NHTSA-98-3588

General Motors Corporation
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August 4, 1998

NHTSA-98-3588-28

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DOCUMENTARY SERVICES DIV.
RECEIVED

The Honorable Philip R. Recht
Deputy Administrator
NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION
400 Seventh Street, S.W., Room 5220
Washington, DC 20590

Dear Mr. Recht:

Re: **Settlement** Agreement
Section B. Fire Safety Research

Enclosed is a report authored by Failure Analysis Associates (FaAA) entitled "Failure Modes and Effects Analysis of Compressed Natural Gas Fuel Systems for Cars and Trucks." This final report relates to B.6 Analyses of Failure Modes and Effects for Alternatively Fueled Vehicles.

On July 25, 1997, GM submitted a draft version of this report to NHTSA. On January 16, 1998, NHTSA provided GM with comments based on peer reviews by Southwest Research Institute in San Antonio, Texas, and Powertech Labs, Inc. in Surrey, British Columbia, Canada, for further consideration by FaAA. The enclosed report reflects the influence of that peer review. Accompanying the report is correspondence from FaAA dated March 10, 1998, which discusses the suggested changes that were implemented as well as those that were not.

Sincerely,

David A. Collins
Attorney

Enclosure

MC 482-207-745 - New Center One Building - 3031 West Grand Boulevard. Detroit. Michigan 48202

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Failure Analysis Associates

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10 March 1998

Dr. Douglas W. Kononen
Manager, Vehicle Fire Safety Research
Safety Research Department
General Motors Research and Development Center
30500 Mound Road
Warren, Michigan 48090-9055

Re: *CNG FMEA Report (FaAA-SF-R-96-01-16) Revisions*

Dear Dr. Kononen:

Pursuant to your request in regards to the above mentioned matter, below please find a summary of changes which were made to our report. Peer review of the report by Powertech Labs, Inc. and Southwest Research Institute led to suggested changes which ware outlined in the January 16, 1998 letter from the NHTSA to David A. Collins, Esq. I contacted Mr. Lou Brown of the NHTSA and discussed each of the peer review suggestions, some of which we mutually agreed should be implemented. A brief summary of each change is presented below, and, in the case where changes were not implemented, an explanation is provided as well.

Implemented Report Changes

1. The two sets of PMEA tables in the appendices have been properly updated to include the likelihood of occurrence index. OC, instead of the PR index. This complies with the recommendation submitted by Mr. Craig Webster of Powertech Labs, Inc.

2. The presentation materials that were previously found in Appendix B have been removed. This complies with the recommendation submitted by Mr. Craig Webster of Powertech Labs, Inc.

3. The description accompanying table entry lg.32 has been changed in both sets of FMEA tables as well as the description in Section 4.2.4. Section 4.2.4 now reads *"This scenario involves the* ignition *of a large gas release due to* a *missing*

or broken ground *strap."* This complies with the recommendation submitted by Mr. Craig Webster of Powertech Labs, Inc.

4. In the last sentence of Section 3.2, the word *effect* has been changed to *affect*. This complies with the recommendation submitted by Mr. Craig Webster of Powertech Labs, Inc.

5. The appendices were reordered to follow their introduction in the text of the report.

Suggested Changes Which Have *Not Been Implemented*

Powertech Labs, Inc.

3, A recommendation was made to reorganize the 18 subsystems to correspond with the major subsystems that are currently used as the focus for NGV standards.

While we agree that this might aid an NGV standards committee in addressing potential issues, the focus *of* this project was to aid the industry as a whole, including vendors, subcontractors and systems integrators. We feel the report provides the best value to the industry in its current format; small vendors are easily able to identify sections which apply to them, and are able to understand the *interaction* of their components with other components *and* conditions in that specific subsystem. Were the analysis to be reorganized, it would be more difficult for many suppliers to identify which potential scenarios are pertinent to their components.

