QUANTITATIVE RISK ASSESSMENT AND MODELING: FIRE RISKS OF CNG-POWERED BUSES

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DEFINITION OF RISK

- Risk is a measure of potential of losses occurred due to natural or human activities.
  - Losses are adverse consequences in form of loss of human life, adverse health effects, loss of property, and damage to natural environment.
- Risk analysis is the process of characterizing (assessing), managing and informing others about existence, nature, magnitude, prevalence, contributing factors, and uncertainties of the potential losses.
  - the loss may be external to the system or internally caused by the system to one or more recipients (e.g., human, organization, economic assets, and environment).

CATEGORIES OF RISK ANALYSIS

Health risk analysis estimating potential diseases and losses of life affecting humans, animals and plants;

Safety risk analysis involves estimating potential harms caused by accidents occurring due to natural events (climatic conditions, earthquakes, brush fires, etc.) or human-made products, technologies and systems (i.e., aircraft crashes, vehicle accidents, nuclear plant accidents, technology obsolescence or failure);

Security risk analysis involves estimating access and harm caused due to war, terrorism, riot, crime (vandalism, theft, etc.) and misappropriation of information (national security information, intellectual property, etc.);

Financial risk analysis involves estimating potential individual, institutional and societal monetary losses such as currency fluctuations, interest rates, share market, project losses, bankruptcy, market loss, misappropriation of funds, and property damage;

Environmental risk analysis involves estimating losses due to noise, contamination, and pollution in ecosystem (water, land, air and atmosphere) and in space (space debris);

RISK ANALYSIS METHODS IN ENGINEERING

Risk analysis can be used in all stages of design, development, construction, and operation of engineering systems:

- **Conceptual Design**
  - Compare alternative design options
- **Design**
  - Provide barriers to prevent, minimize or eliminate harm
  - Minimize life-cycle cost
  - Apportion risk limits and performance goals.
- **Development**
  - Identify systems or subsystems that contribute most to safety and risk
  - Test safety and risk significant elements of the design
  - Quality assurance
  - Warranty development

RISK ANALYSIS METHODS IN ENGINEERING (Cont.)

- **Regulation**
  - Regulate consistent with the significance of the elements of the system that contribute most to risk
  - Set monitoring and performance criteria
  - Perform inspections
- **Operation**
  - Optimize cost of maintenance and other operational activities
  - Define surveillance requirements and schedules
  - Replacement policies and decisions
  - Aging estimation and management
  - Developing security measures
- **Decommissioning**
  - Assess safety of possible decommissioning activities
  - Select most appropriate disposal method
  - Assess long-term liability issue

Common Features and Key Elements of Risk Assessment (Both Quantitative and Qualitative)

- Identification of Hazards
- Identification of Barriers (Human, Structures, Components, Systems, Natural Barriers, etc.)
- Assessment of the Likelihood of Loss of Barriers
- Estimation of the Consequences of Exposure of Hazards
- Evaluation of the Risk (Combination of the Likelihood and Consequence)

STEPS IN RISK ASSESSMENT

1. Hazard Identification

a) **Natural hazards**
- Flood
- Tornado
- Earthquake

b) **Man-made hazards**
- Chemical hazard (e.g., gas and chemical reaction explosions, toxic chemicals released from a chemical processes)
- Thermal hazard (e.g., high-energy explosion from a chemical reactor or gas tank)
- Mechanical hazard (e.g., kinetic or potential energy from a moving object)
- Electrical hazard (e.g., potential difference, electrical and magnetic fields, electrical shock)
- Ionizing radiation (e.g., radiation released from a nuclear plant)
- Nonionizing radiation (e.g., radiation from a microwave oven, sun)
- Biological Hazards

2. Barrier Identification

a) **Physical (passive)**

- Walls (and natural physical barriers, mountain)
- Pipes
- Valves
- Casing
- Protective clothing
- Bunkers

b) **Physical (active)**

- Hazard removal actions
- Safety systems

STEPS IN RISK ASSESSMENT

3. Barriers Performance Assessment

- Historical performance data vs. physics-of-failure approach
- Accumulated damage to the barrier (e.g., hydrogen embrittlement, crack growth due to fatigue) exceeds endurance (e.g., fracture toughness of the tank).
- Barrier strength (or endurance) degrades because of some underlying chemical or mechanical mechanisms:
  - reduced thickness (for example due to geometrical change caused by mechanisms such as fatigue, erosion, or corrosion)
  - change in material properties (e.g., reduction toughness due to hydrogen or radiation damage mechanism).
- Malfunction of process equipment (e.g., failure to detect leak, the emergency cooling system of a nuclear plant)
- Human errors due to poor man-machine interface
- Human errors due to poor organizational communications
- Poor maintenance which does not restore the machinery properly
- Adverse natural phenomena
- Adverse operating environment
- Frequency of Scenarios

4. Exposure Assessment

If the barriers to hazard exposure are compromised, then some or all hazards will be release and potentially expose recipients.

