances, ACTA focused on the Falcon Heavy vehicle, as having the largest amount of propellant, to perform the ground safety assessment. The Falcon Heavy when fully fueled contains 2,720,000 pounds of RP-1 and LOX. ACTA applied DoD Standard 6055.9 to determine the TNT explosive equivalent for this type and quantity of propellant. For launch pad operations, the 6055.9 Standard dictates using 20% of the first 500,000 pounds of propellant and 10% of the residual mass to compute the TNT equivalency. Applying this formula to the 2,720,000 pounds of propellant gives 322,200 pounds of TNT equivalent.

ACTA analyzed overpressure and fragment hazards for the ground explosion scenario using our software program Hazardous Explosion (HAZX). HAZX is in the process of being integrated into the DoD Explosive Safety Board latest software tool set. HAZX blast overpressure and impulse calculations are based on the Kingery Bulmash hemispherical TNT blast data and have been verified against similar calculations incorporated in the DoD Explosive siting standards. Advanced Tier levels in HAZX that provide damage and risk estimates go beyond current practices in established explosive standards and these algorithms draw from risk and damage methods developed and accepted in Air Force flight safety risk analysis tools.[3] The 322,200 pounds of TNT

[3] ACTA's principle developer of the HAZX code is a long standing member of the DoD Explosive Safety Board Science Panel and works closely with members of the DDESB regarding ongoing improvements in explosive siting methods and development of software tools that eventually become endorsed products of the DDESB.

equivalent were applied in HAZX to compute the air blast overpressure contours centered at the launch pad. These contours are presented in Figure 8-1.

Figure 8-1 Air Blast Overpressure Contours Resulting from a 322,200 Pound TNT Equivalent Explosion.

ACTA also applied the Falcon Heavy vehicle fragment debris list (2,505 fragments) and simulated thousands of randomly sampled fragment throw trajectories from the launch pad explosion location. The hazardous fragment density distance (HFDD) was computed to be 462 feet. HFDD is based on a 0.01 probability of a standing person being hit by a fragment with a kinetic energy or 11 foot-pounds (ft-lb) or greater. A more meaningful fragment throw distance is the 99-percentile fragment containment distance, which is computed to be 4,800 feet. The HAZX predicted fragment impact contours are presented in Figure 8-2. Based on the computed overpressure and fragment hazardous threshold contour distances, ACTA concludes that a credible maximum on-pad explosion at the Boca Chica launch pad location will not present any damaging hazards to the Terminal or BSC.

