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September 4, 2008

Environmental Evaluation and Recommendation for NASA Routine Payload Categorization of the Juno Project

The proposed Juno mission has been reviewed in accordance with the Routine Payload criteria established by the "*Final Environmental Assessment for Launch of NASA Routine Payloads on Expendable Launch Vehicles from Cape Canaveral Air Force Station Florida and Vandenberg Air Force Base California,*" dated June 2002 and Finding of No Significant Impact (FONSI) dated June 18, 2002. This review shows that the Juno mission meets all of the Routine Payload Criteria and therefore it is recommended that Juno be designated a NASA Routine Payload. Supporting mission description and Routine Payload Checklist documentation are attached.

Approval:

[signature] 9-4-08

V.S. Ryan, Supervisor
Launch Approval Engineering Group

Date

Concurrence:

[signature] 9/4/08

R. E. Wilcox, Manager
Cross-Program Launch Approval Engineering

Date

Concurrence:

Janis Chodas [signature] 9/4/08

Janis Chodas
Juno Project Manager

Date

Description of Proposed Mission:

Juno, a NASA New Frontiers Program Mission, would place a spacecraft in a polar orbit around Jupiter to investigate the existence of an ice-rock core; determine the amount of global water and ammonia present in the atmosphere; study convection and deep wind profiles in the atmosphere; investigate the origin of the Jovian magnetic field; and explore the polar magnetosphere. The solar-powered spacecraft would arrive at Jupiter in 2016, where it would enter into a low, elliptical orbit circling the planet from pole to pole. The Juno spacecraft would include a suite of eight science instruments and a camera called JunoCam that would be used by student participants in the Juno Education and Public Outreach Program to take the first images of Jupiter's Polar Regions. Juno would be launched from Cape Canaveral Air Force Station (CCAFS), Florida aboard an Atlas V-551 launch vehicle during an opportunity beginning in August 7, 2011. Juno would include an Earth Gravity Assist (EGA) maneuver currently planned for October 2013.

The Juno Mission was proposed in response to a NASA Announcement of Opportunity for the New Frontiers Program in February 2004. The New Frontiers Program aims to explore the solar system with frequent, medium-class spacecraft missions that would conduct high-quality, focused scientific investigations designed to enhance our understanding of the solar system. The Program objective is to launch high-science-return planetary science investigations on an average of one every 36 months. Added to the NASA budget for the first time in 2003, New Frontiers would build on the innovative approaches used in NASA's Discovery and Explorer Programs, but would provide a mechanism for identifying and selecting missions that cannot be accomplished within the cost and time constraints of the these two Programs.

Juno instruments would measure the abundance of oxygen on the planet and monitor localized variations in concentrations of water and ammonia caused by meteorological factors. Juno would build on data from previous Jupiter missions by determining the higher harmonics of the planet's gravity field and the polar region of the magnetosphere. Taking advantage of its unique polar orbit, Juno would also explore the auroral zones and their magnetic coupling to the Jovian plasma environment and the planet's satellites.

The following is a list of instruments and instruments suites that would fly aboard the Juno spacecraft:

- **Microwave Radiometer (MWR)** - to investigate the deep atmosphere of Jupiter at radio wavelengths ranging from 1.3 cm to 50 cm using six separate radiometers to measure the planet's thermal emissions.

- **Jupiter Infrared Auroral Mapper (JIRAM)** - to investigate the upper layers of Jupiter's atmosphere using an imager and a spectrometer.

- **Flux Gate Magnetometer (FGM) and Advanced Stellar Compass (ASC)** - to conduct mapping of the magnetic field, determine the dynamics of Jupiter's interior, and determine the three-dimensional structure of the polar magnetosphere. To achieve these goals, the magnetic field mapping suite employs a Flux Gate Magnetometer as well as an Advanced Stellar Compass that provides accurate information about the Juno spacecraft pointing for precise mapping.

- **Polar Magnetosphere Characterization Instrument Suite** - to conduct measurements of Jupiter's electric currents along magnetic field lines, electromagnetic emissions associated with aurora and electrostatic waves, distribution of energetic particles and distribution of auroral and magnetospheric plasma, and ultraviolet auroral emissions. To obtain these measurements, the spacecraft would carry four separate instruments designed to provide these observations:
    - **Jovian Aurora Distribution Experiment (JADE) -** to measure the angular, energy and compositional distributions of particles in the polar magnetosphere of Jupiter.
    - **Jupiter Energetic-particle Detector Instrument (JEDI)**- to measure the energy and angular distribution of hydrogen, helium, oxygen, sulfur and other ions in the polar magnetosphere of Jupiter
    - **Waves -** to identify the regions of auroral currents that define Jovian radio emissions and acceleration of the auroral particles.
    - **UV Spectrometer (UVS) -** to record the wavelength, position and arrival time of detected ultraviolet photons during the time when the spectrograph slit views Jupiter during each turn of the spacecraft.

- **Gravity Science** - measures the Doppler frequency shift of the X- and Ka-band radio frequency subsystem during perijove passes. Used to investigate whether a rock/ice core exists, constrain the core size, characterize internal convection by mapping Jupiter's high order gravity field, and investigate the response to tides raised by the Jovian satellites.

Special Considerations:

The following special considerations are applicable to the Juno spacecraft:

- Calibration Sources
  The *Final Environmental Assessment for Launch of NASA Routine Payloads on Expendable Launch Vehicles from Cape Canaveral Air Force Station Florida and Vandenberg Air Force Base California* (NRP-EA) allows routine payload spacecraft (e.g., Juno) to use small amounts of radioactive material as scientific instrument components and limits their approval authority level to the NASA HQ Nuclear Flight Safety Assurance Manager (NFSAM). Juno would carry three Americium 214 (Am-241) instrument calibration sources within the JEDI instrument with a total activity of 3 x 10-6 Curies (1.11x10-7 terabecquerel [Tbq]).

  As detailed in the attached Juno Radiological Materials Report, the A2 Mission Multiple for these sources is 5.55 x10-4, which is within the approval authority of the NFSAM (per NPR 8715.3C). Since routine payloads are allowed to use small amounts of radioactive materials as scientific instrument components with an approval authority level delegated to the NFSAM, the use of radioactive material aboard the Juno spacecraft, as proposed above, falls within the scope of a NASA routine payload.

- Hydrazine Propellant Load - Launch
  The Juno spacecraft would utilize 1285 kilograms (kg) (2833 pounds) of hydrazine propellant and would launch on an Atlas V 551, which uses liquid oxygen and liquid hydrogen for the core vehicle propellants and 5 solid rocket motors for augmented thrust. The 1285 kg (2833 lb) of hydrazine is 285 kg (628 lb) more than the threshold listed in the Envelope Payload Characteristics (EPC) of the current NRP-EA. However, propellant loads for certain NRP-EA approved launch vehicles, such as the Delta II

which carries 2064 kg (4550 lb) of Aerozine-50 hydrazine, well exceed the 1285 kg propellant load planned for Juno and prior NEPA documentation by both NASA and the USAF state that the quantities of hydrazine on the Delta II do not create a substantial impact. Since the amount of hydrazine on the Juno spacecraft is less than the amount on the Delta II LV, and Juno is not launching on a LV utilizing hydrazine, it logically follows that the additional 285 kg (628 lb) of hydrazine over the EPC threshold would not create a substantial impact. Thus, the 1285 kg (2833 lb) of propellant aboard Juno is not expected to substantially increase impacts to the environment.

Launch Failure Resulting in a Suborbital Reentry

After clearing the launch pad area, the major land mass on which there could be an impact would be Africa. Spacecraft breakup would likely occur at about 70 km (43 miles) for reentries, which could lead to spacecraft debris impacting Africa. Nominally, either breakup of the spacecraft or aerodynamic heating would lead to the failure of the outlet or pressurant lines on the hydrazine tank, thereby venting the hydrazine which is expected to vaporize under the low pressure ambient environment. In the unlikely event that these lines do not fail and vent the hydrazine, the reentry analysis completed indicates that the tank would burst due to the vapor generated during reentry heating. Reentry analysis results suggest that the potential for the Juno hydrazine tanks to impact Africa is less than 1 in a million and is considered to be non-credible. It is not anticipated that a Juno launch malfunction resulting in failure to reach orbit would have a significant impact on human health and the environment.

Launch Failure Resulting in an Orbital Reentry

It is estimated that the time to reenter from the nominal Juno park orbit would be between 2 and 3 days; this estimate has been corroborated (on the order of 6 days), by Li and Jaffe [JPL, 2008]. From a conservative thermal analysis to assess the time it would take to freeze the hydrazine, it was determined to take a minimum of 2.5 days before the fuel temperature would drop sufficiently to begin freezing, and another 22 days to completely freeze all of the hydrazine. Thus, little or no frozen hydrazine is anticipated to be contained in the tanks at the end of the reentry heat pulse.

Without any frozen hydrazine, orbital reentry of the hydrazine would follow a similar path to the suborbital case, except that it could impact land anywhere within the band of 28.5 to -28.5 degrees from the equator. Spacecraft breakup would likely occur at about 78 km (48 miles). Nominally, either breakup of the spacecraft or aerodynamic heating would lead to the failure of the outlet or pressurant lines on the hydrazine tank, thereby venting the liquid hydrazine which would be expected to vaporize under the low pressure ambient environment. In the unlikely event that these lines do not fail and vent the hydrazine, the reentry analysis completed indicates that the tank would burst due to the vapor generated during reentry heating.

If frozen hydrazine was present and the reentry heat pulse did not melt it all, then frozen hydrazine would likely still be in the tank upon impact. However, the major considerations are 1) whether the quantity of hydrazine on board at impact would be less than 0.45 kg[1] and 2) whether the spacecraft would impact land. Analysis employing event sequence diagrams indicates that the probability of a tank impacting land with hydrazine still on board is less than 1 in 100 thousand. Since the likelihood that a tank

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[1] The amount of hydrazine used in the above end state definitions was obtained from an Environmental Protection Agency standard that requires spills or accidental releases into the environment of 0.45 kg (1 pound) or more be reported. (http://www.atsdr.cdc.gov/tfacts100.html)

with 0.45 kg or more of hydrazine on board would impact land is very low, an assessment of the potential for hydrazine exposure and health effects based upon population distribution was not completed as part of the reentry analysis. It is not anticipated that an unplanned reentry of Juno from orbit would have a significant impact on human health and the environment.