Assess the amount and characteristics (toxicity, concentration, temperature, etc.) resulted by the release of the hazards.

Order of magnitude type calculations is possible , or
entirely relying on expert judgment.

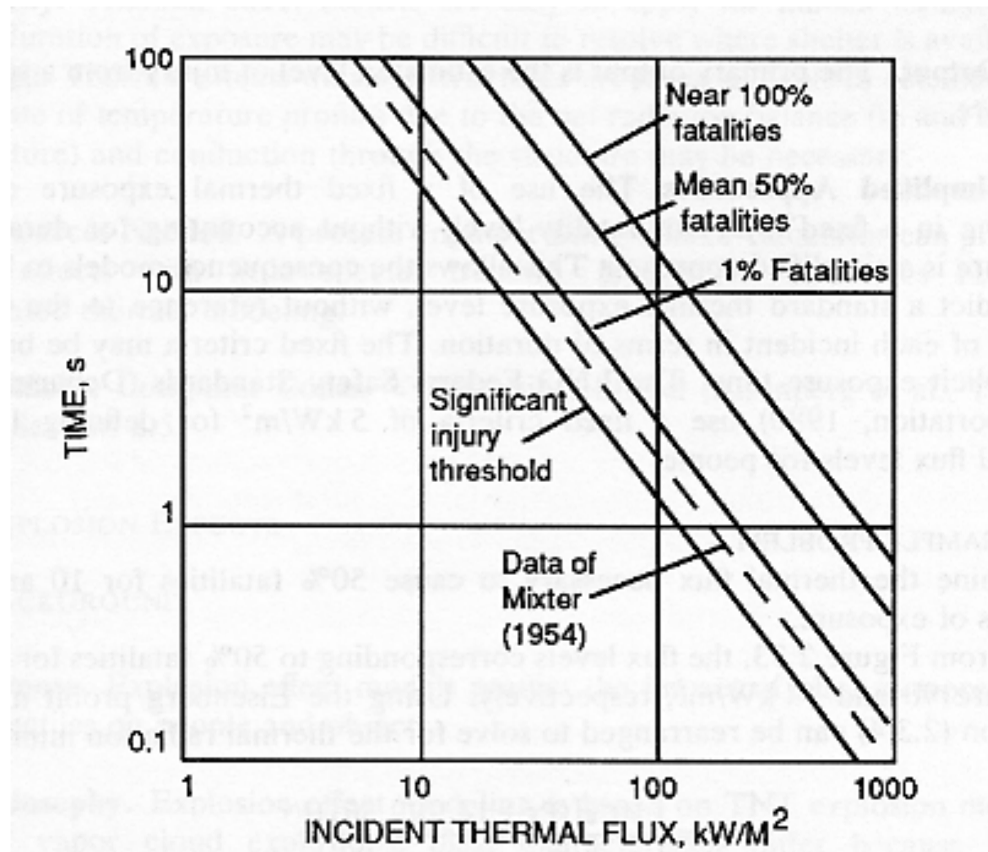
In quantitative assessment:

Models of barrier failure developed and the amount of exposure estimated.

Characterization of uncertainties associated with the risk values.

5. Risk Characterization (Assessment)

- Correlations of hazard exposure to damage: e.g., dose-to-fatality such as 10,000 person-rem = 1 cancer
- Extrapolation issues



Thermal Radiation Fatality Modeling

What is a QRA?