Southwest Research Institute (SWRI)

1. A recommendation was made to change the report from a failure modes and effects analysis (FMEA) to a hazards and operability analysis (HAZOPS) due to the method in which the study was conducted and the way the results are presented.

The SWRI reviewer states "It is a valid and a useful analysis; it is just not a traditional FMEA". The reviewer would have been correct had the statement been "...it is just not a traditional *automotive* industry FMEA." However, as is clearly outlined in the book "Failure Modes and Effect Analysis, FMEA from Theory to Execution" listed as Reference 2 in Section 5, there are numerous method8 of performing FMEAs. The current report *clearly* falls *within the*

Ex.

different types identified in the reference, and, in addition, the differences between the automotive industry's version of an FMEA and the approach taken during thii project are discussed in the text of the report.

2. A recommendation was made to provide more detailed information regarding each of the 17 components or subsystems. Specifically, the author requested additional information on:

- The basic function(s) of the *item.*

We feel that the basic function of each item is clear to persons associated with the supply and construction of such systems.

- The design and construction of the item.

As facilitator for this FMEA, FaAA is not qualified to describe the design and construction of many of the components. It is not clear how this would be done when a particular subsystem contains many different components (such as valves, tubing, connectors, and electronics), each with its own design and construction intricacies. The design and construction also varies depending upon the supplier of the component.

Furthermore, due to the confidentiality agreements with the third party suppliers in this matter, FaAA is not at liberty to release much of this information.

- The typical operating parameters, such as temperatures. pressures, flow rates, and volumes.

of *were*
discussed for purposes *of* fully listing all applicable operating parameters. As facilitator for thii FMEA, FaAA is not qualified to describe the operating parameters for these subsystems. Should this information need to be provided, series of further questionnaires will need to be submitted to all parties involved, the results tabulated, and conflicting information resolved on individual basis.

Furthermore, due to the confidentiality agreements with the third party suppliers in this matter, FaAA is not at liberty to release much of the information which it currently holds.

Current controls or hazard mitigation features commonly associated with the item.

Ex.

This information was provided in an earlier version of the report. Upon consensus of several parties, the information was removed to make the tables more clear in the presentation of the current analysis.

If you have any further questions regarding this report, please do not hesitate to call me at 310-302-7200. I look forward to hearing from you.

Sincerely,

Dr. John E. Moalli
Principal Engineer

Ex.

95-020-GR-160

POWERTECH COMMENTS ON B.6 REPORT ENTITLED

"FAILURE MODES AND EFFECTS ANALYSIS OF COMPRESSED NATURAL GAS FUEL SYSTEMS FOR CARS AND TRUCKS"

95-020-GR-160

HLL

POWERTECH

We find a better way

Powertech Labs Inc
12388 - 88th Ave
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CANADA

Phone: 604 590 7413
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TELEFAX

To: Lou Brown
NHTSA

Date: December 2, 1997

Telefax No.: 202 366 5930

From: Craig Webster

No. of Pages: 2

RE: Failure Modes and Effects Analysis of CNG Fuel Systems for Cars and Trucks - REVIEW OF REPORT

Follwing are the comments that I had prepared in September and have been unsuccessful in e-mailing to you.

Powertech Labs is the Research and Development division of a government-owned utility. We have been involved in NGV research since 1983, and are recognized worldwide as an authority on CNG cylinder technology. We participated in one of the two workshops held by FaAA to provide input into the FMEA.

The Failure Analysis Associates report "Failure Modes and Effects Analysis of CNG Fuel Systems for Cars and Trucks" contains a considerable amount of useful information applicable to all CNG fuel systems. The results are tabulated in Appendix C in no particular order for each of 18 fueling system subsystems, and again under Appendix E in order of the perceived risk for all subsystems combined. Overall, I believe the report could be more useful to the Natural Gas Vehicle industry if the 18 subsystems identified by FaAA were reduced in number to correspond with the major subsystems that are currently used as the focus for NGV standards. For example, the following standards currently apply to major subsystems:

filling receptacles = ANSI NGV1
fuel tanks = ANSI NGV2
pressure relief devices = CGA PRD-I
installation (high pressure lines) = ANSI NFPA 52
etc.