There are no other special considerations. See attached environmental checklist.

Statement of Purpose and Need:

Jupiter has had a number of spacecraft fly-bys including Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini and New Horizons, and one orbital mission, Galileo, which returned data from Jupiter that included information about the composition of the upper layer of the giant planet's atmosphere and a partial map of its magnetosphere. Although Galileo returned a great deal of new information, it also raised many additional crucial questions including:

- How did the giant planets form?
- Does Jupiter have a rock-ice core, and if so how large is it?
- How different is the composition of Jupiter from the original solar nebula, and if it's different, what is the cause?
- How deep into the atmosphere do the Great Red Spot and other atmospheric features reach?
- How does the dynamo on Jupiter work?

The Juno mission seeks to answer these questions which are also central to the following NASA Science Themes: Earth-Sun System, Solar System, and the Universe. Achieving the Juno objectives would significantly advance our knowledge about Jupiter's true nature as well as our understanding of planets similar to Jupiter that orbit distant stars in other solar systems. The origins of life itself may have critical ties to the special conditions under which solar systems such as our own were born and evolved.
Beyond the project's science value, a camera called JunoCam would show us the regions of Jupiter as our instruments explore them and would be used by student participants in the Education and Public Outreach Program to take the first color images of Jupiter's polar regions.

The New Frontiers Program represents a critical step in the advancement of solar system exploration. The missions in the Program, including Juno, tackle specific solar system exploration goals identified as top priorities by consensus of the planetary community as reported in “New Frontiers in the Solar System: An Integrated Exploration Strategy” in July 2002. This first decadal study was conducted by the Space Studies Board of the National Research Council at NASA’s request. The high-priority scientific goals identified by this decadal study directly state that the understanding Jupiter’s internal structure, water abundance, and deep atmospheric composition is a key to unlocking the origin of life and to understanding the dynamics of solar systems in general.

REFERENCES

JPL, 2008. *Hydrazine Tank Assessment,* JPL presentation, Pasadena, CA July 24, 2008.

NASA Routine Payload Checklist (1 of 3)

PROJECT NAME:	Juno	DATE OF LAUNCH:	August 2011		
PROJECT CONTACT:	Janis Chodas (PM)	PHONE NUMBER:	818-354-0370	MAILSTOP:	301-360
PROJECT START DATE:	March 2005	PROJECT LOCATION:	JPL		
PROJECT DESCRIPTION:	Juno would be a spinning, solar-powered spacecraft that would operate in a highly elliptical Jovian polar orbit for approximately one year. Launch is scheduled for August 2011 from Cape Canaveral, Florida. An Earth Gravity Assist (EGA) maneuver is currently planned for October 2013. The Juno mission is designed to address and accomplish the following science themes and objectives, respectively: • *Origin* - Determine O/H ratio (water abundance) and constrain core mass to decide among alternative theories of origin. • *Interior* - Understand Jupiter's interior structure and dynamical properties by mapping its gravitational and magnetic fields. • *Atmosphere* - Map variations in atmospheric composition, temperature, cloud opacity and dynamics to depths greater than 100 bars. • *Polar Magnetosphere* - Explore the three-dimensional structure of Jupiter's polar magnetosphere and aurorae.				

A. SAMPLE RETURN:	YES	NO
1. Would the candidate mission return a sample from an extraterrestrial body?		X

B. RADIOACTIVE SOURCES:	YES	NO
1. Would the candidate spacecraft carry radioactive materials?	X	
2. If Yes, would the amount of radioactive sources require launch approval at the NASA Associate Administrator level or higher according to NPG 8715.3 (NASA Safety Manual)?		X

Provide a copy of the Radioactive Materials Report as per NPG 8715.3 Section 5.8.3.

Note: Juno is not a nuclear powered mission, but has 9 microCurie calibration sources that includes a 1 microCurie Americium 214 (Am-241) calibration source within the JEDI instrument, and six 48 microCurie Strontium 90 (Sr-90) sources within the Scalar Helium Magnetometer (SHM) sensor of the Magnetic Field Mapping Instrument Suite (MFI). The sum of these sources gives Juno a combined A2 mission multiple of 2.2E-4. Juno will comply with NASA Policy Requirement (NPR) 8715.3 for this A2 value and obtain Nuclear Safety Launch Approval from the NASA HQ Nuclear Flight Safety Assurance Manager prior to launch.

C. LAUNCH AND LAUNCH VEHICLES:	YES	NO
1. Would the candidate spacecraft be launched using a launch vehicle/launch complex combination other than those indicated in Table 1 below?		X
2. Would the proposed mission cause the annual launch rate for a particular launch vehicle to exceed the launch rate approved or permitted for the affected launch site?		X

Comments:

D. FACILITIES:	YES	NO
1. Would the candidate mission require the construction of any new facilities or substantial modification of existing facilities?		X
2. If Yes, has the facility to be modified been listed as eligible or listed as historically significant?		

Provide a brief description of the construction or modification required:

E. HEALTH AND SAFETY:	YES	NO
1. Would the candidate spacecraft utilize any hazardous propellants, batteries, ordnance, radio frequency transmitter power, or other subsystem components in quantities or levels exceeding the Envelope Payload characteristics (EPCs) in Table 2 below?	X	
2. Would the candidate spacecraft utilize any potentially hazardous material as part of a flight system whose type or amount precludes acquisition of the necessary permits prior to its use or is not included within the definition of the Envelope Payload (EP)?		X
3. Would the candidate mission release material other than propulsion system exhaust or inert gases into the Earth's atmosphere or space?		X

4. Would launch of the candidate spacecraft suggest the potential for any substantial impact on public health and safety?		**X**
5. Would the candidate spacecraft utilize a laser system that does not meet the requirements for safe operation (ANSI Z136.1-2000 and ANSI Z136.6-2000)? For Class III-B and IV laser operations, provide a copy of the hazard evaluation and written safety precautions (NPG 8715.3).		**X**
6. Would the candidate spacecraft contain pathogenic microorganisms (including bacteria, protozoa, and viruses) which can produce disease or toxins hazardous to human health?		**X**
Item 1. Will use ~1285 kg of hydrazine (exceeds the 1000 kg limit in Table 2). Oxidizer quantities are within table limits.		

F. OTHER ENVIRONMENTAL ISSUES:	YES	NO
1. Would the candidate spacecraft have the potential for substantial effects on the environment outside the United States?		**X**
2. Would launch and operation of the candidate spacecraft have the potential to create substantial public controversy related to environmental issues?		**X**
Comments:		

Table 1: Launch Vehicles and Launch Pads

Launch Vehicle	Eastern Range (CCAFS Launch Complexes)	Western Range (VAFB Space Launch Complexes)
Atlas IIA & AS	LC-36	SLC-3
Atlas IIIA & B	LC-36	SLC-3
Atlas V Family	LC-41	SLC-3
Delta II Family	LC-17	SLC-2
Delta III	LC-17	N/A
Delta IV Family	LC-37	SLC-6
Athena I & II	LC-46 or -20	California Spaceport
Taurus	LC-46 0r -20	SLC-576E
Titan II	N/A	SLC-4W
Pegasus XL	CCAFS skidstrip KSC SLF	VAFB airfield

Table 2: Summary of Envelope Spacecraft Subsystems and Envelope Payload Characteristics (EPC)

Structure	**Unlimited:** aluminum, magnesium, carbon resin composites, and titanium **Limited:** beryllium [50 kg (110 lb)]
Propulsion	Mono- and bipropellant fuel; 1000 kg (2200 lb) (hydrazine); 1000 kg (2200 lb) (monomethyhydrazine) Bipropellant oxidizer; 1200 kg (2640 lb) (nitrogen tetroxide) Ion-electric fuel; 500 kg (1100 lb) (Xenon) SRM; 600 kg (1320 lb) (AP)-based solid propellant
Communications	Various 10-100 W (RF) transmitters
Power	Solar cells; 150 A-Hr (Ni-H_2) battery; 300 A-Hr (LiSOC) battery; 150 A-Hr (NiCd) battery
Science instruments	10 kW radar ANSI safe lasers (Section 4.1.2.1.3)
Other	Class C EEDs for mechanical systems deployment Radioisotopes limited to quantities that are approved for launch by NASA Nuclear Flight Safety Assurance Manager Propulsion system exhaust and inert gas venting

Radioactive Materials Report
Juno Step 2 Proposal

NPR 8715.3C, Para. 6.4.2: Report of Planned Launches of Radioactive Material								
Vehicle/Spacecraft (1)	Planned Launch Date (1)	Launch Site	Number of Sources	Isotope	Total Activity (TBq)	A2 Limit for Isotope (TBq)	A2 Multiple for Total Activity	Remarks
Atlas-V LV/Juno Spacecraft	August 2011	KSC, FL	3	Am-241	1.11E-07	1.00E-03	1.11E-04	EPD Instrument
Juno Multiple Sum							**1.11E-04**	

(1) - Current Baseline

Hydrazine Tank Assessment

Presented by
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Aerospace Nuclear Safety Engineering
Jet Propulsion Laboratory

July 24, 2008

Subsequent to the completion of this assessment, additional data became available that indicates that this analysis contains inherent conservatism (i.e. the probability of significant quantities of hydrazine reaching Earth's surface could be lower than estimated).

Summary

- The objective of this effort is to provide a conservative estimate of the probability of the various end states of the hydrazine on board the Juno spacecraft in the event of postulated launch vehicle failures
- Postulated end states include:
  - Hydrazine dispersed at-altitude: the hydrazine in the propellant tank is dispersed at-altitude, with the potential residual hydrazine left in the tank at ground impact being less than 0.45 kg (1 pound)
  - Hydrazine impacts land: the hydrazine left in the tank at ground impact is greater than 0.45 kg
  - Hydrazine impacts water: the hydrazine left in the tank at water impact is greater than 0.45 kg
  - The amount of hydrazine used in the above end state definitions was obtained from an Environmental Protection Agency standard that requires spills or accidental releases into the environment of 0.45 kg (1 pound) or more be reported

Summary (cont.)