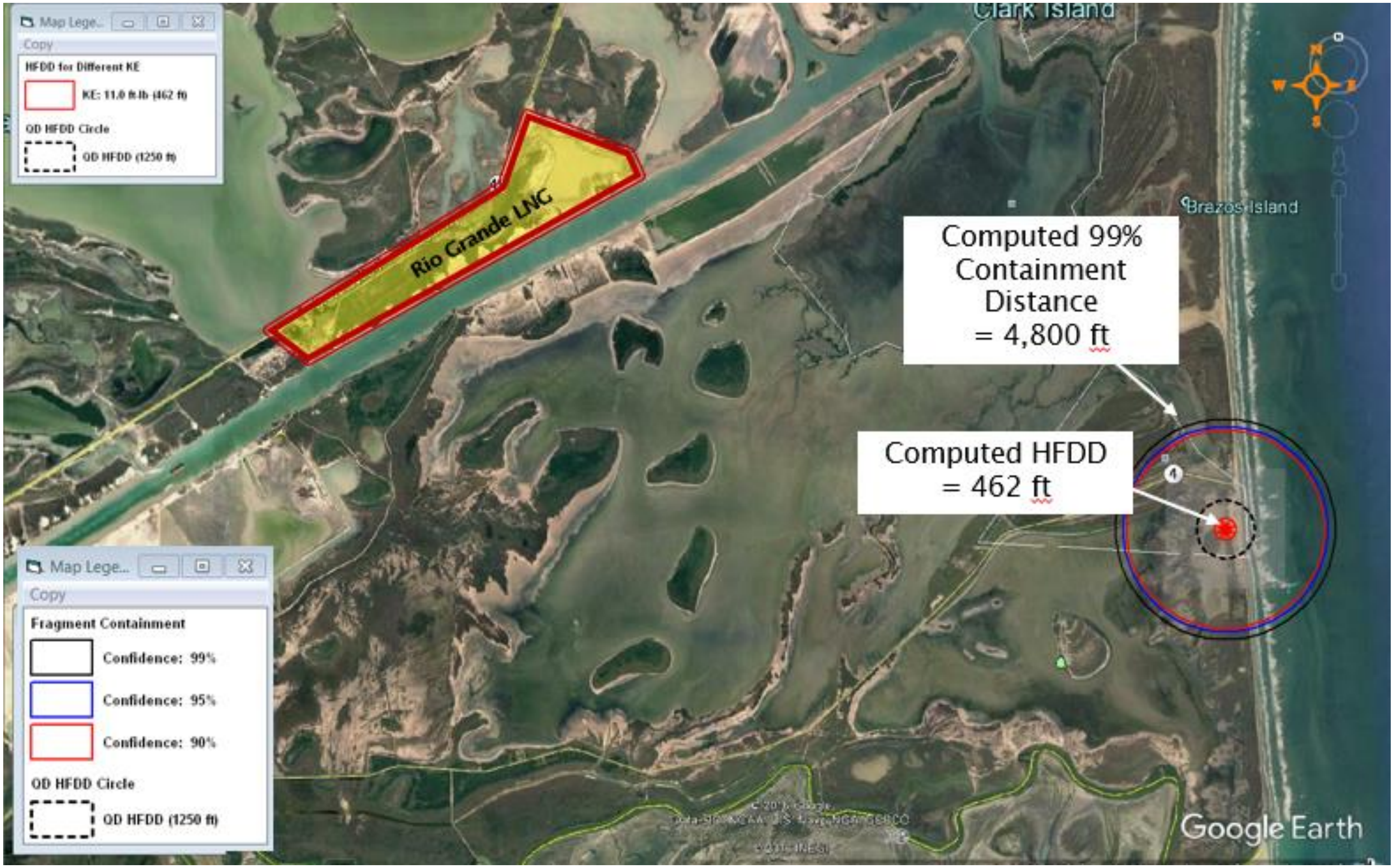


Figure 8-2 Predicted Fragment Impact Contours Resulting from an On-Pad Falcon Heavy Vehicle Propellant Explosion.

9. DISTANCES TO PROJECTILES (FLIGHT SAFETY DEBRIS HAZARD ANALYSIS RESULTS)

Toxic, thermal, flammability, and overpressure hazards have been evaluated in screening analyses described in previous report sections and determined to be non-threatening to the Terminal and BSC areas. Debris impacts from rocket launch failures are expected to have a non-zero probability of presenting a potential hazard to the Terminal and BSC areas are therefore covered in greater detail in this report section.

Launch vehicle failures during powered fight have the potential to throw debris into areas well away from the launch pad for the following reasons:

- Fragment velocities are increased over those in an on-pad event by the vector sum of the vehicle velocity at the time of breakup plus the explosion induced velocity.
- The height of the vehicle above the ground will allow some fragment trajectories to travel a greater horizontal distance before impacting the ground.
- Prevailing winds are typically stronger at higher altitudes and the fall time is increased allowing for a greater wind drift effect on lower ballistic coefficient fragments.
- A subset of random vehicle flight failures can turn the vehicle toward the Terminal. This has two effects:
    1) the vehicle position at breakup is closer to the Terminal than an on-pad or on-trajectory failure; and
    2) the vehicle velocity vector is pointing in the general direction of the Terminal thereby increasing the final fragment velocities in the direction of the Terminal.

ACTA applied the vehicle trajectory data and range safety rules to our Trajectory Toolkit (TTK) range safety model to simulate Random Attitude, Malfunction Turn, Loss of Thrust and Catastrophic On-Trajectory failures. Random attitude failures generate the credible worst case conditions that lead to vehicle breakup locations that are closest to the Terminal. TTK randomly samples errant vehicle flight directions at one second intervals along the nominal flight path and applies the CG and MI properties assuming a 5 -degree maximum thrust deflection angle to turn the vehicle from its nominal heading into the new flight heading. During the simulated turn, TTK computes dynamic pressure and sine of the angle of attack. If the multiplied value of these terms exceeds the Q-sin(α) structural load limit, the vehicle is assumed to breakup before the turn to the new heading can be completed. If the vehicle is predicted to survive the turn, it is allowed to fly normally on the new heading until it reaches one of the following end conditions:

- The vehicle computed IIP violates a range safety flight termination line.
- The vehicle present position violates a range safety termination line.
- The vehicle impacts the ground.
- The vehicle reaches end of powered flight and enters a ballistic fall trajectory.

As a conservative assumption applied to the debris analysis, ACTA assumed that when the launch vehicle violates a termination limit, the vehicle will explosively break up. In fact, SpaceX will likely only terminate thrust by shutting down the engines, and they may begin venting propellant by opening valves. Under these conditions the vehicle acceleration is stopped and the vehicle projected impact position stops moving. After thrust termination, the vehicle, which is aerodynamically unstable, will begin to tumble and is subject to aerodynamic breakup if the structural load conditions are exceeded. An aerodynamic breakup may lead to an explosive event as the propellant tanks buckle and rupture. In this case, debris may be thrown from a different location and at a lower altitude. A higher altitude breakup (i.e. at the time the vehicle violates a termination condition) may maximize the dispersion of debris with a potential increase in the probability of allowing debris to impact an area within the Terminal site boundaries or the BSC.