Thus, if the results were presented in the order of perceived risk for each of the areas covered by specific NGV standards, then the concerns identified in the report could then be readily addressed by the relevant standards committee for each major CNG subsystem.

Specific observations on the report are as follows:

a) Page 12 of the report discusses the use of frequency of occurrence (OC) index, but the Tables in Appendix C and Appendix E appear to change the terminology to "PR".

b) It appears unnecessary for the presentation materials in Appendix B to be included in the report Much of what is discussed in the overheads is already reviewed in the first chapters of the report. Besides, the overheads presented FaAA's initial approach to the workshops, and do not necessarily relate to the final FMEA approach adopted by both the NGV industry and FaAA to address CNG fuel systems.

c) Under section 4.2, a high RPN event is discussed for ID 18.32; however, it is not at all clear to me how the absence or breakage of a grounding strap could result in the major release of compressed natural gas from a closed (gas tight) fuel system. Perhaps FaAA is referring to a tank removed from a vehicle for servicing (i.e. disconnected from the fuel line tubing), but even then I do not understand the possible failure mechanism. Further elaboration is required in the report.

d) Of a very minor nature, on page 12, last sentence of section 3.2, the word should be affect, not effect.

Craig Webster, P.Eng.

95-020-GR-161

SOUTHWEST RESEARCH INSTITUTE

COMMENTS ON B.6 REPORT ENTITLED

"FAILURE MODES AND EFFECTS ANALYSIS OF COMPRESSED

NATURAL GAS FUEL SYSTEMS FOR CARS AND TRUCKS"

95-020-GR-161

SOUTHWEST RESEARCH INSTITUTE

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Materials and Structures Division
December 5, 1997

FAX: 202-366-5930

Mr. Louis J. Brown, Jr.
Office of Research and Development
NHTSA
400 seventh Street, S.W.
Washington, D.C. 20590

Re: B.6 Settlement Agreement
Final Report Peer Review

Dear Mr. Brown:

Pursuant to your request, please find attached our peer review of the report entitled ***Failure Modes and Effects Analysis of Compressed Natural Gas Fuel Systems for Cars and Trucks*** by Failure Analysis Associates, Inc. Please note that the attached document is a preliminary review and that additional comments or specific inquiries may be submitted by the reviewer as deemed appropriate.

Sincerely,

Michael A. Miller
Senior Research Scientist
Materials Development Section
Materials Engineering Department

mam/mss

Attachment: Report Peer Review

C:\...\...\...\...-rev.doc

Preliminary Comments From Review of
FaAA-SF-R-96-01-16
"Failure Modes and Effects Analysis
of Compressed Natural Gas Fuel Systems
for Cars and Trucks"
dated April 1997

Comments By
Neil W. Blaylock
Southwest Research Institute
(210) 522-3238
November 18, 1997

The document is well written. It provides a clear explanation of the methodology used. It provides all of the detailed analysis sheets in an appendix. Anyone interested in exploring in detail the reasoning that lies behind the study conclusions and recommendations will find sufficient information between the report and appendices to do so (with one exception noted in the last paragraph of these comments).

The hazards analysis seems "very professional," and appears to have been conducted by individuals experienced and knowledgeable about compressed natural gas fuel systems and about hazards assessment methodologies. Consequently, I believe that their conclusions and recommendations carry some weight of experience and deserve careful consideration by the industry.