- Two primary scenarios were considered
  - Suborbital reentry with impact onto Africa
    - An impact onto Africa is the first primary opportunity for fall back onto land after the launch vehicle clears the launch area and Cape Canaveral, Florida
  - Orbital reentry from a park orbit which is achieved at the conclusion of the first burn of the Centaur 2nd stage
  - Probabilities for the suborbital and orbital reentries were estimated using an Atlas V 541 launch vehicle and are believed to be representative of those for the Juno launch vehicle
    - Based on MSL AV 541 Databook, which has been extensively reviewed by KSC and interagency panel (MSL INSRP)
- The conditional probabilities for each of the end states were derived using event sequence diagrams (ESDs).
  - An ESD provides a sequence of logical steps from the beginning of the scenario to each of the possible end states
  - ESDs typically include logical branches, where the conditional probability of proceeding along alternative paths must be evaluated using analytic models or expert elicitation

Summary (cont.)

- Consistent with the end state definitions, this assessment does not quantify the hydrazine released upon impact, but only qualifies it as being greater than 0.45 kg
- Population distribution, potential for exposure, and health effects have not been included in this assessment
- Juno Suborbital Reentry End State Probabilities for Impact onto Africa:

End State	Probability
Liquid hydrazine dispersed at-altitude	7.97E-05
Liquid hydrazine impacts land	8.05E-07

- Juno Orbital Reentry End State Probabilities for an Orbital Inclination of 28.5 degrees (band between -28 and +28 degrees):

End State	Probability
Liquid hydrazine dispersed at-altitude	3.11E-03
Hydrazine impacts land	9.14E-06
Hydrazine impacts water	2.55E-05

- Note that probabilities are summed and are based on data for the Atlas V 541 launch vehicle which is believed to be representative for this mission

Objective

- Define the end states of a spacecraft propellant tank initially containing liquid hydrazine for various launch vehicle/spacecraft failure scenarios
- Estimate the probability of those end states

Approach/Quantification

- The end states were derived inductively based on the initial condition of the hydrazine at the time of the launch vehicle failure and the environment which the hydrazine may be subjected prior to, during and immediately after the reentry heating, but prior to possible land/water impact.
- The conditional probabilities for each of the end states were derived using event sequence diagrams (ESDs).
  - An ESD provides a sequence of logical steps from the beginning of the scenario to each of the possible end states
  - ESDs typically include logical branches, where the conditional probability of proceeding along alternative paths must be evaluated using analytic models or expert elicitation

Suborbital Reentry with Impact onto Africa

- An impact onto African is the first primary opportunity for fall back onto land after the launch vehicle (LV) clears the launch area and Cape Canaveral, Florida
- The probability of LV/spacecraft debris impacting Africa can be estimated by determining the probability of a catastrophic launch vehicle failure during the period in which the instantaneous impact point (IIP) crosses Africa
  - The IIP is calculated by assuming that the LV thrust is terminated when the LV is on the nominal trajectory and the spacecraft with attached remnants of the launch vehicle falls back to Earth on a ballistic trajectory with no air drag.
  - The IIP is found to cross Africa during the period from 664.4 to 674.6 seconds mission elapsed time (MET)
    - During this time interval, the payload fairing (PLF) has been jettisoned and the Centaur is thrusting
  - The total probability of a suborbital reentry and subsequent impact of debris onto Africa is estimated to be 8.05E-05 (M. Yau, ASCA, Inc.) using the Mars Science Laboratory/Atlas V 541 LV data
    - Although other missions may differ from this estimate due to mission unique trajectory and failure probabilities, this estimate is believed representative.

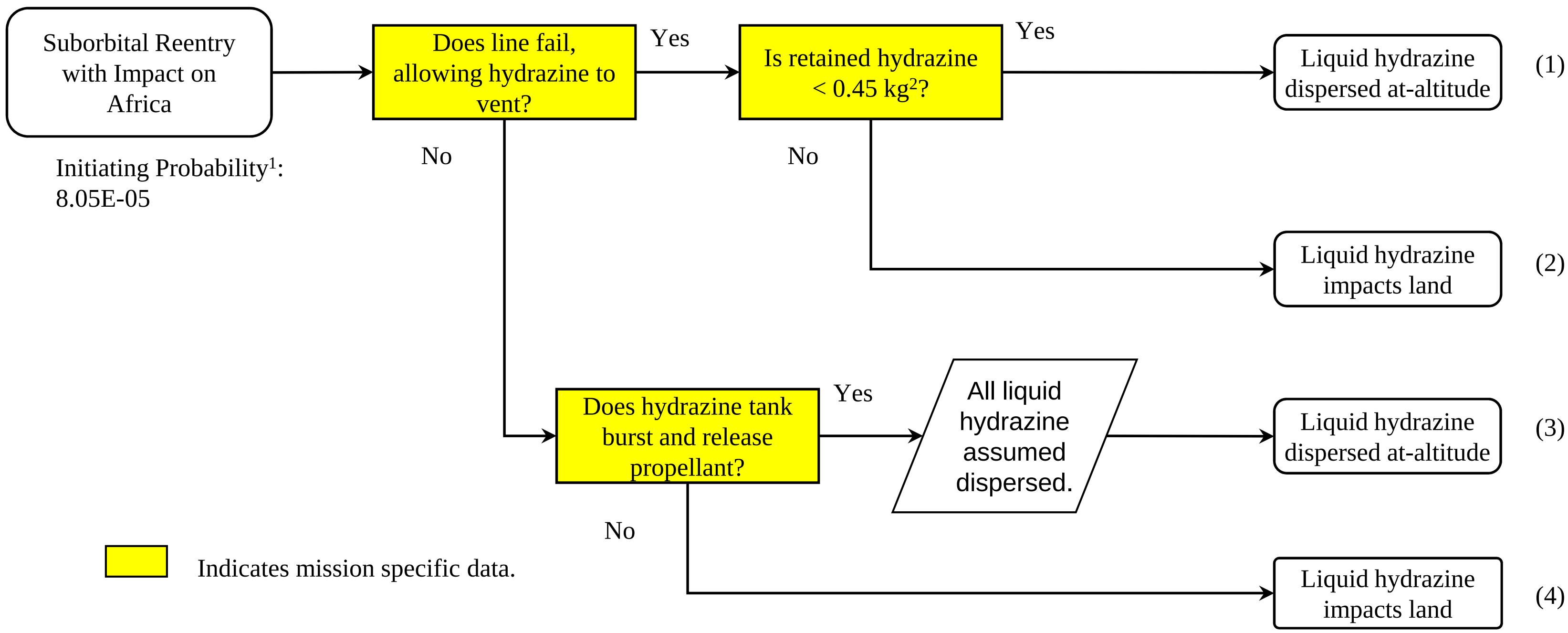
Suborbital Reentry with Impact onto Africa (cont.)

- The major accident initial condition (AIC) contributors to this probability include
  - an attitude control malfunction failure in the 281 to 688.4 second MET interval (3.86E-05)
  - a Centaur liquid rocket engine catastrophic failure also in the 281 to 688.4 second MET interval (3.17E-05)
  - trajectory control malfunctions in the 111.7 to 214.3 and 281 to 688.4 second MET intervals (2.11E-06 and 2.38E-06, respectively
- A destruct action, either commanded or automatic, would be taken for nearly all (94%) of these cases
  - The blast and blast driven fragment environments which occur as a result of a Centaur destruct prior to jettison of the PLF will be negligible after the PLF has been jettisoned. Thus the spacecraft and propellant tank(s) are expected to remain intact and undamaged.
- Upon destruct, the engine thrust is terminated and the spacecraft and remnants of the Centaur above the Centaur liquid oxygen/liquid hydrogen common bulkhead will continue on a ballistic trajectory upward, reach a peak altitude and then begin their fallback to Earth.
- Spacecraft breakup will likely occur at an altitude of about 70 km (NASA JSC)
- Release of the liquid hydrazine in the propellant tank during suborbital reentry occurs due to
  - Failure of the propellant line or other tank penetration which would allow the hydrazine to vent/empty
    - Mechanical failure due to breakup of the spacecraft during reentry
    - Burn through due to direct aerodynamic heating
  - Burst of the propellant tank when the internal pressure is not vented through a previously failed propellant line or other penetration
    - Function of the hydrazine mass; initial pressure, ullage volume, burst pressure and diameter of the tank

Suborbital Reentry with Impact onto Africa (cont.)

- Postulated end states
  - Liquid hydrazine dispersed at-altitude with potential residual hydrazine left in tank at ground impact being less than 0.45 kg: "Liquid hydrazine dispersed at-altitude"
  - Liquid hydrazine left in tank at ground impact is greater than 0.45 kg: "Liquid hydrazine impacts land"
- Develop event sequence diagram (ESD) starting with the accident outcome condition (AOC) Suborbital Reentry with Impact onto Africa and map into defined end states

Event Sequence Diagram
Suborbital Reentry with Impact on Africa



1. ASCA provided estimate based on Atlas V 541/trajectory for Mars Science Laboratory (MSL).
2. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.

Point Values Corresponding to Branch Point Probability Qualifiers (from ASCA*, Inc.)