9.1.1. Wind Data Processing

Debris impact calculations are sensitive to prevailing wind speeds and directions on the day of launch. The trajectory of a falling piece of light debris is strongly influenced by wind and if the debris is released from a breakup at high altitude (e.g. 10,000 feet or higher) the light debris may be essentially falling vertically downward and moving with the prevailing wind at the time and location of ground impact. Heavy debris will be less influenced by wind and will follow a trajectory determined by the initial breakup state coupled with a random explosion induced velocity.

Adverse wind conditions result in the greatest debris impact probability at the Terminal and BSC, however, when an adverse wind condition is not present (i.e., a day with near pristine to pristine launch conditions), the probability of debris impacts near, or within, the Terminal perimeter is reduced by at least an approximate 1 to 2 orders of magnitude (a factor of at least 10 to 100).

In order to identify and isolate adverse wind conditions, ACTA acquired and processed over 12,000 weather balloon data sets from the national weather service archives for the Brownsville, Texas weather station[4]. These balloon soundings were prescreened running quality control checks on the data to eliminate bad data sets, leaving a count of 10,869 “good” balloon soundings. The remaining good data sets were further filtered by running a “wind power” screening tool that computes the relative potential for the combination of wind speeds and directions within the profile to move a falling debris piece significantly in the north, east, south or west directions. A weather vertical profile with little directional shear and high wind magnitudes blowing to the north would get a high north “wind power” rating.

Since the Terminal is west-northwest from the Boca Chica spaceport, wind profiles with high west wind power ratings would be flagged as potential “worst case” wind scenarios that would be most likely to drive debris toward the Terminal. The wind power selection process reduced the 10,869 weather samples down to 294 cases representing 0.027 of the full weather data set. The 294 “adverse” cases were binned into 24 groups representing the range of north and west wind power combinations. ACTA then drew 53 weather samples drawing some from every one of the 24 bins in an effort to model the randomness of the adverse wind conditions.

[4] Weather data acquired from the NOAA/ESRL Radiosonde Database https://esrl.noaa.gov/raobs/. Date range: Jan 1 2000 to Jan 13 2017 consisting of twice daily weather balloons released at 1200 and 0000 hours Zulu time.

9.1.2. Potential Operational Constraints on Wind Conditions

The debris impact analyses presented in this study are significantly affected by identification and evaluation of adverse wind conditions that will tend to blow rocket abort debris inland toward the Terminal location.

However, it is noted that SpaceX proposes to build their launch control center approximately 2 miles west of the planned launch pad location. The control room location is also close to a public housing area called Boca Chica Village [2]. Adverse wind conditions (i.e. where the average wind speeds within the vertical profile are in the 25 to 35 knot range and blowing predominately to the west or west-northwest) that produce the highest probability of debris impacts on the Terminal site will likely also increase debris impact probabilities at the control room and within Boca Chica Village, both of which are located much closer to the launch pad than the Terminal area. In order to conduct a launch, SpaceX will need to ensure that the risk to these areas is below the upper limits established by FAA regulations (including 1×10^{-4} cumulative risk and 1×10^{-6} maximum individual risk, per 14 CFR Part 417). It is highly probable that SpaceX would self-impose a day-of-launch weather constraint to reduce risk to their own facilities and nearby general public area. The FAA license would likely leave it to SpaceX's discretion on how to limit risk and SpaceX has not publicly disclosed the details of its risk mitigation strategy. However, it anticipated that steps that lower risk for Boca Chica Village and the SpaceX control room area (e.g., a SpaceX self-imposed day-of-launch adverse winds constraint) would also reduce the level of risk identified in this report for the Terminal site.

The analyses in this report did not presume any additional launch constraints that SpaceX might elect to put in place.

9.1.3. Terminal Critical Asset Data Preparations

The probability of debris impacting a critical Terminal area is dependent on the size and location of the area. The total Terminal area is large and not entirely occupied by critical assets, and therefore, it was desirable to refine the probability of impact analysis by identifying the critical areas of the Terminal. The Terminal critical areas, as identified by RG LNG in the FERC Engineering Information Request received by RG LNG on October 27, 2016, are depicted in Figure 9-1.

[redacted]

Figure 9-1 Planned Layout of the Rio Grande LNG Terminal Depicting Location and Size of Critical Asset Areas.

Using the information in Figure 9-1, ACTA defined the Terminal critical areas listed in Table 9-1. These were formatted in terms of an RRAT population library in order calculate impact probabilities on each individual critical asset.