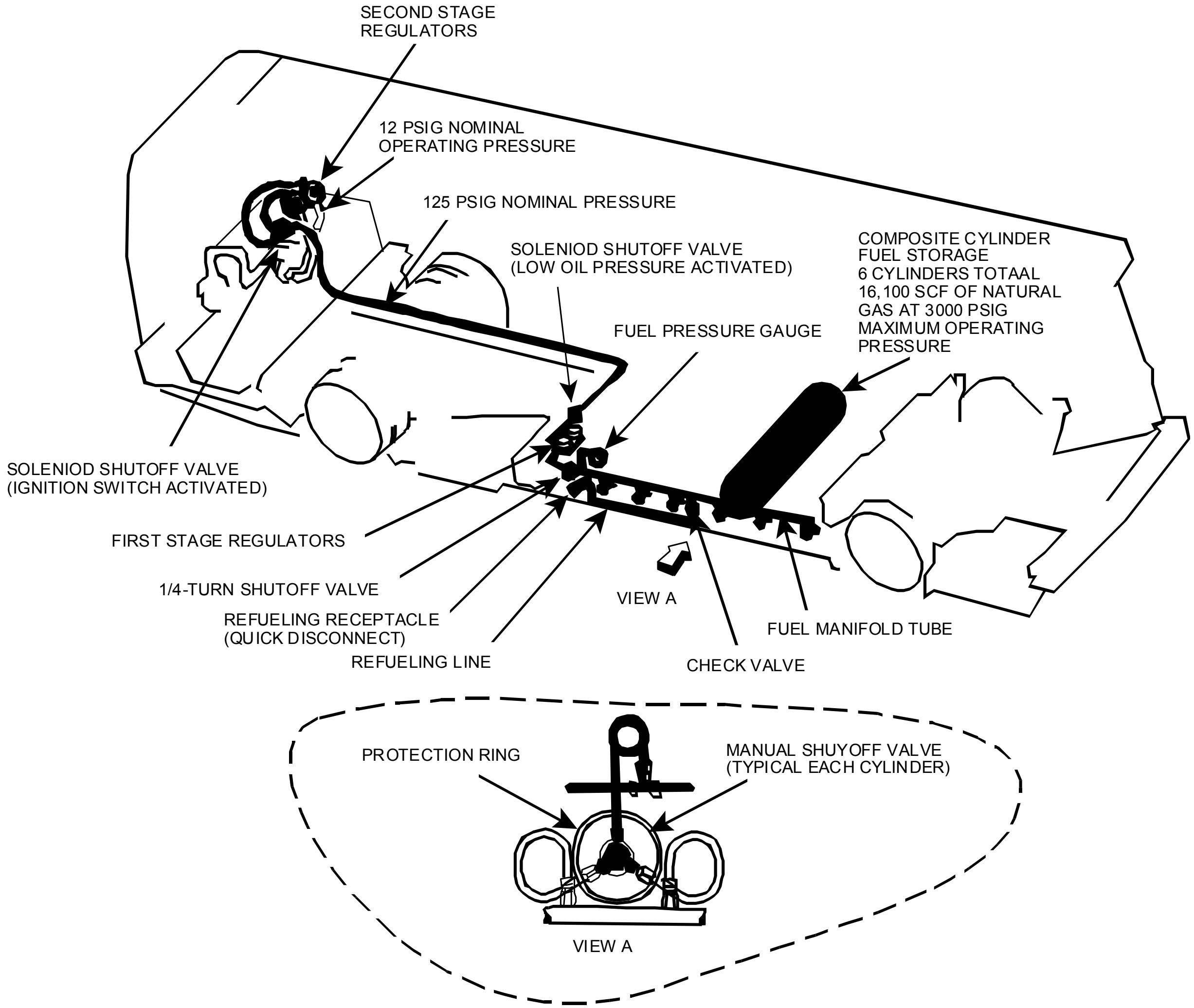
- QRA is a special kind of risk assessment where the frequency (or likelihood) and consequence are quantitatively measured
- The "potential" loss (i.e., risk) in a quantitative sense is probabilistic in nature
- QRA has been practiced for several decades for nuclear power plants under the name of probabilistic risk assessment (PRA) and PSA(the preferred international acronym)
- For our purposes QRA, PRA, and PSA are all considered to have the same meaning

CASE STUDY: QRA OF CNG-FULED BUSES

PERFORMED 2000-2003 WITH THE OBJECTIVES:

- **IDENTIFY FIRE SCENARIOS**
- **IDENTIFY RISK-SIGNIFICANT ONES**
- **ASSESS FIRE CAUSED FATALITY RISKS OF TYPICAL CNG BUSES**
- **COMPARE CNG FIRE RISKS TO DIESEL**

PART 1-QUALITATIVE ASSESSMNET



A NUMBER OF CNG BUS FIRES HAVE BEEN REPORTED

QUALITATIVE RISK ASSESSMENT

Step 1 Hazards

The hazard is the natural gas (primarily methane gas) fire and explosions leading to passenger and non-passenger fatalities.

Step 2 Barriers

Barriers are CNG storage tanks, pressure control systems, operators, warning and gas detection devices, and preventive maintenance activities.

QUALITATIVE RISK ASSESSMENT (Cont.)

Step 3 Barrier Performance

Several possible failures of barriers leadings to fire are possible. Barriers performance in critical risk scenarios:

- CNG tank or control system catastrophic failures (internally caused failures) leading to instantaneous release of CNG in the presence of an ignition source.
- CNG tank or control system degraded failures (e.g., internally caused leak) resulting in gradual release of CNG in the presence of an ignition source.
- CNG tank, control system, or human errors leading to release of CNG and ignition due to Electrostatic discharge sparks.
- Accidental impact of CNG tank and other hardware with external bodies (e.g., due to collisions with other vehicles) resulting in gas release in the presence of an ignition source.
- Operator/Driver error resulting in the release of CNG in the presence of an ignition source.