Range (Branch 1)	Range (Branch 2)	Value (Branch 1)	Value (Branch 2)
Very Likely (VL1)	Extremely Unlikely (EU)	0.999	0.001
VL2	Very Unlikely (VU)	0.99	0.01
VL3	Unlikely (U)	0.8	0.2
Likely (L)	U	0.7	0.3
Likely/Unlikely (L/U)	L/U	0.5	0.5

* KSC launch vehicle databook contractor

Hydrazine Tank Data

Mission / Number of Tanks	Shape / Size	Wall Thickness	Empty Mass of Tank	Total Tank Volume & Max. Propellant Volume	Hydrazine Mass per Tank & Total for Spacecraft	Nominal temperature & pressure	Design Burst Pressure	Launch Vehicle	Mission Description
MSL Descent Stage / 3	Cylinder with hemispherical endcaps http://www.psi-pci.com/Data_Sheets_Library/DS505.pdf 23.13" (587.5 mm) ID x 28.46" (722.8 mm) long	1.092 mm minimum (0.043" minimum) Thicker at bosses.	16 kg (35 lb)	8521 cu. in. total Up to 8163 cu. in. of propellant	129 kg/tank 294 lb/tank 387 kg total 1176 lb total	535 psig	1188 psig	AV 541	Planetary
MSL Cruise Stage / 2	Sphere http://www.psi-pci.com/Data_Sheets_Library/DS274.pdf 19" ID	0.584 mm minimum (0.023" minimum) Thicker at bosses.	6.0 kg	59.5 l total (3,660 cu in.) Up to 45.03 l of propellant (2,748 cu in)	36 kg/tank 72 kg total	377 psig	754 psig		
Juno / 4	Sphere 35.26" (0.896 m) ID	0.940 mm minimum (0.037" minimum) Thicker at bosses.	18.3 kg	22,953 cu in. 0.376 m^3	358 kg/tank 1431 kg total (3148 lb) total	40 C, 325 psig	525 psig @ 40C	AV 551	Planetary
MRO / 1	Cylinder with hemispherical endcaps http://www.psi-pci.com/Data_Sheets_Library/DS456.pdf 48.9" (1242 mm) ID x 58.885" (1496 mm) long (Length is 4.45" shorter than standard tank.)	0.787 mm (0.031" minimum)	45.0 kg (99.2 lb)	87,575 cu in.	1149 kg/tank	250 psig	375 psig	AV 401	Planetary
CGRO / 4	Elliptical tank http://psi-pci.com/Data_Sheets_Library/DS315.pdf 36" (914 mm) ID x 47.5" (1206 mm) long	1.219 mm (0.048 in. minimum)	44.45 kg (98.0 lb)	600.2 l total (36,626 cu in) Up to 28,000 cu in. of propellant	470 kg/tank (1034 lb/tank) Mission used 1900 kg (4200 lb) total (475 kg/tank)	400 psig	800 psig		Earth Orbiter
Cassini / 1	Spherical tank http://psi-pci.com/Data_Sheets_Library/DS325.pdf 28" (711 mm) ID sphere	1.194 mm (0.047 in. minimum)	20 kg (44.0 lb)	186 l total (11,350 cu in.) Up to 132.1 l (8,060 cu in.) of propellant	135 kg/tank (298 lb/tank)	21 C, 400 psig	900 psig (From Cassini Safety Databook)	Titan IV	Planetary

NASA JSC* Supporting Analyses for Suborbital Reentry ESD

Table 1. Approximated Geometry Used in ORSAT code

	Empty Tank Mass (kg)	Interior Diameter (m)	Material Thickness (m)	Outer Diameter (m)
MSL Descent	16.00	0.64367	0.00275	0.64916
MSL Cruise	6.00	0.48260	0.00183	0.48627
Juno	18.30	0.89560	0.00163	0.89887
MRO	45.00	1.39946	0.00164	1.40275
CGRO	44.45	1.04659	0.00290	1.05238
Cassini	20.00	0.71120	0.00281	0.71683

*This is the same team that did the NRO hydrazine analysis

NASA JSC Supporting Analyses for Suborbital Reentry ESD (cont.)

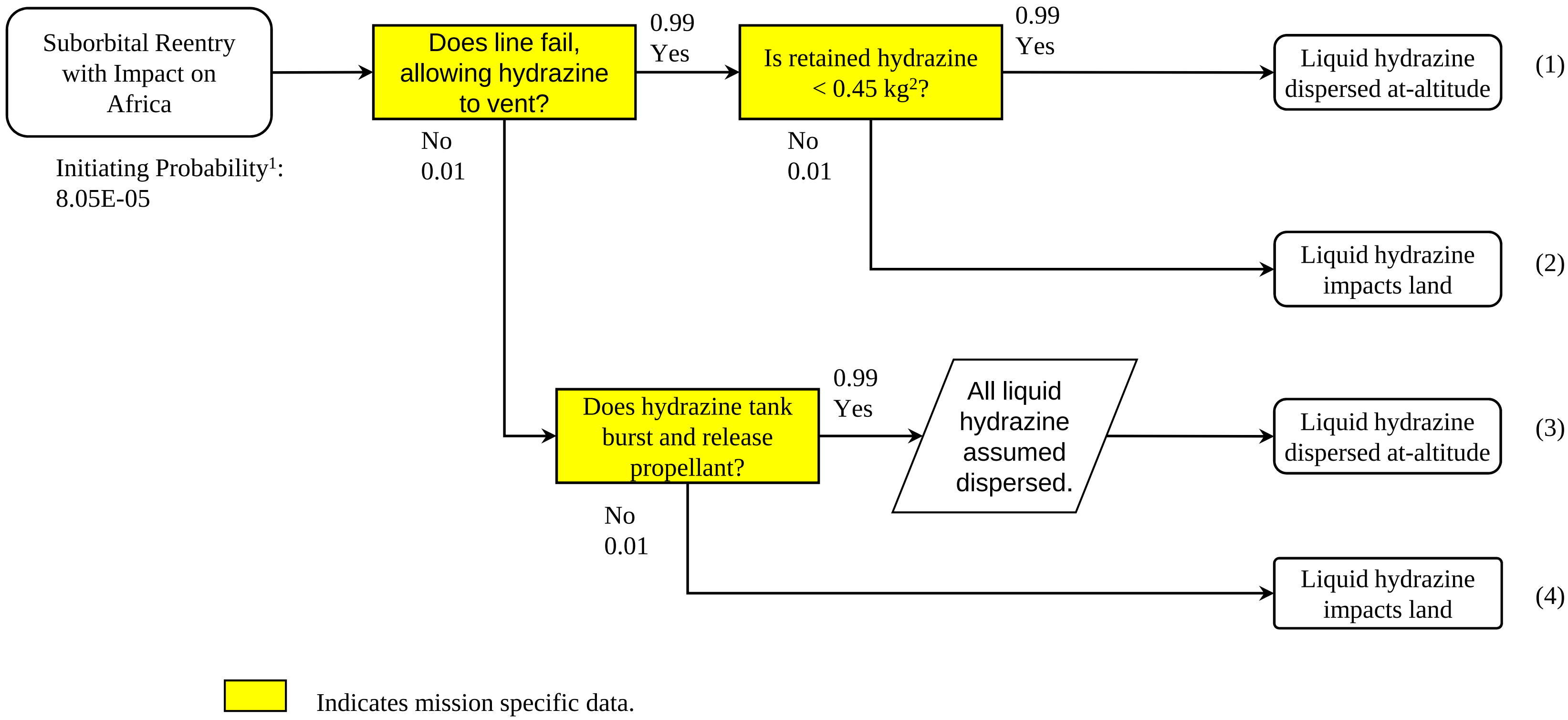
Table 2. Burst Altitude of Liquid Filled Hydrazine Tank With and Without Pressurant for Various Initial Altitudes of Exposure to Heat Pulse

	122 km initial altitude		78 km initial altitude		70 km initial altitude	
	Burst Altitude (km) with fuel and pressurant	Burst Altitude (km) with fuel	Burst Altitude (km) with fuel and pressurant	Burst Altitude (km) with fuel	Burst Altitude (km) with fuel and pressurant	Burst Altitude (km) with fuel
MSL Cruise	65.8	56.6	65.2	53.5	57.7	48.5
MSL Descent	68.5	52.4	64.5	49.9	59.7	45.6
Cassini	57.3	36.2	54.1	0	50.1	0
Juno	69.8	53.2	65.2	50.5	60.4	46.7
CGRO	52.5	0	49.5	0	45.5	0
MRO	52.8	0	50.2	0	46.5	0

Suborbital Reentry ESD Branch Point Probabilities

- Does line fail, allowing hydrazine to vent?
  - Small lines (ranging from 0.25 to 1-in. diameter) into or out of the tank may fail. Propellant and/or pressurant lines may vent hydrazine depending on tank design (propellant management device or diaphragm type).
  - Justified by high stagnation heating rate for small diameter lines, fracture due to general spacecraft breakup.
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.
- Is retained hydrazine < 0.45 kg?
  - All, or nearly all (with < 0.45 kg remaining), of the hydrazine may vent through the failed propellant line.
  - Justified by low ambient pressure leading to low boiling temperature and high vaporization rate of hydrazine; ability of broken propellant line to vent large quantity of gas during fall back (Don Li, JPL).
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.
- Does hydrazine tank burst and release propellant?
  - Based on burst analysis completed by NASA JSC. (In general, a function of tank size, propellant mass, burst pressure, etc.),
  - Assessment should be made by comparing mission specific tank with NASA JSC example tanks
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Juno Specific Event Sequence Diagram
Suborbital Reentry with Impact on Africa



1. ASCA provided estimate based on Atlas V 541/trajectory for Mars Science Laboratory (MSL).
2. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.

Juno Specific Event Sequence Diagram
Suborbital Reentry with Impact on Africa (cont.)