In my opinion, the analysis that has been conducted is not a "failure modes and effects analysis (FMEA)" in the sense that this term is commonly used in the risk assessment industry. This is not to say that the analysis is deficient. It is a valid analysis, and a useful analysis; it is just not a traditional FMEA. It is much more akin to a HAZOPS (hazards and operability) analysis, and I suggest that it be called such in the report. The methodology used was to convene a committee composed of industry experts in the design and performance of all the major components of a CNG fuel system. Several facilitated meetings were then held, with Failure Analysis Associates personnel serving as facilitators, to work through a structured series of "what if" scenarios that start with a failure effect, and work backward to list potential failure modes that could have caused that effect. This is exactly the way that a HAZOPS analysis is traditionally conducted. Someone doing a literature search for an FMEA of a CNG system would expect to find something different than what is presented in this report. Again I emphasize that this does not imply that the reported analysis is poor, simply that it is different from an FMEA. The authors readily admit in the report that they deviated significantly from traditional FMEA methods.

The schematic drawing labeled Figure 1 in the report is the baseline road map for the analysis. It identifies 17 major components or subsystems that compose a typical CNG fuel system. There is no discussion in the report about the characteristics of these 17 items. I believe that it would be helpful to provide a generic description of each one, either in the report or in an appendix. This description should (1) elaborate upon the basic function(s) of the item; (2) discuss how the item is typically designed or constructed; (3) give some indication of typical operating parameters associated with the item, e.g., a range of temperatures, pressures, flow rates, volumes; and (4) point out any safety controls or hazard mitigation features commonly associated with the item. Such details were almost certainly discussed and developed during the committee meetings in the course of postulating failure modes and failure effects, but they are not documented in the report.

Failure Analysis Associates

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FaAA-SF-R-96-01-16

Failure Modes and Effects Analysis of Compressed Natural Gas Fuel Systems for Cars and Trucks

Prepared for:
General Motors Corporation

Failure Analysis Associates, Inc.
Menlo Park, California

February 1998

TABLE OF CONTENTS

EXECUTIVE SUMMARY

On March 7, 1997 General Motors Corporation (GM) and the US Department of Transportation entered into an agreement (hereafter referred to as the Agreement or Settlement Agreement) to settle a dispute regarding the safety of 1970-1991 full-sized GM pickup trucks equipped with fuel tanks mounted outboard of the frame rails. Part of this Agreement involves establishment of a 5 year, $10 million motor vehicle fire safety research program to be funded by GM. The overall objectives of this research program are to better understand how vehicle fires start and spread and to determine what can be done to prevent, contain, and extinguish such fires. To this end, GM and the National Highway Traffic Safety Administration have jointly developed 14 separate vehicle fire safety research projects. One of these projects (project B.6), entitled "Analysis of Failure Modes and Effects for Alternatively Fueled Vehicles," is the subject of this technical report.

The project statement for B.6 reads:

> "Failure modes and effects analyses (FMEAs) will be prepared and unique potential fire hazards associated with generic designs of alternatively fueled vehicles will be analyzed. Priority of analyses shall be given in the following order: CNG fueled vehicles, propane fueled vehicles, electric vehicles, and hybrid vehicles."

Compressed natural gas (CNG) powered vehicles have been the subject of much interest because of their low emissions. To address concerns regarding potential risks associated with CNG vehicles, GM, in conjunction with CNG component suppliers, undertook an innovative broad-based analysis of the CNG fuel system design that addressed a comprehensive range of issues including design, manufacturing, usage, servicing, and consumer considerations.

GM contracted with Failure Analysis Associates, Inc. (FaAA), to facilitate the analysis which used a failure modes and effects analysis (FMEA) format. This provided a systematic procedure for identifying potential failure scenarios, quantifying the relative risk associated with them, and prioritizing follow-up actions. Although the initial intent was to keep the FMEA completely generic, a specific bi-fueled (gasoline and CNG) design which utilizes a steel tank with carbon fiber overwrap was assumed in order to make the exercise useful. Despite the fact that the fuel system considered in this FMEA contains many components which are present in other existing designs, it does not represent all CNG fuel systems. Hence this FMEA should not be used solely as the FMEA for a reader's specific design. Instead, the reader is encouraged to glean the information relevant to his or her particular design.