QUALITATIVE RISK ASSESSMENT (Cont.)

Step 4 Exposure

Four possible fire characteristics

CNG release mode	Ignition mode	Expected consequence
Instant	Immediate	Fireball
	Delayed	Vapor cloud explosion or flash fire
Gradual	Immediate	Jet flame
	Delayed	Vapor cloud explosion or flash fire

1. **Fireball** (Catastrophic cylinder rupture)
   - Immediate ignition
   - Secondary fireball
2. **Unconfined Vapor Cloud Explosion and Flash Fire** (Dispersion of natural gas)
   - Delayed ignition
   - Secondary fireball
3. **Confined Explosion** (Dispersion inside bus or building)
   - Delayed ignition
   - No explosion venting (Deflagration and Detonation)
4. **Jet Fire** (Crack in cylinder wall)
   - Immediate ignition
   - Blow out expected
5. **Cylinder Physical Explosion** (Catastrophic cylinder rupture)
   - Fragmentation produced
   - Missiles generated

QUALITATIVE RISK ASSESSMENT (Cont.)

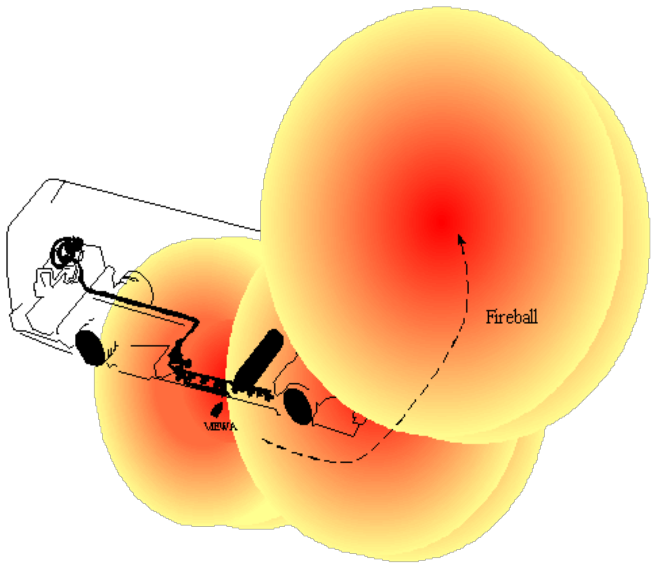
SEVERITY DESCRIPTION FROM EXPOSURE OF THE FIRE

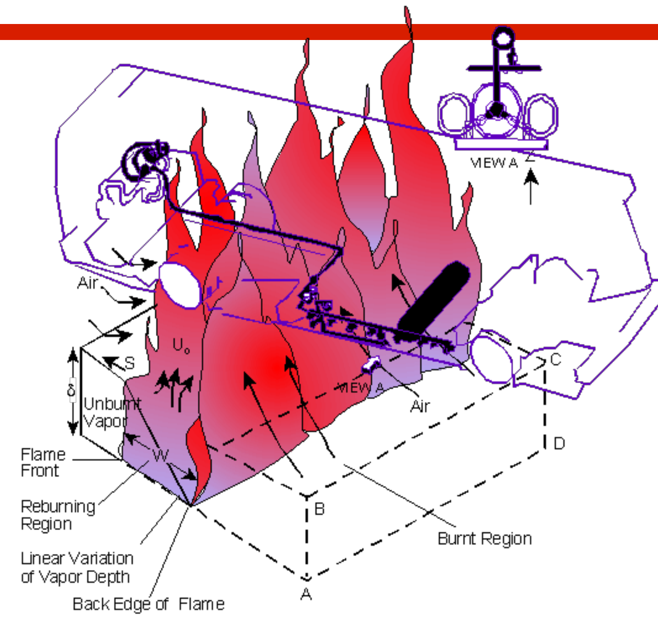
Severity Category	Severity Category Description
Catastrophic	CNG release involving catastrophic fire or explosion.
Critical	Unconfined CNG release with critical fire or explosive potential.
Marginal	Small CNG release with marginal ignition potential or fire effects.
Minor	Failure with minor fire potential and only loss of system operation.

RELATIVE FREQUENCY CATEGORIES FOR FIRE SCENARIOS

Frequency Category	Frequency Category Description
A - Frequent	Likely to occur within 1 year or less.
B - Probable	Likely to occur within 10 years or less.
C - Unlikely	Probable within the expected life of 20 years for a bus or station.
D - Remote	Possible but not likely during the expected life of 20 years.