Table 3. Juno Suborbital Reentry End State Probabilities

End State	Probability
Liquid hydrazine dispersed at-altitude	7.97E-05
Liquid hydrazine impacts land	8.05E-07

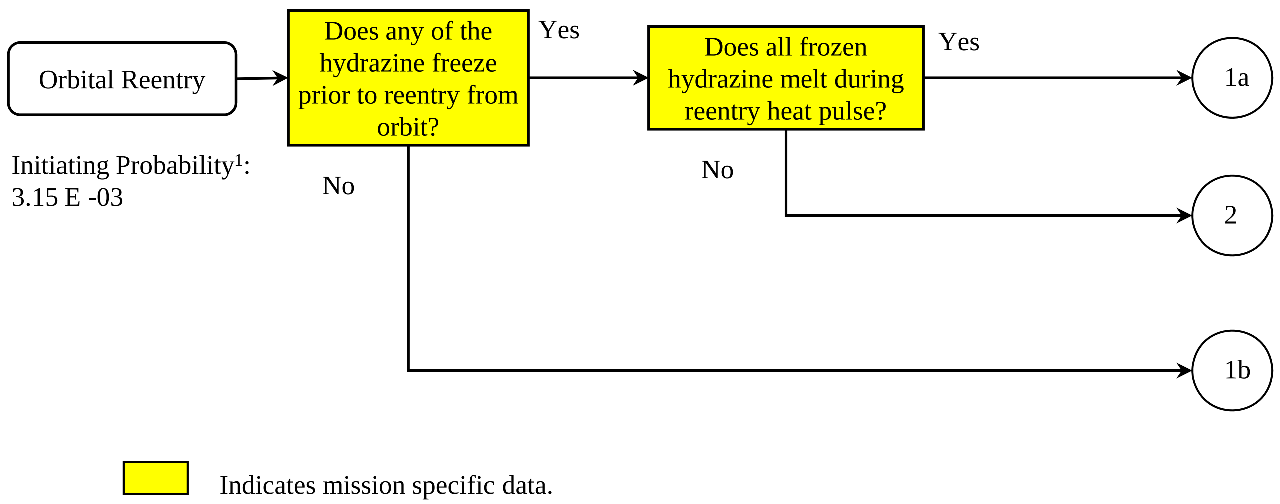
Orbital Reentry

- Orbital reentries result in both water and land impacts
- Orbit inclination is 28.5 degrees
- The total probability of an orbital reentry and subsequent debris on water or land is estimated to be 3.15E-03 (ASCA, Inc.) using the Mars Science Laboratory/Atlas V 541 LV data
  - Although other missions may differ from this estimate due to mission unique trajectory and failure probabilities, this estimate is believed representative.
- The major accident initial condition (AIC) contributors to this probability include
  - an attitude control malfunction failure in the 688.4 to 1904.8 and 1904.8 to 2607.1 second MET intervals (1.12E-04 and 1.17E-03, respectively)
  - a Centaur liquid rocket engine catastrophic failure in the 1904.8 to 2384.1 second MET interval (1.27E-03)
  - a Centaur liquid rocket engine failure to restart at 1904.8 seconds MET (3.41E-04)

Orbital Reentry (cont.)

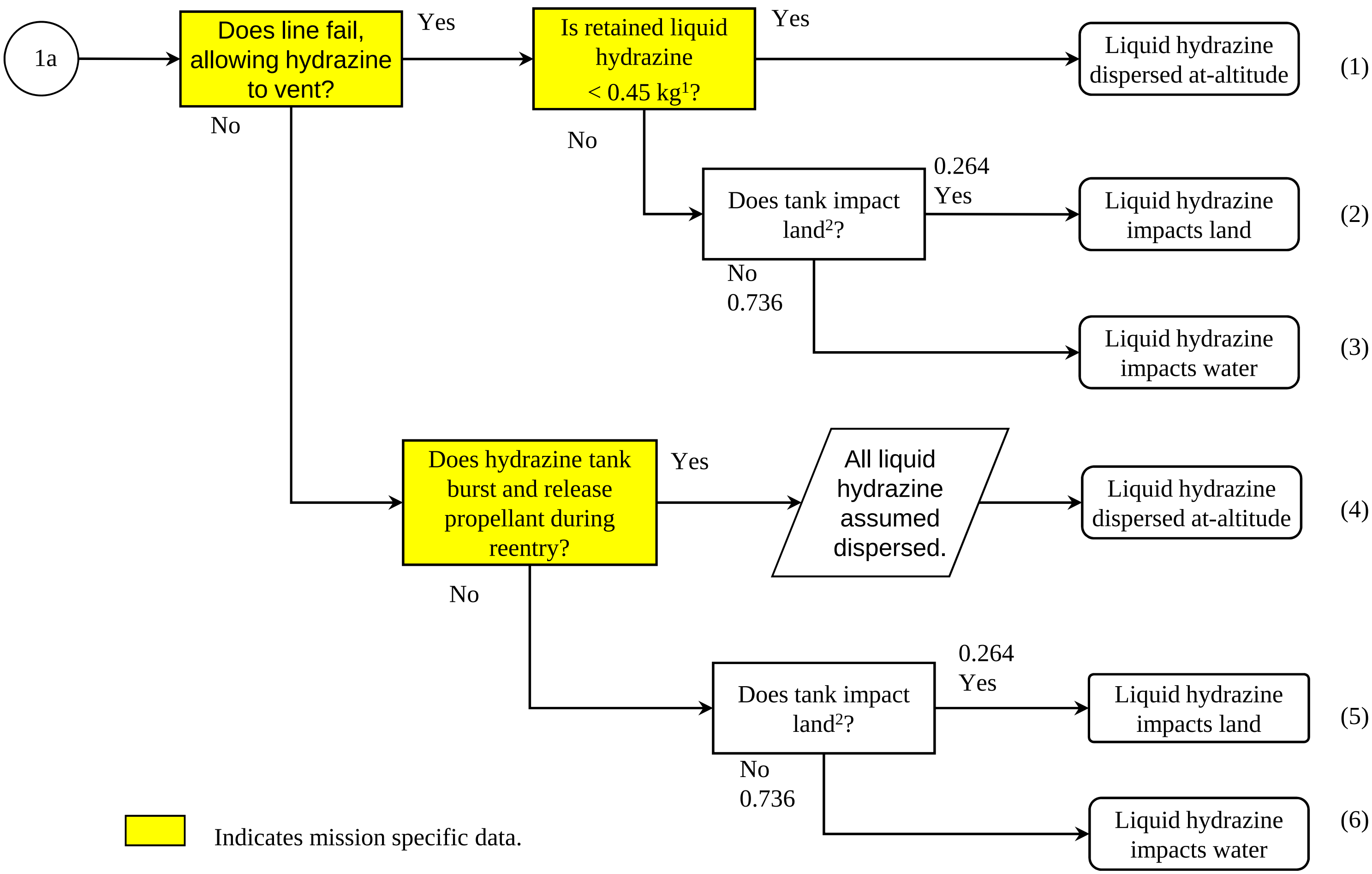
- Postulated end states
  - Liquid hydrazine dispersed at-altitude with potential residual hydrazine left in tank at ground impact being less than 0.45 kg: "Liquid hydrazine dispersed at-altitude"
  - Liquid hydrazine left in tank at ground impact is greater than 0.45 kg: "Liquid hydrazine impacts land"
  - Liquid hydrazine left in tank at ground impact is greater than 0.45 kg: "Liquid hydrazine impacts water"
  - Liquid & frozen hydrazine left in tank at ground impact is greater than 0.45 kg: "Liquid & frozen hydrazine impacts land"
  - Liquid & frozen hydrazine left in tank at ground impact is greater than 0.45 kg: "Liquid & frozen hydrazine impacts water"
- Develop event sequence diagram (ESD) starting with the accident outcome condition (AOC) Orbital Reentry and map into defined end states

Event Sequence Diagram
Orbital Reentry – Initial ESD



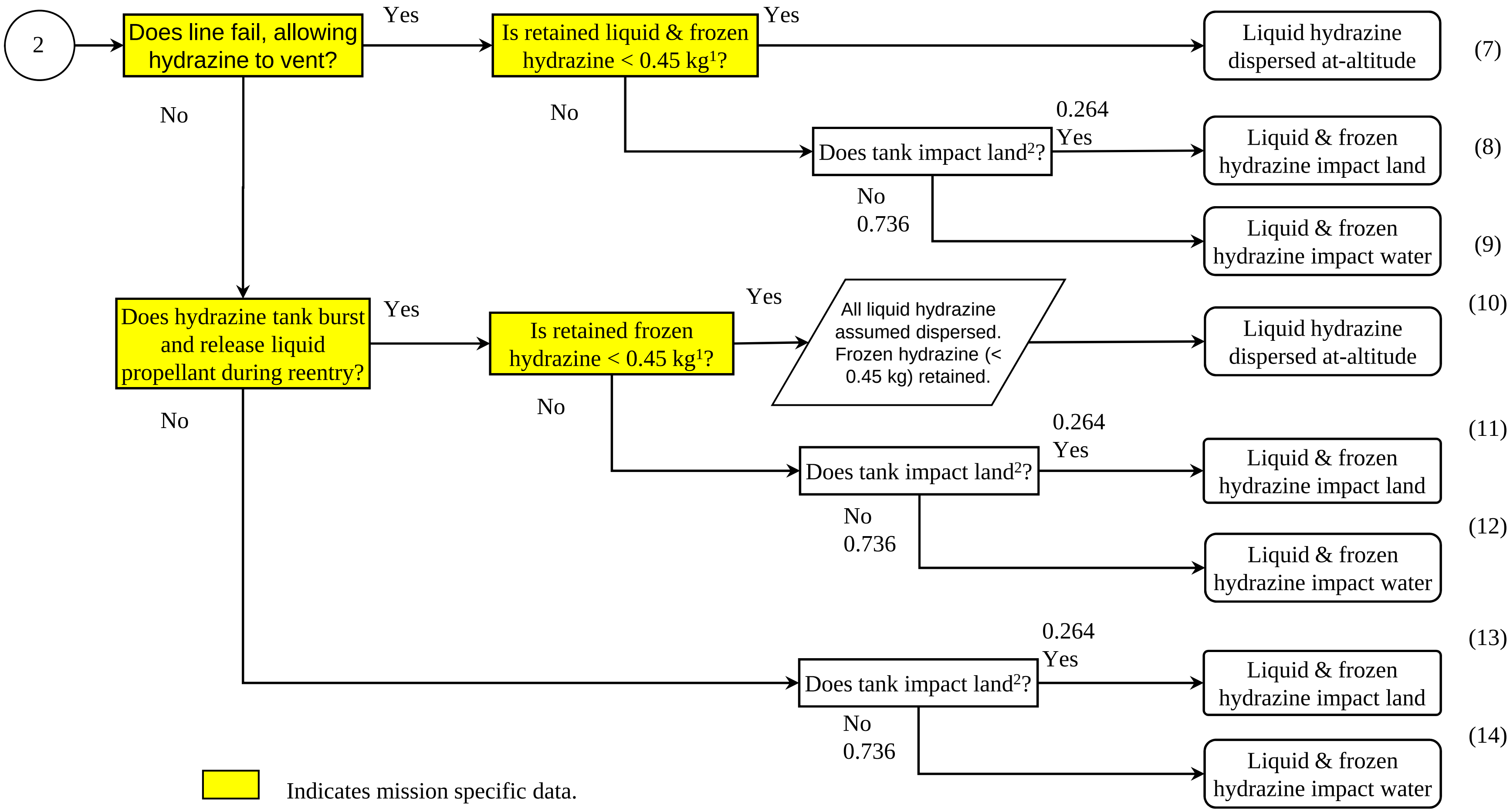
1) Probability estimate based on Atlas V 541/trajectory for the Mars Science Laboratory (MSL) planetary mission. A probability estimate for an Earth orbiting mission will depend on the spacecraft failure probabilities that lead to frozen hydrazine.