Table 9-1 Terminal Critical Areas and Size

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

9.1.4. Debris Dispersion Analyses-AFSS Successful

ACTA ran full TTK and RRAT mission flight safety risk analyses for the first 100 seconds of flight of the Falcon 9 V1.1 and the Falcon Heavy vehicles for each of 48 selected adverse weather cases that passed screening for data quality and non-hurricane weather conditions. A duration of 100 seconds was analyzed in order to simulate failures up to a point in flight where the vehicle was well above the jet stream and had established a significant downrange eastward velocity (1,130 ft/s for the Falcon 9 and 1,990 ft/s for the Falcon Heavy). The vehicle position at the end of this time is also moved downrange increasing the separation distance between the vehicle and the Terminal location such that debris impact footprints are moving offshore even under adverse wind conditions. RRAT generated impact probabilities for each of the 5 Terminal critical areas accounting for all 1,332 Falcon 9 V1.1 and all 2,505 Falcon Heavy vehicle debris pieces that spanned a wide range of kinetic energies. The impact data was further filtered to partition the impact probabilities into the following 7 kinetic energy classifications:

- 11 ft-lb or greater
- 100 ft-lb or greater
- 1,000 ft-lb or greater
- 10,000 ft-lb or greater
- 100,000 ft-lb or greater
- 1,000,000 ft-lb or greater
- 3,000,000 ft-lb or greater

The RRAT output files from the 48 cases were screened to identify the minimum, maximum, average and median impact probabilities. All 48 of these cases are deemed to represent the class of adverse weather conditions that have a probability of occurrence of about 0.027. However, within the set of adverse winds, the difference between minimum and maximum impact probability on a Terminal critical area falls between 2 and 3 orders of magnitude and is dependent on the kinetic energy class. This is illustrated in Table 9-2 for an example impact probability set for the LNG Storage critical area and all potentially hazardous debris. ACTA recommends that the median impact probability for each kinetic energy class and critical area be used to represent the impact probability for the full set of adverse winds. An alternative would be to select a smaller set of worst case winds from the 48 cases. For example, in Table 9-2, the 8 cases with impact probabilities above 1 X 10^{-6} could be selected, in which case the probability of experiencing this subset of winds would be (8/48) = 0.167. Weighting the 1 X 10^{-6} impact probabilities by 0.167 would give an impact probability of about 1.7 X 10^{-7}, which is approximately the same magnitude as the median value for the full set (3.7 X 10^{-7}). Due to variations in debris trajectory propagation characteristics and critical area locations and sizes that affect impact probabilities, it is not possible to select a single set of winds, and therefore a single probability of wind occurrence, that fits all critical areas and debris kinetic energy classes. For this reason, ACTA recommends using the median impact probability and retain the 0.027 probability of adverse wind occurrence.

Table 9-2. Falcon 9 V1.1 Debris Impact Probabilities Ranked in Ascending Order Over 48 Adverse Wind Profiles-Not Weighted by Probability of Adverse Winds.

[redacted]

[redacted]

In each individual RRAT simulation the weather data is a given condition, however the impact probability numbers have been weighted by the probability of occurrence of the adverse weather condition. The final screening and summary calculations produced the data listed in Table 9-3 and Table 9-4.

The following general observations can be made regarding these debris impact results:

- These results are based on the presumption that the AFSS system works properly to terminate thrust of the vehicle.
- Within a given kinetic energy threshold data set there is about an order of magnitude variation in impact probability among the various critical assets (due primarily to area differences).
- Probability of impact decreases as the kinetic energy of impact threshold is increased (there are fewer and fewer fragments in the debris list that meet the heavier mass needed to achieve the higher and higher impact kinetic energy).
- The rate of occurrence of adverse wind conditions on the day of a launch that would not exceed FAA guidance on continuing with the launch is 0.027 and is applied to the median impact probability, as noted above.
- The summarized numbers below have been adjusted to take into account the rate of occurrence of an adverse wind condition on the day of the launch, which includes wind speeds that may be too high to be considered credible for launch.

Table 9-3 Predicted Falcon 9 V1.1 Impact Probabilities on Rio Grande Critical Assets and the Entire Property Perimeter Given Adverse Wind Conditions on a Per Launch Basis

KE [ft-lb]	Facility Asset	Max Pi	Min Pi	Median Pi	RRAT wind case
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 9-4 Predicted Falcon Heavy Impact Probabilities on Rio Grande Critical Assets and the Entire Property Perimeter Given Adverse Wind Conditions on a Per Launch Basis

KE [ft-lb]	Facility Asset	Max Pi	Min Pi	Median Pi	RRAT wind case
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Figure 9-2 illustrates a representative set of impact probability contours for the Falcon 9 V1.1 vehicle for a selected set of impact reference area and minimum impact kinetic energy, and Figure 9-3 illustrates a representative set of impact probability contours for the Falcon Heavy vehicle for the same selected set of impact reference area and minimum impact kinetic energy.