QUALITATIVE RISK ASSESSMENT (Cont.)

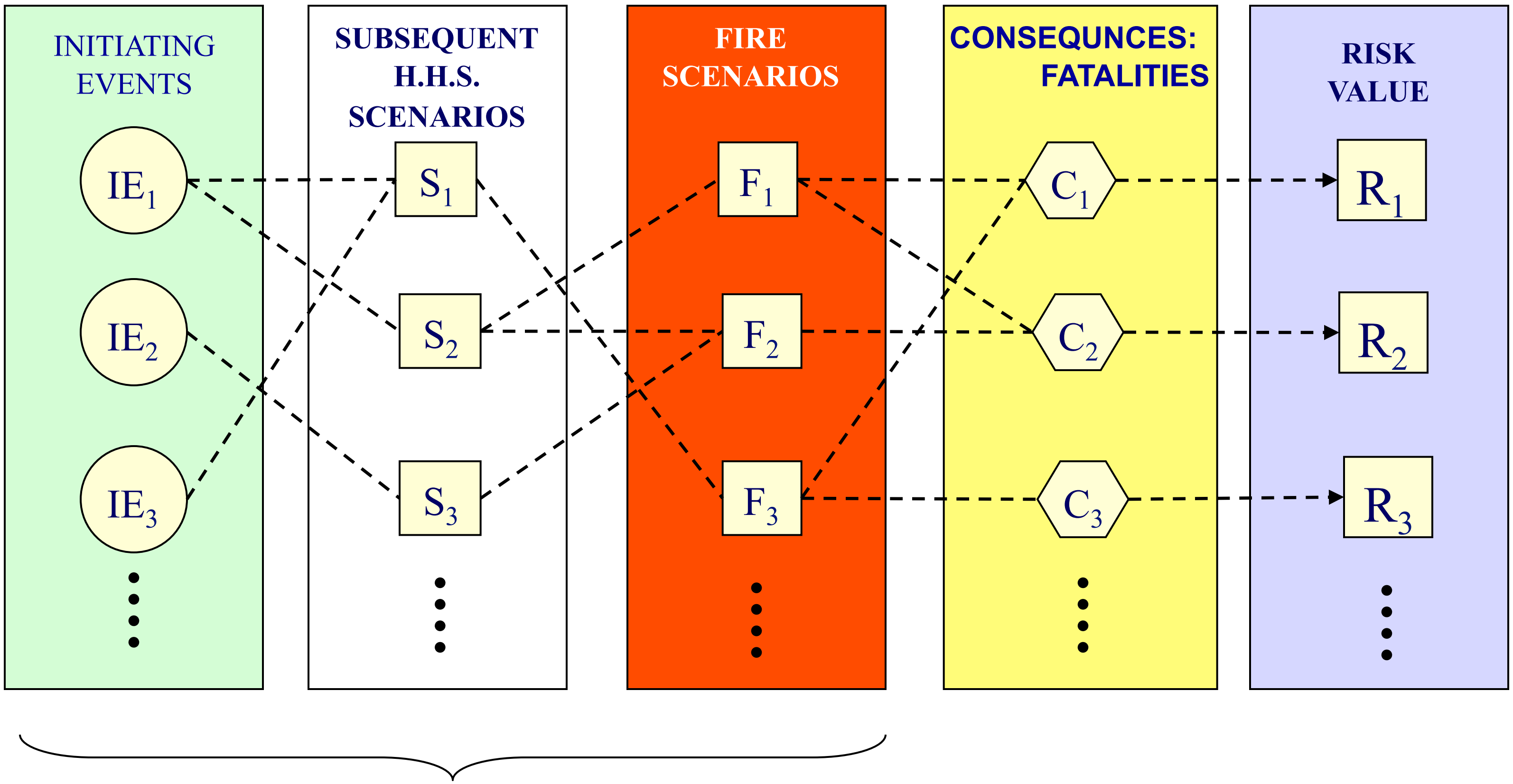




RISK MATRIX SHOWING THE NUMBER OF SCENARIOS FALLING INTO THE VARIOUS RISK CATEGORIES

	Catastrophic	Critical	Marginal	Minor
Likely	0	0	0	4
Probable	1	8	6	15
Unlikely	3	7	12	19
Remote	4	3	2	3