Event Sequence Diagram
Orbital Reentry – 1a



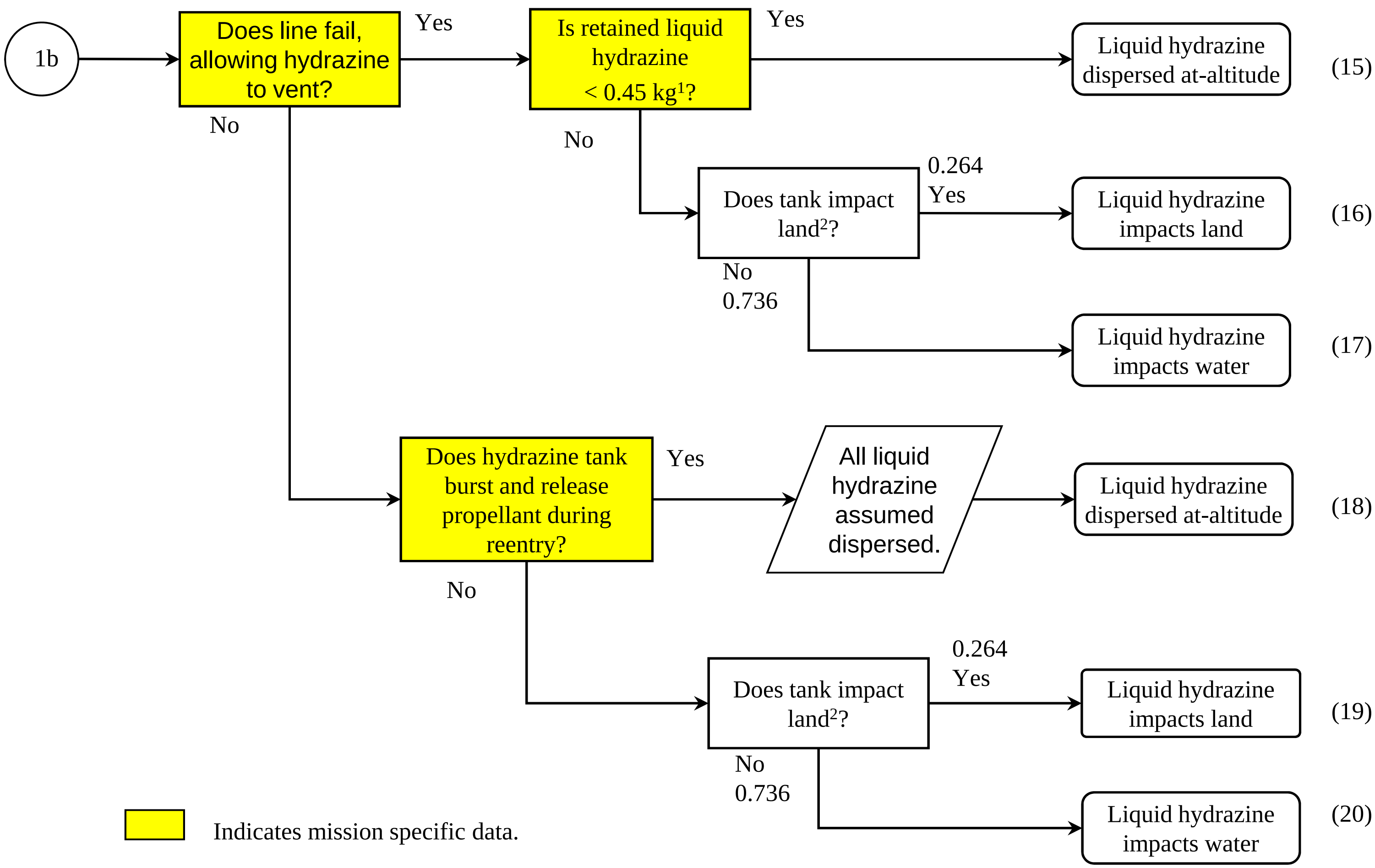
1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

Event Sequence Diagram
Orbital Reentry - 2



1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

Event Sequence Diagram
Orbital Reentry – 1b



1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

NASA JSC Supporting Analyses for Orbital Reentry ESDs

Table 4. Burst Altitude of Liquid Filled Hydrazine Tank With and Without Pressurant for Various Initial Altitudes of Exposure to Heat Pulse

	122 km initial altitude		78 km initial altitude	
	Burst Altitude (km) with fuel and pressurant	Burst Altitude (km) with fuel	Burst Altitude (km) with fuel and pressurant	Burst Altitude (km) with fuel
MSL Cruise	83	74	75.6	72.5
MSL Descent	89.9	74.7	76.5	72.4
Cassini	78.1	64.8	74.1	64.2
Juno	92.7	77.5	76.8	73.3
CGRO	78.5	55.8	73.4	53.1
MRO	80.1	47.8	73.4	39.2

NASA JSC Supporting Analyses for Orbital Reentry ESDs (cont.)

Table 5. Response of Initially Frozen Hydrazine Filled Tank With and Without Pressurant for Various Initial Altitudes of Exposure to Heat Pulse (as modified by 7/22/08 telecon with R. Kelley, JSC)

122 km Initial Altitude								
Vehicle	Initial Fuel Mass (kg)	Mass Liquid Fuel (kg)	% Fuel Melted	Tank Burn Through Altitude (km)	Bursts w/ Pressurant (Y/N)	Burst Altitude w/ Pressurant	Bursts w/o Pressurant (Y/N)	Burst Altitude w/o Pressurant
Cassini	135	133.0	98.55%	0.0				
CGRO	470	313.1	66.61%	0.0				
Juno	358	207.6	58.00%	51.7				
MRO	1149	596.2	51.89%	0.0				
MSL Cruise Stage	36	36.0	100.00%	0.0	Y	71.5	Y	63.4
MSL Descent Stage	129	97.4	75.54%	49.7				
78 km Initial Altitude								
Vehicle	Initial Fuel Mass (kg)	Mass Liquid Fuel (kg)	% Fuel Melted	Tank Burn Through Altitude (km)	Bursts w/ Pressurant (Y/N)	Burst Altitude w/ Pressurant	Bursts w/o Pressurant (Y/N)	Burst Altitude wo/ Pressurant
Cassini	135	126.2	93.51%	0.0				
CGRO	470	286.9	61.04%	0.0				
Juno	358	186.2	52.01%	47.3				
MRO	1149	530.2	46.14%	0.0				
MSL Cruise Stage	36	36.0	100.00%	0.0	Y	62.9	Y	51.2
MSL Descent Stage	129	97.9	75.91%	0.0				

JPL Supporting Analyses for Orbital Reentry ESDs

- Time to reenter from the nominal Juno park orbit was estimated to be between 2 and 3 days using the 1976 Standard Atmosphere (Salama and Ma)
  - The 1976 Standard Atmosphere does not account for any variability (e.g., diurnal, seasonal, solar flux, latitude, etc.) other than altitude.
- Time to freeze the liquid hydrazine assuming a failure of all tank heaters at time of LV/SC separation estimated by Juno Flight Systems
  - Minimum of 2.5 days before the fuel temperature would drop sufficiently to begin freezing the hydrazine
  - An additional 22 days to completely freeze the hydrazine, for a total of 24.5 days from launch.
  - Actual cool down/freeze time will be longer since the analysis
    - does not assume any heat input to the tanks from the Sun or Earth albedo
    - assumes the tanks have direct exposure to space in all directions, when in reality more than half of the tank surface area faces other tanks and spacecraft structure which would reduce heat loss from the tanks by reflecting some of the radiated heat back to the fuel tanks

Branch Point Probabilities
Orbital Reentry – Initial ESD

- Does any of the hydrazine freeze prior to reentry from orbit?
  - For a planetary mission, orbital reentry may occur after a launch vehicle failure leaves the spacecraft in park orbit, with time to reenter being relatively short.
  - For an Earth orbiter mission, orbital reentry may occur after the spacecraft is placed in Earth orbit, with the time to reenter being relatively long
  - Branch probability depends on the time to reenter versus the time to freeze the hydrazine.
  - Juno:
    - Nominal reentry time from park orbit is between 2 and 3 days (Salama and Ma).
    - Conservative estimate to initiate freezing is about 2.5 days and to completely freeze is about 22 days later (Juno project).
    - Strawman values: Because of the potential overlap in reentry time versus freeze time distributions (complete analysis not available at this time), this branch probability is assessed Unlikely, U (0.2) for yes; Very Likely, VL3 (0.8) for no.

Branch Point Probabilities
Orbital Reentry – Initial ESD (cont.)