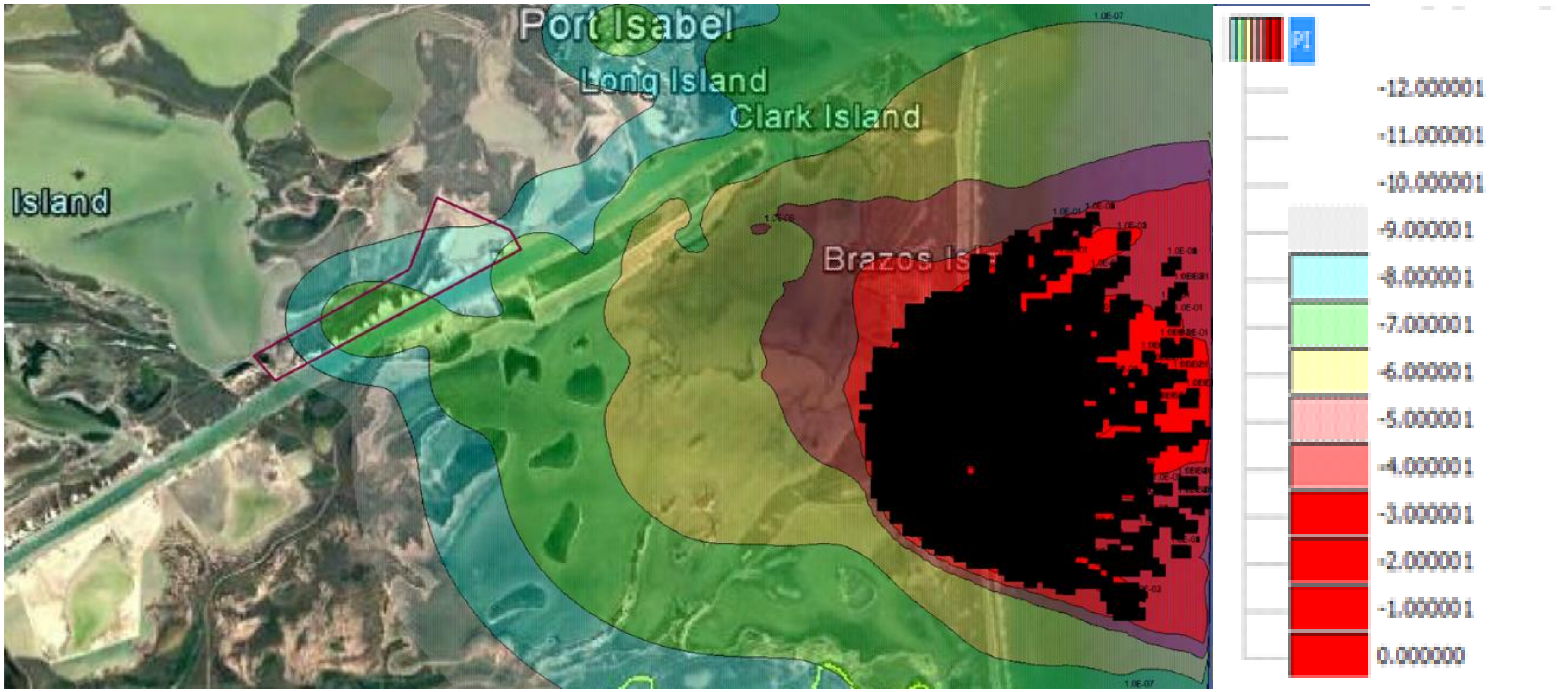

Figure 9-2 Falcon 9 V1.1 Impact Probability Contours for a 100,000 Square Foot Reference Impact Area with Debris Impact Kinetic Energy Above 10,000 Foot-Pounds Using a Representative Adverse Wind Profile.