Two FMEA workshops were conducted with participants from GM and its suppliers. The analysis indicates that the assumed fuel system design is generally mature at this time, except for a few areas which need additional effort. The most significant issue, on a relative basis, identified by the analysis is the system-wide risk of gas release. The analysis indicates a need to review the broad leak-control design strategies of the system and revisit some of the basic engineering. For example, a review of connection fittings may provide options for reducing the probability of leakage. There are also two isolated scenarios which require some attention. One involves the consumer failing to properly connect the filling line during refueling, and the second involves the consumer misinterpreting the fuel mode indication. Both of these can be mitigated by developing a specific one-time design or process change. Finally, the analysis indicates that another subsytem-level review effort for the fuel tank may be useful.

FMEA of Compressed Natural Gas Fuel Systems for Cars and Trucks

1. INTRODUCTION

1.1 Background

Many automotive manufacturers are considering production of compressed natural gas (CNG) powered vehicles. The use of natural gas offers a number of significant advantages over gasoline, including low emissions, improved fuel efficiency, and lower cost fuel.

On March 7, 1997 General Motors Corporation (GM) and the US Department of Transportation entered into an agreement (hereafter referred to as the Agreement or Settlement Agreement) to settle a dispute regarding the safety of 1970-1991 full-sized GM pickup trucks equipped with fuel tanks mounted outboard of the frame rails. Part of this Agreement involves establishment of a 5 year, $10 million motor vehicle tire safety research program to be funded by GM. The overall objectives of this research program are to better understand how vehicle tires start and spread and to determine what can be done to prevent, contain, and extinguish such tires. To this end, GM and the National Highway Traffic Safety Administration have jointly developed 14 separate vehicle fire safety research projects. One of these projects (project B.6), entitled "Analysis of Failure Modes and Effects for Alternatively Fueled Vehicles," is the subject of this technical report.

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To address concerns regarding potential risks associated with CNG vehicles, GM, in conjunction with CNG component suppliers, undertook an innovative broad-based analysis of a bi-fueled (gasoline and CNG) system design that addressed a comprehensive range of issues including design, manufacturing, usage, servicing, and consumer considerations.

The general format selected for the analysis was a failure modes and effects analysis (FMEA), since it offered the flexibility to comparably address a very broad range of issues in a relatively concise form. GM contracted with Failure Analysis Associates, Inc. (FaAA), to facilitate a broad-based FMEA for compressed natural gas fueled systems for cars and trucks. FaAA also provided specific technical expertise and input in appropriate areas. FaAA has extensive experience performing FMEAs for a wide variety of manufactured products and industrial processes, and particularly in performing broad-based FMEAs involving multiple parties and organizations such as OEMs and suppliers.

1.2 Objectives

The objective of this activity was to step back from typical detailed evaluations and take a broader look at the complex interactions between product design, production, and usage. This approach allows for the most benefit to the industry as a whole. Another key objective of this FMEA was to include suppliers so that component-specific data could be obtained. This allowed the suppliers to bring to bear the best possible information to the analysis and allowed suppliers to share their experiences on their best practices.

1.3 FMEA Approach

An FMEA is a systematic procedure for identifying potential failure scenarios in a product or process. It also provides a means for prioritizing mitigating actions for these failure scenarios, based on the relative risk associated with each of the scenarios. In a typical FMEA, each component in the product is examined for potential failure modes in which a sequence of events can lead to an undesirable result. The relative risk associated with each of the potential failure scenarios is quantified by three indices representing the severity, likelihood of occurrence, and control measures of each scenario. The product of these three indices is the risk priority number (RPN), and it provides a relative measure of risk associated with each failure scenario.