- Does all frozen hydrazine melt during reentry heat pulse?
  - Branch probability is mission dependent based on reentry analysis completed by NASA JSC. (In general, a function of tank size and propellant mass.)
  - Juno:
    - Analysis shows that reentry heat pulse may melt between 186 kg (52%) to 208 kg (58%) assuming all (358 kg) of hydrazine is initially frozen prior to the reentry heat pulse
    - Strawman values: Because of the potential overlap in reentry time versus freeze time, less than half of the hydrazine might be expected to freeze. Given the severity of the reentry heating, it is Very Likely, VL2, that all of the frozen hydrazine will melt (0.99 for the "yes" branch) and Very Unlikely that the frozen hydrazine will remain frozen (0.01 for the "no" branch).

Branch Point Probabilities
Orbital Reentry – 1a

- Reminder: This sub-branch is conditional on all liquid hydrazine in the tank.
- Does line fail, allowing hydrazine to vent?
  - Small lines (ranging from 0.25 to 1-in. diameter) into or out of the tank may fail. Propellant and/or pressurant lines may vent hydrazine depending on tank design (propellant management device or diaphragm type).
  - Justified by high stagnation heating rate for small diameter lines, fracture due to general spacecraft breakup.
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Branch Point Probabilities
Orbital Reentry – 1a (cont.)

- Is retained hydrazine < 0.45 kg?
  - All, or nearly all (with < 0.45 kg remaining), of the hydrazine may vent through the failed propellant line.
  - Justified by low ambient pressure leading to low boiling temperature and high vaporization rate of hydrazine; ability of failed propellant line to vent large quantity of gas during fall back (Don Li, JPL).
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.
- Does hydrazine tank burst and release propellant?
  - Based on burst analysis completed by NASA JSC. (In general, a function of tank size, propellant mass, burst pressure, etc.),
  - Assessment should be made by comparing mission specific tank with NASA JSC example tanks
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Branch Point Probabilities
Orbital Reentry – 2

- Reminder: This sub-branch is conditional on both liquid and frozen hydrazine being in the tank at the end of the reentry heat pulse.
- Does line fail, allowing hydrazine to vent?
  - Small lines (ranging from 0.25 to 1-in. diameter) into or out of the tank may fail. Propellant and/or pressurant lines may vent hydrazine depending on tank design (propellant management device or diaphragm type).
  - Justified by high stagnation heating rate for small diameter lines, fracture due to general spacecraft breakup.
  - The possible existence of a small mass of frozen hydrazine in line is not expected to have an impact on whether the line fails during reentry due to the expected overwhelming reentry heat flux into the line.
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Branch Point Probabilities
Orbital Reentry – 2 (cont.)

- Is retained liquid and frozen hydrazine < 0.45 kg?
  - All, or nearly all (with < 0.45 kg remaining), of the liquid hydrazine may vent through the failed propellant line.
    - Justified by low ambient pressure leading to low boiling temperature and high vaporization rate of hydrazine; ability of broken propellant line to vent large quantity of gas during fall back (Don Li, JPL).
  - Frozen hydrazine remaining after the reentry heat pulse is not expected to pass through the failed line. The quantity remaining is not known.
  - Strawman values for Juno: Likely/Unlikely, L/U (0.5) for yes; Likely/Unlikely, LU (0.5) for no.

Branch Point Probabilities Orbital Reentry – 2 (cont.)

- Does hydrazine tank burst and release liquid propellant during reentry?
  - Since this sub-branch is conditional on both liquid and frozen hydrazine being in an intact tank, with insufficient heat from the reentry heat pulse being available to melt all of the frozen hydrazine if it were to remain in the tank through the reentry, it is difficult envisioning how sufficient hydrazine vapor could be produced to cause the tank to burst at its burst pressure.
  - Strawman values for Juno: Very Unlikely, VU (0.01) for yes; Very Likely, VL2 (0.99) for no.
- Is retained frozen hydrazine < 0.45 kg?
  - Tank material (Titanium 6Al-4V) selected since it is less sensitive to cracks and other imperfections. Thus, the tank is not expected to shatter, but remain essentially intact. Therefore, pieces of frozen hydrazine may be retained even after the tank fails. The quantity remaining is unknown.
  - Strawman values for Juno: Likely/Unlikely, L/U (0.5) for yes; Likely/Unlikely, LU (0.5) for no.

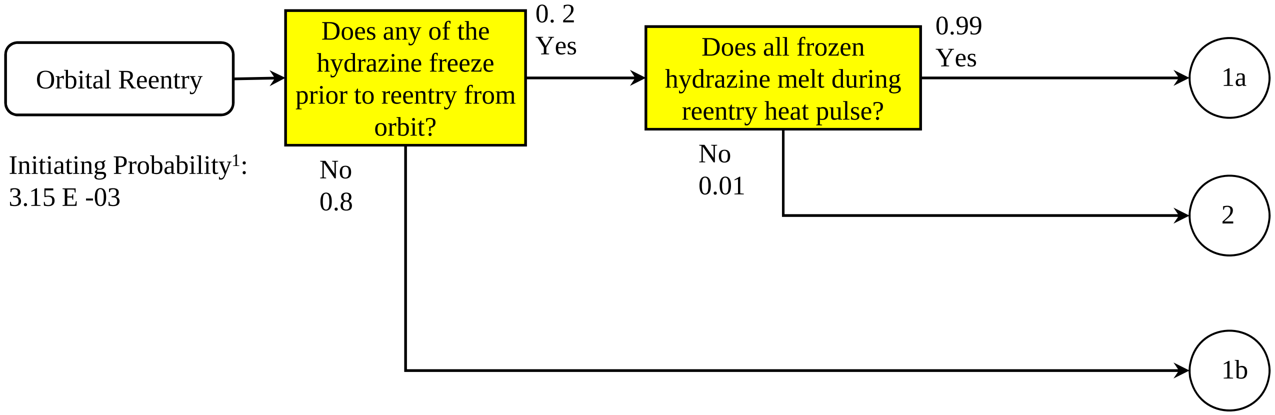
Branch Point Probabilities
Orbital Reentry – 1b

- Reminder: This sub-branch is conditional on all liquid hydrazine in the tank.
- Does line fail, allowing hydrazine to vent?
  - Small lines (ranging from 0.25 to 1-in. diameter) into or out of the tank may fail. Propellant and/or pressurant lines may vent hydrazine depending on tank design (propellant management device or diaphragm type).
  - Justified by high stagnation heating rate for small diameter lines, fracture due to general spacecraft breakup.
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Branch Point Probabilities
Orbital Reentry – 1b (cont.)

- Is retained hydrazine < 0.45 kg?
  - All, or nearly all (with < 0.45 kg remaining), of the hydrazine may vent through the failed propellant line.
  - Justified by low ambient pressure leading to low boiling temperature and high vaporization rate of hydrazine; ability of failed propellant line to vent large quantity of gas during fall back (Don Li, JPL).
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.
- Does hydrazine tank burst and release propellant?
  - Based on burst analysis completed by NASA JSC. (In general, a function of tank size, propellant mass, burst pressure, etc.),
  - Assessment should be made by comparing mission specific tank with NASA JSC example tanks
  - Strawman values for Juno: Very likely, VL2 (0.99) for yes; Very Unlikely, VU (0.01) for no.

Juno Specific Event Sequence Diagram
Orbital Reentry – Initial ESD

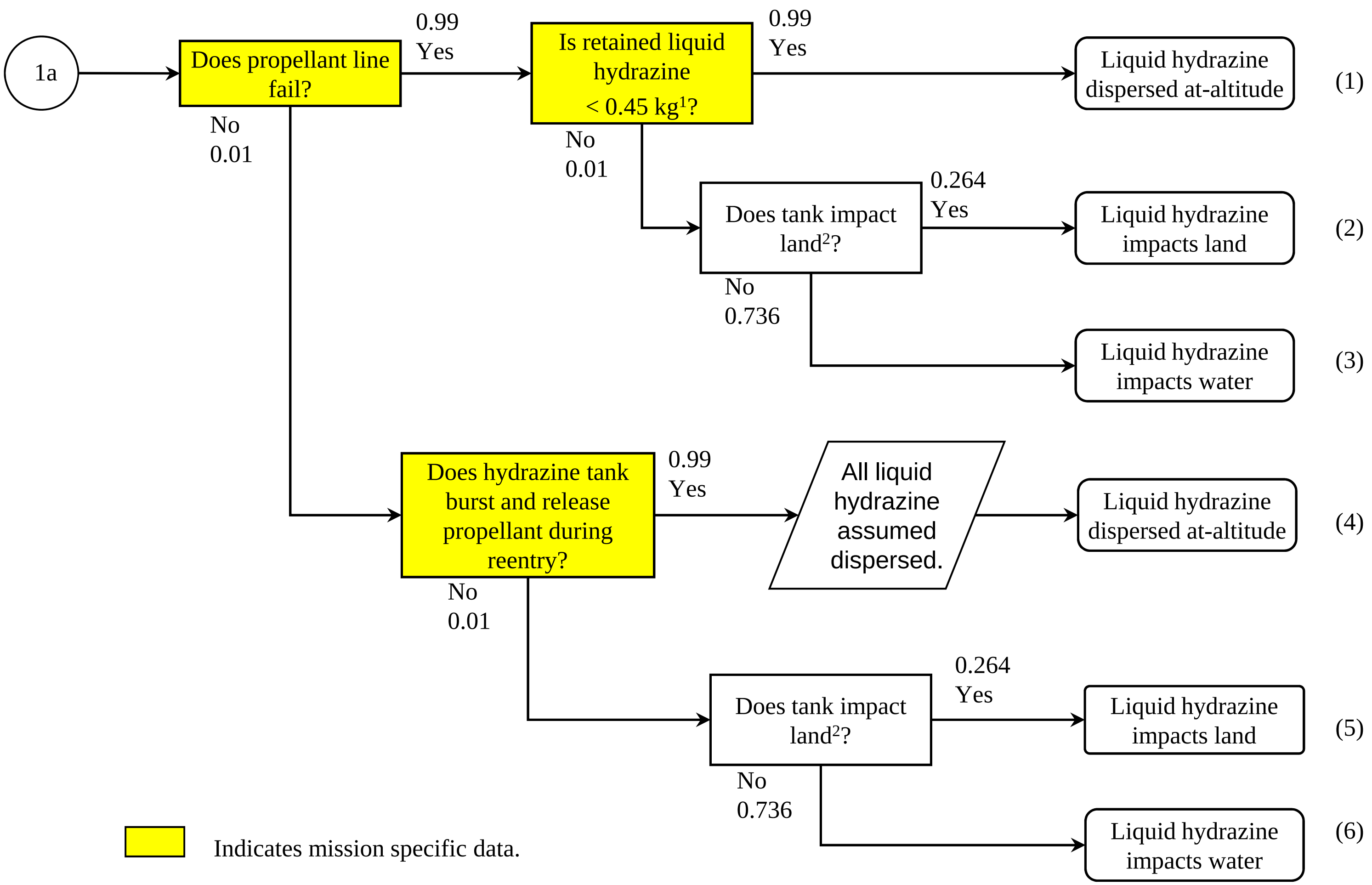


Initiating Probability[1]:
3.15 E -03

Indicates mission specific data.