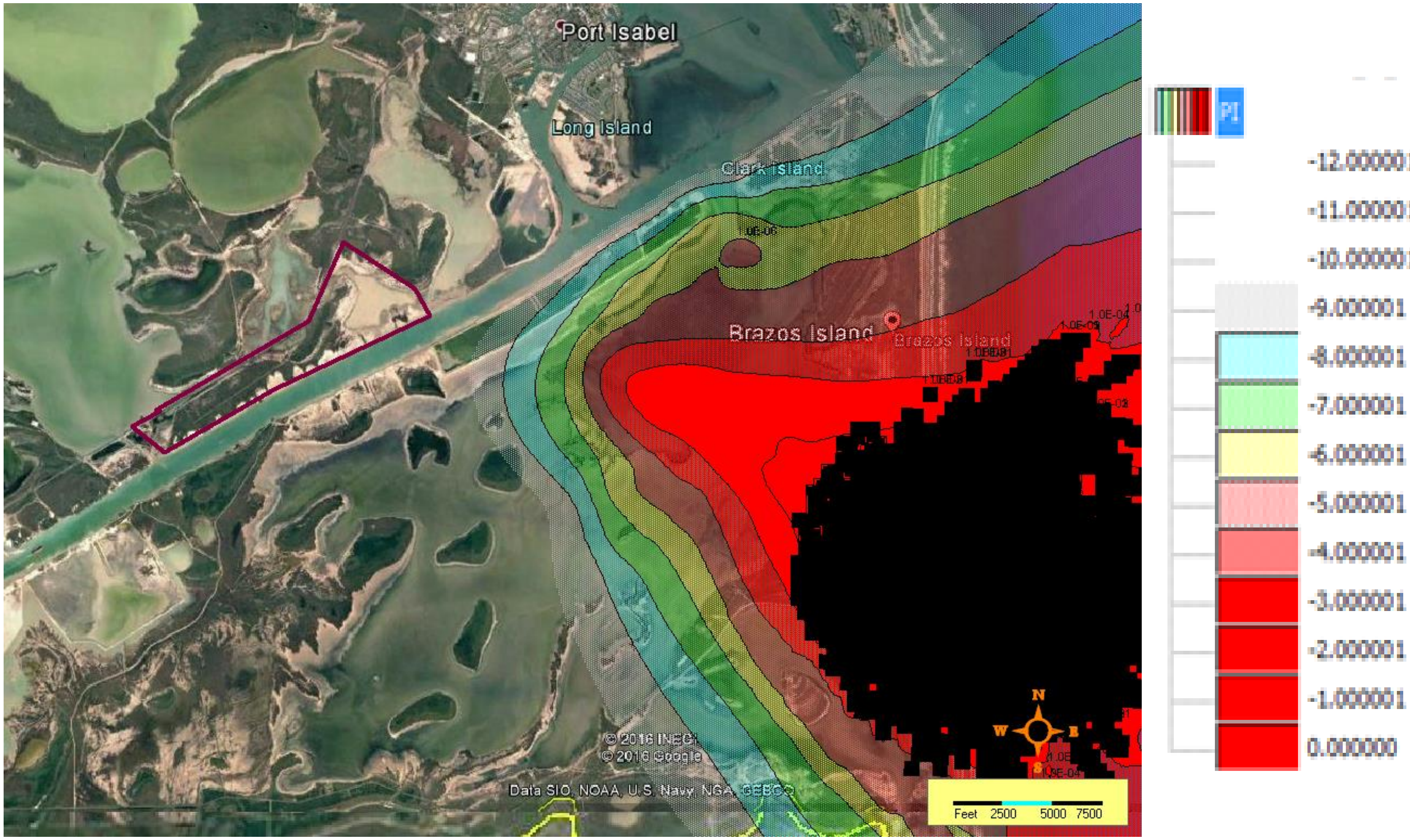

Figure 9-3 Falcon Heavy Impact Probability Contours for a 100,000 Square Foot Reference Impact Area with Debris Impact Kinetic Energy Above 10,000 Foot-Pounds Using a Representative Adverse Wind Profile.

10. CONCLUSIONS

ACTA evaluated hazard levels posed to the Rio Grande LNG Terminal critical areas due to ground processing and in-flight failures of the SpaceX Falcon 9 V1.1 and Falcon Heavy launch vehicles. SpaceX has specifically named these vehicle variants in the Final Environmental Impact Statement for the SpaceX launch site located at Boca Chica, Texas. The Terminal is located approximately 5.93 miles from the spaceport launch pad. Launch system failures primarily generate debris impact, explosive overpressure, thermal hazards that result from explosion of the RP-1 and LOX propellants used on the vehicles. Other hazards are also associated with toxic emissions and hydrocarbon vapor clouds with concentrations between the upper and lower flammability limits.

This analysis included an initial screening of the potential SpaceX hazards to the Terminal and BSC. From this initial screening the following was determined:

- Toxic emissions of vaporized RP-1 are predicted to have AEGL hazard zones close to the release source with no predicted impacts to the Terminal or BSC.
- Flammable RP-1 vapor plumes and clouds are also predicted to have hazard areas close to the release source location with no predicted impacts to the Terminal or BSC.
- Ground explosion direct incident overpressure is not predicted to impact the Terminal or BSC.
- Ground explosion of a fully fueled Falcon Heavy is the worst-case event identified for ground processing accidents. The predicted containment distance for thrown fragments was not predicted to impact the Terminal or BSC.
- Launch vehicle debris generated by catastrophic breakup of the launch vehicle during a portion of stage Stage 1 flight duration can, under adverse wind conditions, impact within the Terminal area.

Debris impact hazards to Terminal critical areas were calculated for both the Falcon 9 and the Falcon Heavy. These two vehicles have different flight histories that drive the expected stage Stage 1 failure rates of the vehicles, which are estimated to be 0.035 for the Falcon 9 and 0.083 for the Falcon Heavy. The vehicles also differ in acceleration rate, number of debris pieces and explosion induced fragment velocities, all of which affect the debris impact probability distributions.