The FMEA technique is widely used in military and commercial manufacturing industries. A variety of approaches are taken in developing failure scenarios and assigning indices. Potential failure scenarios can be developed strictly inductively (i.e., by identifying a series of root cause events and evaluating the subsequent chain of events) or partially deductively (i.e., by first identifying a set of end conditions and then reviewing potential pre-cursor conditions).

MIL-STD 1629A[1] describes the approach developed by the military. In this approach, scenario development can be either inductive or deductive. FMEAs performed on concept designs or leading edge products, such as in the medical industry, generally use a partially deductive approach in which first a set of undesirable end conditions are defined.[2] Each condition defines a specific loss of functionality (performance, safety, etc.). Failure scenarios leading up to these conditions are then developed.

An example of a largely deductive approach was one used in the marine industry for analyzing risks to a floating production unit (FPU).' In this analysis all potential failure effects were categorized into eight groups ranging from injury/fatality, production shut-down, and material damage to pollution, fire or explosion. Causes leading up to these conditions were then developed. On the other hand, process FMEAs (PFMEAs) generally develop failure scenarios inductively by examining undesirable variations in process parameters and examining the resulting effects.

The risk indices can also be assigned in a variety of ways. Although most often the scales range from 1 to 10, scales ranging from 1 to 5 are also used. They may be based on a qualitative or quantitative scale. Appendix A shows examples of scales used in various industries. Quantitative scales are often absolute scales; for example, in the scale shown in Table F.l of Appendix A (page A-2), a failure frequency between 1/50 and 1/1 0 for the automotive industry is always assigned an occurrence index of 4, regardless of the range of failure frequencies actually encountered in the system being analyzed. Other scales are relative, such as those based on the distribution of actual failure frequencies, or those qualitatively described as high, medium, or low.

Automotive industry guidelines for design FMEAs (DFMEAs) performed as a standard part of product quality planning require a hierarchical approach where a separate analysis is performed for each level of the system or subsystem. This allows the scope of each DFMEA to be restricted to the specific functionality of the subsystem. Within this scope, potential root causes can be identified in great detail. Typically, each root cause has an immediate effect on the functionality of the subsystem, resulting in a cause-effect failure scenario. In this type of analysis, inductive scenario development is very effective. Furthermore, since a large number of separate subsystem DFMEAs comprise the analysis of the entire system, a standardized, absolute scale for the risk indices makes it easier to maintain uniformity among them.

The scope of systems analyzed in this FMEA was comprehensive and the focus was on capturing the end effect on the consumer. Therefore, a different approach was called for. Specifically, a deductive approach was taken for scenario generation, much like the one described previously for the FPU.[3] This allowed each component supplier to think of their subsystems not only in the context of their immediate functional specifications, but ultimately as a part of the final product delivered to the consumer. In this approach, the failures of the individual components were viewed as causes leading to more generic failure modes whose impact on the performance or safety of the vehicle could be quantified. This facilitated the identification of generic failure modes at a sufficiently high level to allow for effective prioritization to take place. This also allowed for the evaluation of potential failure scenarios and prioritization on a common and consistent basis.

The scales for assigning each of the risk indices were defined in a relative manner to reflect the full range of conditions encountered in the scenarios. The consequences of a particular failure scenario on the performance of the product was quantified by the severity of failure index. The severity index (SV) was assigned on a scale of 1 to IO, with 10 representing the most severe effect. The probability that a particular sequence of events leading to a failure scenario will occur was quantified by the likelihood of occurrence index. The occurrence index (OC) was also assigned on a scale of 1 to 10, with 10 representing the high frequency of occurrence. The probability that a particular sequence of events leading to a failure will be controlled by detection or mitigation before the consequences occur is normally quantified in the third index, sometimes called the detection index. Since this FMEA covered all aspects of the CNG design, as well as usage, this index was used to quantify the effect of a variety of risk minimization measures. The risk minimization index (MN) was also assigned on a scale of 1 to 10, with 10 representing the highest risk or minimum possibility of control.