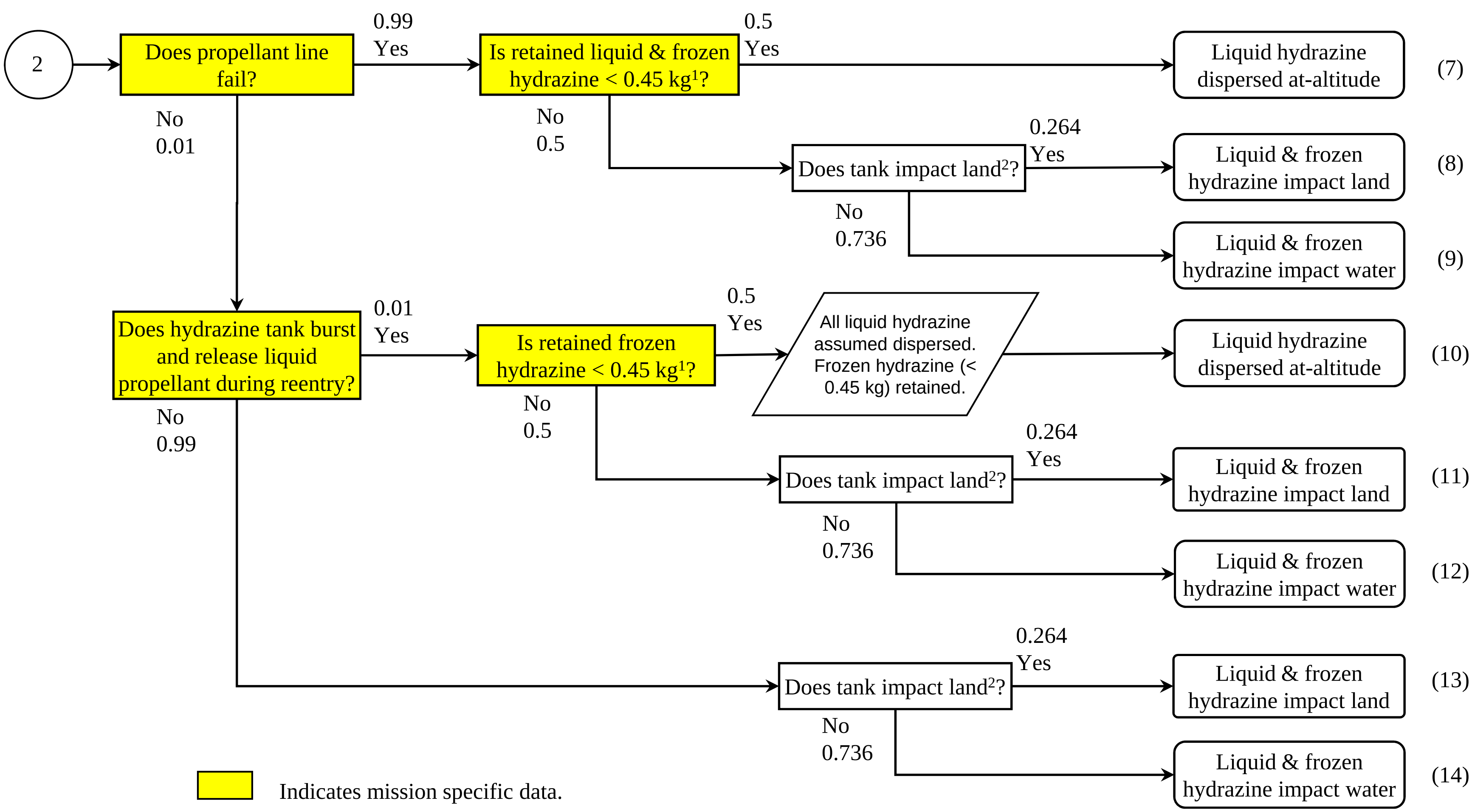
1) Probability estimate based on Atlas V 541/trajectory for the Mars Science Laboratory (MSL) planetary mission. A probability estimate for an Earth orbiting mission will depend on the spacecraft failure probabilities that lead to frozen hydrazine.

Juno Specific Event Sequence Diagram
Orbital Reentry – 1a



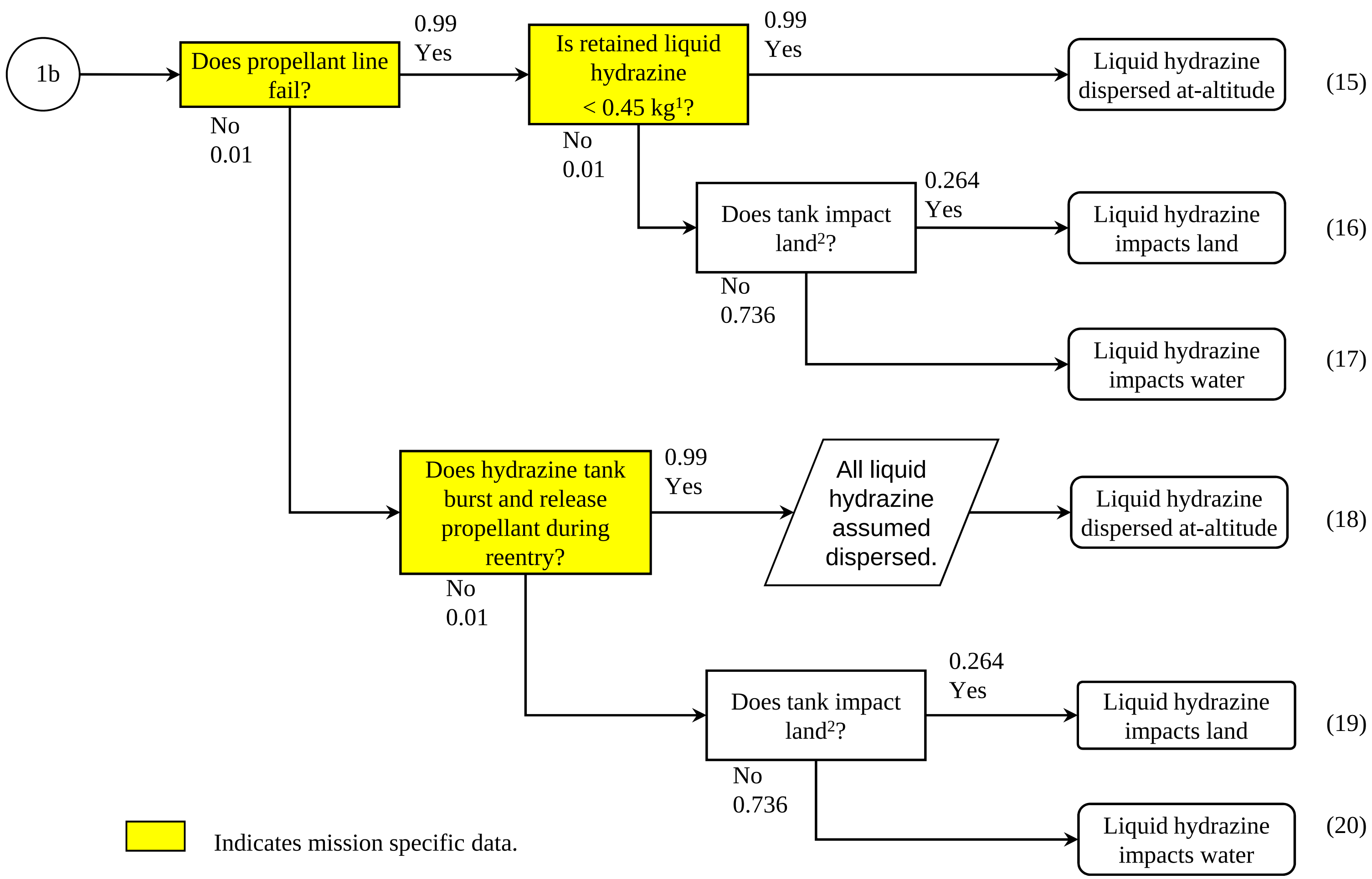
1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

Juno Specific Event Sequence Diagram
Orbital Reentry – 2



1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

Juno Specific Event Sequence Diagram
Orbital Reentry – 1b



1. A spill or accidental release into the environment of 0.45 kg (1 pound) or greater must be reported to the Environmental Protection Agency.
2. Data from United Nations Atlas of the Oceans at http://www.oceansatlas.org/unatlas/about/physicalandchemicalproperties/background/seemore1.html.

Juno Specific Event Sequence Diagram
Orbital Reentry – End State Probabilities

Table 6 Juno Orbital Reentry End State Probabilities

End State	Probability
Liquid hydrazine dispersed at-altitude	3.11E-03
Liquid hydrazine impacts land	8.30E-06
Liquid hydrazine impacts water	2.31E-05
Liquid and frozen hydrazine impact land	8.40E-07
Liquid and frozen hydrazine impact water	2.34E-06

Table 7 Juno Simplified End State Probability Summary

Simplified End State	Probability
Liquid hydrazine dispersed at-altitude	3.11E-03
Hydrazine impacts land	9.14E-06
Hydrazine impacts water	2.55E-05