Adverse wind cases that have strong winds blowing to the west from the launch site move the debris pieces in the direction of the Terminal site. Computed impact probability values on Terminal critical areas for all fragments with kinetic energies greater than, or equal to 11 ft-lb$_f$ range from [redacted] [redacted] [redacted] [redacted] for Falcon 9 launch failures and from [redacted] [redacted] [redacted] [redacted] for Falcon Heavy launch failures. These impact probabilities are calculated and presented on a per-mission basis, which is the standard evaluation method used by the FAA and the Federal launch ranges.

Non-adverse wind cases, observed to be occurring up to 97.3% of the time, are anticipated to have impact probability values on Terminal critical areas for all fragments with kinetic energies greater than, or equal to 11 ft-lb$_f$ range from [redacted] [redacted] [redacted] [redacted] for Falcon 9 launch failures and from [redacted] [redacted] [redacted] [redacted] for Falcon Heavy launch failures. This is due to non-adverse wind cases having an anticipated minimum 1 to 2 orders of magnitude (i.e. a factor of 10 to 100) less probability of occurrence than those associated with adverse wind cases.

Based upon information found in the Final Environmental Impact Statement for the SpaceX Boca Chica Spaceport, it is anticipated that 10-12 launches of the Falcon 9 V1.1 and up to 2 launches of the Falcon Heavy will occur in a given year. The cumulative annual frequency of a launch failure from the SpaceX Boca Chica Spaceport which could impact a Terminal critical area from debris, and during adverse winds, is calculated to be between [redacted] per year.

For either the Falcon 9 V1.1 or the Falcon Heavy, the impact probability values on the BSC are anticipated to be one order of magnitude greater than those presented for the Terminal, solely due to the closer proximity of the BSC to the SpaceX Boca Chica spaceport. Therefore, the probability that an impact on the BSC in excess of 11 ft-lbs occurs would range from [redacted] for Falcon 9 launch failures and from [redacted] for Falcon Heavy launch failures. The cumulative annual frequency of a launch failure from the SpaceX Boca Chica Spaceport which could impact the BSC is calculated to be between [redacted] per year.

11. REFERENCES

[1] Falcon 9 Launch Vehicle PAYLOAD USER's GUIDE, Rev. 2, SpaceX, October 21, 2015.

[2] Final Environmental Impact Statement SpaceX Texas Launch Site, Volume 1, Executive Summary and Chapters 1-14, Federal Aviation Administration, May 2014.

[3] Range Commanders Council, Range Safety Group, Supplement: Standard 321-10, Common Risk Criteria Standards for National Test Ranges: Supplement, Range Safety Group Risk Committee, Secretariat, RCC, U.S. Army White Sands Missile Range, New Mexico, January, 2010.

[4] Mathew Morris et. al., Risk Analysis Data Development FY 2012 Activities, Report No. 12-152/4.1, ACTA SC, Vandenberg AFB, CA, September 2012.

[5] Lane, Bob, and Kyle Johnson, *Trajectory Toolkit (TTK) Independent Verification and Validation (IV&V) Report*, Report No. 3761.113.RT.01, ENSCO Inc., Cocoa beach, FL., September, 2013.

[6] Carbon, Steve, Elliot Porterfield, Erik Larson, *Trajectory Toolkit (TTK) 3.3 Technical Description Manual*, Report No. 16-958-02, ACTA Inc., Torrance, CA, September, 2016.

[7] Lane, Bob, Juli Miller, Kyle Johnson, *Common Real Footprint (CRTF) Independent Verification and Validation (IV&V) Report*, Report No. 03038.102.RT.01, ENSCO Inc., Cocoa beach, FL., 31 July, 2012.

[8] Steve Carbon, *Common Real-Time Debris Footprint (CRTF) Version 4.4.0 Technical Description Manual*, Report No. 16-958-03, ACTA Inc., Torrance, CA, September, 2016.

[9] Hanna, Steven R., David G. Strimaitis, and Jeffrey Weil, *IV&V of LATRA3D Software*, Report No. P122-4, Hanna Consultants, Kennebunkport, ME 04046, March 28, 2010.

[10] Herndon, Mark, Randy Nyman, Tim Naughton, Ken Conley, *LATRA3D Technical Description Manual*, Report #12-152/2.1-03, ACTA Inc., Torrance, CA, September, 2012.

[11] Chrostowski, Jon and Ron Lambert, *HAZX Explosion Effects Software*, Report No. 09-696/WR16-01, ACTA Inc., Torrance, CA, September, 2009.

[12] Chrostowski, Jon, Li Cao, George Lloyd, *HAZX Tool Development*, Report No. 16-968-01, ACTA Inc., Torrance, CA, September 30, 2016.