ELEMENT OF QUANTITATIVE RISK ASSESSMENT



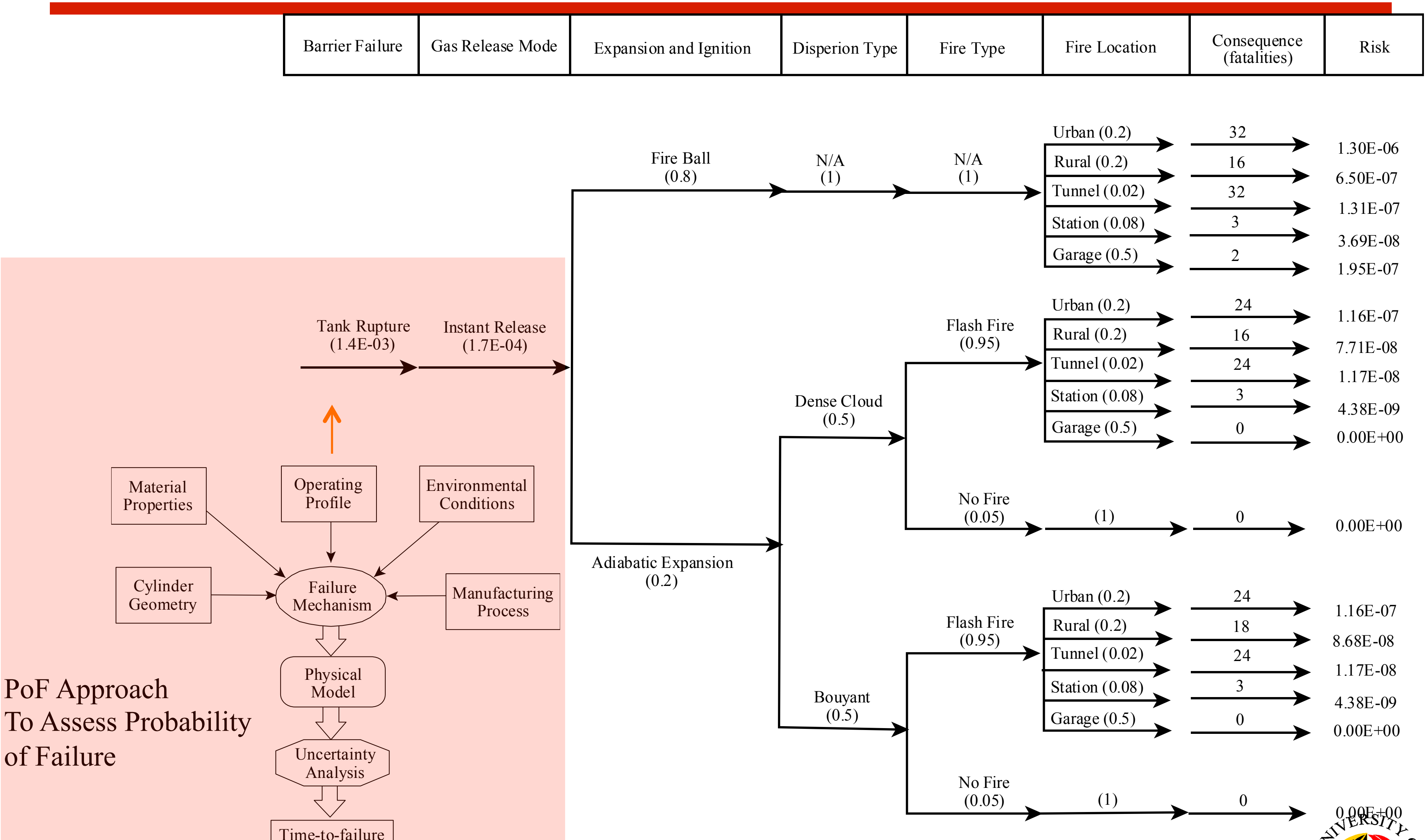
FREQUENCY X CONSEQUENCE = RISK

H.H.S.=Hardware, Human & Software

INITIATING EVENTS

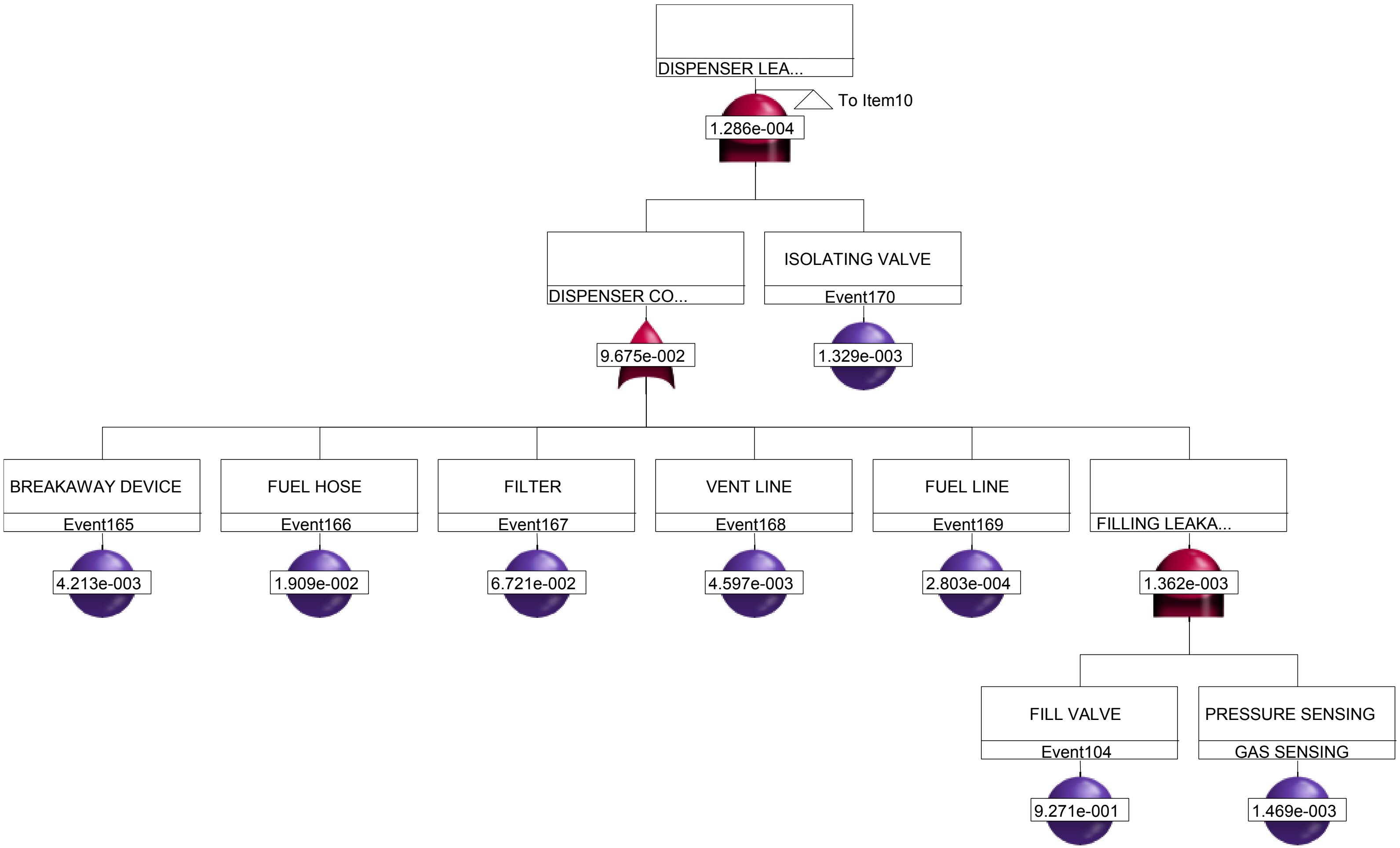
- HARDWARE CATASTROPHIC FAILURES RESULTING IN FIRE
- HARDWARE DEGRADED FAILURES RESULTING IN FIRE
- ELECTRO-STATIC DISCHARGE FIRES
- ACCIDENTAL IMPACTS RESULTING IN FIRE
- HUMAN ERRORS RESULTING IN FIRE
- NON-CNG RELATED FIRES RESULTING IN CNG FIRE

SCENARIOS INVOLVING A CNG TANK FAILURE



QUANTITATIFICATION OF SCENARIOS

SAMPLE FAULT TREE



QUANTITATIVE RISK FOR ALL SCENARIOS (COMBINED INTO GROUPS)

CNG Bus Fire Scenarios Involving Failure of The Following Class of Barriers	Frequency of Occurrence/ Bus/Year)	Risk (Fatalities/ Bus/Year)	Risk (Fatalities/ 100 Million Miles of Travel)
Bus Hardware (Such as the gas tank)	1.4×10^{-3}	2.7×10^{-6}	2.8×10^{-2}
Refueling Station Hardware	3.7×10^{-3}	7.5×10^{-6}	7.8×10^{-2}
Electrostatic Discharge of CNG	1.4×10^{-5}	3.7×10^{-6}	3.9×10^{-2}
Impact Failures due to Collisions	3.6×10^{-2}	4.6×10^{-6}	4.8×10^{-2}
Non-CNG Hardware	3.6×10^{-4}	3.1×10^{-6}	3.2×10^{-2}
Operator Error	4.0×10^{-2}	3.5×10^{-7}	3.5×10^{-3}
Total Fire Fatality Risk	---	2.2×10^{-5}	2.3×10^{-1}