2. METHODOLOGY

2.1 Mechanics of the FMEA

Typically, FMEAs are conducted on mature designs by a relatively small group of individuals within the same company who can freely exchange information. Most often, only a small system or subsystem is analyzed in detail. Consistent with this, a bottom-up approach is taken, whereby each of the individual components of an assembly and their potential failure modes are identified. The current analysis differed from the typical case in several ways. First of all, as discussed earlier, a top-down approach was taken in this analysis. The system as a whole and its usage by the consumer were the primary focus. Potential scenarios leading to performance and safety risks were developed by a systematic review of subassemblies and interfaces.

A second important difference was the composition of the FMEA team. In this case, engineers from GM, FaAA, and the component manufacturers participated in the FMEA. A list of component and subsystems manufacturers who participated is presented in Appendix B. By bringing together all of the participants in the product design, it was possible to evaluate the functionality of each of the subassemblies both under normal and abnormal conditions, and to consider the interactions between subassemblies and between the subassemblies and the vehicle platform itself.

However, it was also important to consider supplier competitiveness issues and to balance the necessary exchange of information with appropriate confidentiality. To accomplish this objective, FaAA served as the intermediary for compiling information obtained under a separate confidentiality agreement with each of the participants. FaAA also reviewed and maintained the documentation and provided general information to the entire team without identifying individual sources.

FaAA made every attempt to either directly document or identify relevant documents useful in evaluating each scenario. This included information on the likelihood of occurrence, the effectiveness of any risk control measures, and evidence of previous failures - either documented or anecdotal. Each supplier was given every opportunity to provide input and comment on all scenarios associated with their product.

Two FMEA workshops were conducted with participants from GM and its suppliers. Following each workshop, FaAA *sent* letters to each of the suppliers requesting supporting data on the scenarios discussed during the workshop. Suppliers were also contacted several times by phone to ensure that the maximum and best possible data was available for the analysis.

3. ANALYSIS OF FAILURE SCENARIOS

3.1 Generic Failure Conditions and Consequences

The focus of the current FMEA was performance and safety risks. Thus, at the outset, a number of general situations involving CNG fuel systems were identified. These situations were defined as "generic" failure conditions or failure modes. The potential consequences of these failure conditions were evaluated and ranked by a subjectively estimated severity index. In order to maintain consistency in the analysis, all potential failure scenarios were defined with respect to the potential for resulting in these generic failure conditions. A list of eight generic failure conditions were identified.

Each condition or mode was initially ranked in order of its relative severity with respect to other modes. The potential consequences were then evaluated to assign a preliminary severity index on a scale of 1 to 10. Typically, FMEA indices are assigned such that an increase of 1 in the index represents an order of magnitude increase in the risk. Hence, modes with different severity ranks may be assigned the same severity index if the difference in their consequences are judged to be small. There was considerable uncertainty about the exact nature of many of the consequences. Hence, higher severity indices were conservatively assigned in cases where there were differing opinions on the severity of the modes. The identified modes, along with their current severity ranks and indices are shown in Table 1. The indices may need to be revised when more information is available on the consequences.

Table 1. Generic Failure Modes

Generic Failure Mode	ID	Description of Potential Effects	Severity Rank	Severity Index
Customer dissatisfaction	A	warranty claim, customer only uses gasoline and resulting environmental impact, loss of repeat sales, inconvenience, customer anxiety	1	1
Leakage (does not involve injury)	B	smell of gas, customer discomfort, warranty claims, reduced operating range, inconvenience	2	2
Driveability and Performance	D	collision, collision/injury, warranty claims, recall	3	5
Loss of compliance	E	recall, warranty claim, customer inconvenience	4	7
Vehicle inoperative	C	walk-home, warranty claim, inconvenience	5	8
Loss of crashworthiness	F	collision resulting in: explosion and tire, explosion without tire, injury, property damage; reduced range, render vehicle inoperative, damage to vehicle, recall	6	9
Large gas release (Customer may haveadvanced warning)	G	fire, explosion, asphyxiation of operator, vehicle becomes inoperative, property damage, reduced range, damage to vehicle, smell of gas, noise and resulting anxiety, injury, warranty claim, recall, cryogenic burn	7	9
Catastrophic high pressure failure (Unexpected event)	H	explosion and tire, explosion without tire, injury, property damage, reduced range, vehicle becomes inoperative, damage to vehicle, warranty claim, recall	8	10