[13] *DOD Ammunition and Explosives Safety Standards*, DOD 6055.9-STD, Office of the Deputy Under Secretary of Defense (Installations 7 Environment), February 29, 2008.

[14] *Methods and Algorithms for DOD Risk-Based Explosives Siting*, DDESB Technical Paper No. 14, Revision 4, 21 July, 2009.

[15] Prince, S. P. and D. W. Banning, *Launch Vehicle Abort Source Strength Model – Final Report-Source Characterization*, Report No. MCR-94-506, Martin Marietta Astronautics, Denver, CO. March 4, 1995.

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

Attachment C

Table EIR 2-1 Falcon 9 Projectile Impact Probabilities by Kinetic Energy Classification and Area on a Per Launch Basis Given Adverse Wind Conditions

Table EIR 2-2 Falcon Heavy Projectile Impact Probabilities by Kinetic Energy Classification and Area on a Per Launch Basis Given Adverse Wind Conditions

Table EIR 2-3 Cumulative Annual Frequency Assuming Twelve Launches of the Falcon 9 Per Year Given Adverse Wind Conditions

Table EIR 2-4 Cumulative Annual Frequency Assuming Eleven Launches of the Falcon 9 and One Launch of the Falcon Heavy Per Year Given Adverse Wind Conditions

Table EIR 2-5 Cumulative Annual Frequency Assuming Ten Launches of the Falcon 9 and Two Launches of the Falcon Heavy Per Year Given Adverse Wind Conditions

Attachment C contains Critical Energy Infrastructure Information.

It is being submitted under separate cover pursuant to 18 CFR § 388.112.

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

FERC October 27, 2016 Engineering Information Request, No. 3 on Rocket Launch Failures Siting Concerns:

Describe how the consequences above would impact plant safety, operations, emergency response capabilities, etc. The description should be based on number of personnel injured irreversibly or fatally and should include the potential exceedance of design values of occupied and unoccupied buildings (walls and roofs), tanks (outer walls and roofs), piping, LNG ships, and other equipment. In addition, discuss cascading effects from an initiating event that would cause subsequent cascading failures and consequences on and off the facility property. Initiating events occurring at the plant or at the LNG ship—while docked and while in transit—should be considered.

Response:

The associated assumptions and resulting calculated probabilities (and inherent uncertainties) of a launch failure of the Falcon 9, Falcon Heavy or Falcon 9 derivative suborbital launch vehicle impacting the Rio Grande LNG Project (further enumerated in Attachment A of the response to the FERC October 27, 2016 Engineering Information Request No. 2) does not produce an individual or cumulative equivalent annual failure rate greater than or equal to 3×10^{-5} within the Rio Grande LNG Project site perimeter, or boundaries of the Brownsville Ship Channel[1].

As such, there exists no credible scenarios of consequences that would impact plant safety, operations, emergency response capabilities, etc. at the plant or at the LNG ship while docked and while in transit.

List of Responders

Response to FERC's October 27, 2016 Engineering Information Request No. 3

Item	Author	Title	Contact Information
Response	Nick Verell, PE	Project Engineer NextDecade, LLC	(832) 426-1553

[1] A cumulative equivalent annual frequency of 3×10^{-5} failures per year is identified by the FERC in the October 27, 2016 Engineering Information Request No. 2, part b.

Rio Grande LNG, LLC (Terminal) and Rio Bravo Pipeline, LLC (Pipeline System)
Docket Nos. CP16-454-000 and CP16-455-000

FERC October 27, 2016 Engineering Information Request, No. 4 on Rocket Launch Failures Siting Concerns:

Describe any mitigation measures and design features that would reduce risk of irreversible and fatal injuries to personnel and damage occupied and unoccupied buildings (walls and roofs), tanks (outer walls and roofs), piping, LNG ships, and other equipment.

Response:

Upon further review of the consequences, likelihood and overall risk analysis of a rocket launch failure from the SpaceX Boca Chica Spaceport, the RG Developers have determined that there exists no need to include any mitigation measures or design features beyond those already included in the design of the Rio Grande LNG Project.

List of Responders

Response to FERC's October 27, 2016 Engineering Information Request No. 4

Item	Author	Title	Contact Information
Response	Nick Verell, PE	Project Engineer NextDecade, LLC	(832) 426-1553

I declare under penalty of perjury that the foregoing is true and correct. Executed on March 21, 2017.

Komi Hassan
NextDecade Director – Regulatory Affairs and Permitting
For and on behalf of RG LNG and RB Pipeline

Certificate of Service

I hereby certify that I have this day served the foregoing document upon each person designated on the official service list for this proceeding.

Dated at Washington, D.C. this 21st day of March, 2017.

/s/ Maguette Fame
Maguette Fame
Special Services Manager on behalf of Rio Grande LNG, LLC and Rio Bravo Pipeline Company, LLC

Document Content(s)