**Assuming ~11,000 miles of travel per bus per year*

COMPARATIVE ANALYSIS OF RISK RESULTS

- 448,000 School Buses (Primarily Diesel)
- 85% of School Buses Are Diesel Powered
- 8,500 CNG School Buses
- 130 Deaths and 12,000 Injuries Involving School Buses Per Year (ALL CAUSES)
- 10 Deaths Per Year For School Bus Occupants (~8% of ALL CAUSES)
- 4.3 Billion Miles Per Year
- 3.43 Fatalities Per 100-Million Miles (ALL CAUSES)
- 0.26 Fatalities per 100-Million Miles (Only School Bus Occupants)
- 26 Fires for every 1,000 bus collisions involving fatalities
- 3% of all occupant fatalities occur in fire crashes
- 0.09 Fire-caused fatalities per 100-Million Miles in diesel school buses
- 0.0007 Fire-caused fatalities per 100-Million Miles for occupants of the diesel School Buses
- 0.23 Fire-caused fatalities per 100-Million Miles in CNG buses
- 0.16 Fire-caused fatalities per 100-Million Miles for occupants of CNG buses
- 70% of Fire related fatalities are due to bus occupants in CNG buses

UNCERTAINTY ANALYSIS

Steps in uncertainty analysis include:

1. Identify models and parameters that are uncertain and the method of uncertainty estimation to be used for each.
2. Describe the scope of the QRA.
3. Estimate and assign probability distributions depicting model and parameter uncertainties in the QRA.
4. Propagate uncertainties associated with the hazard barrier models and parameters to find the uncertainty associated with the risk value.
5. Present the uncertainties associated with risks and contributors to risk in an easy way to understand and visually straightforward to grasp.

UNCERTAINTY ANALYSIS RESULTS

RESULTS OF RISK UNCERTAINTY ASSESSMENT

CNG Bus Fire Scenarios Resulting from the Following Causes	Frequency of Occurrence/ Bus/year	5%	95%
Catastrophic failure of bus or station hardware components.	1.4E-3	2.7E-7	6.1E-6
Degraded failure of bus or station hardware components.	3.7E-3	5.6E-7	2.5E-5
Electro-STATIC discharge of CNG	1.4E-5	4.1E-7	6.6E-6
Accidental Impact due to Collision	3.6E-2	4.3E-7	1.2E-5
Non-CNG Related Fires	3.6E-4	3.7E-7	8.5E-6
Operator Error	4.0E-2	2.4E-8	9.8E-7
Total Fire Fatality Risk		**9.1E-6**	**4.0E-5**

SENSITIVITY AND IMPORTANCE ANALYSIS METHOD

1. (Re)Design: To support decisions of the system design or redesign by adding or removing elements (barriers, subsystems, human interactions, etc.)
2. Test and Maintenance: To Address questions related to the plant performance by changing the test and maintenance strategy for a given design.
3. Configuration and Control: To measure the significance or the effect of failure of a component on risk or safety or temporarily taking a component out of service.
4. Reduce uncertainties in the input variables of the QRAs.

RESULTS: Four components identified from the sensitivity and importance analysis to contribute most to fire fatality risk:

1. Pressure Relief Valves on Cylinders
2. CNG Storage Cylinders on Bus
3. CNG Storage Cylinders in Stations
4. Bus Fuel Piping

SUMMARY OF FINDINGS

1. Best Estimate CNG School Bus Fire Risk is Higher than Diesel (By a Factor of 2 to 3)
2. CNG School Bus Occupant Fire Risk is 230 Times Greater Than Diesel Bus Occupant Fire Risk
3. Worst Case Fire Scenarios in CNG Buses are Expected to be Far More Serious Than Diesel Buses
4. Need Additional Analysis to Physically Model Failure, Variations in CNG Bus Designs, Fueling Stations, and Gas Container Materials
5. Need Robust Analysis to Estimate the Uncertainty Associated with Best Estimate Fire Risks
6. Risk of Injuries Should be Calculated and Included
7. Safety Risk Should be Considered and Integrated With any Benefits From Expected Reduction in Environmental and Health Risks

STRENGTHS OF QRA

The most important strengths of the QRA, as the formal engineering approach to risk assessment are:

1. Integrated and systematic examination of a broad set of design and operational features of an engineered system.
2. Incorporates the influence of system interactions and human-system interfaces.
3. Incorporating operating experience with the engineered system and updating risk estimates.
4. A process for the explicit consideration of uncertainties.
5. Analysis of competing risks (e.g., of one system vs. another or of possible modifications to an existing system).
6. Analysis of (assumptions, data) issues via sensitivity studies.
7. Measure of the absolute or relative importance of systems, components to the calculated risk value.
8. Measure of overall level of health and safety for complex and new engineered systems.