3.2 Identification of Failure Causes and Probabilities

Figure 1 shows a schematic drawing of the assumed CNG fuel system. The components included in this analysis were those considered to be basic and expected to contribute to the performance and safety of the vehicle.

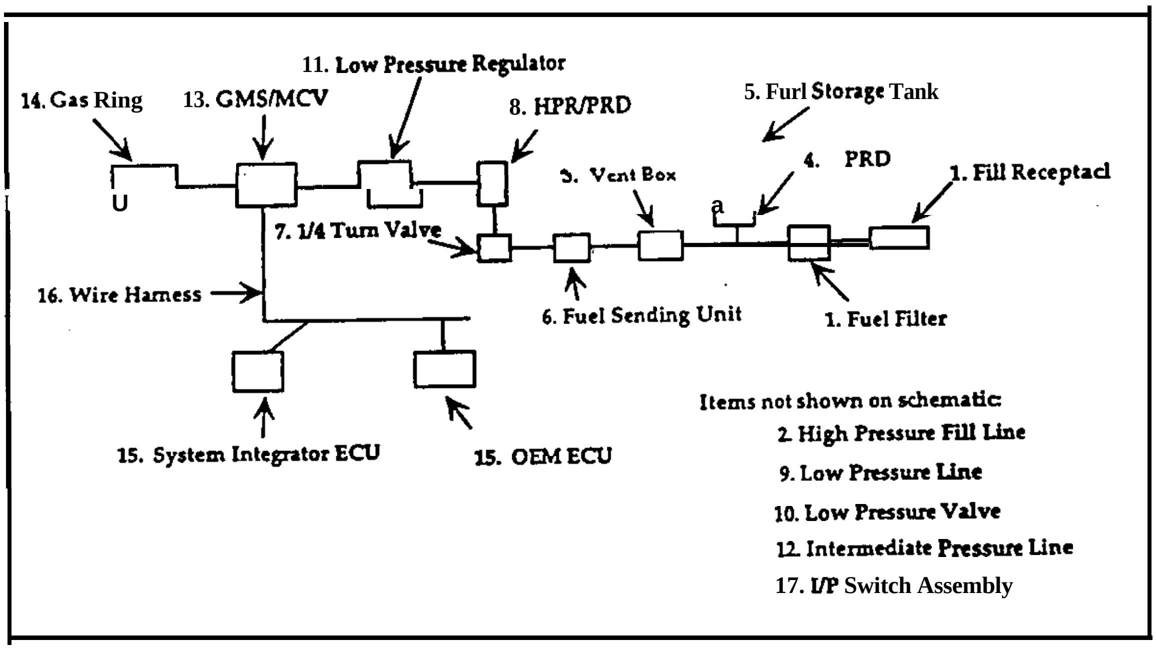

Figure 1. Schematic Drawing of Typical CNG Fuel System (numbers represent subsystem designation)

The components associated with the CNG system were grouped into 17 subsystems based on the main functions required of the fuel system, plus one group of interface issues, as follows:

1. Fill Receptacle and Filter
2. High Pressure Fill Line
3. Ventilation System
4. High Pressure Solenoid Valve I PRD
5. Fuel Storage Tank

6. Fuel Sending Unit
7. 1 /4 Turn Valve
8. High Pressure Regulator / PRD
9. Intermediate Pressure Line
10. Low Pressure Valve
11. Low Pressure Regulator
12. Low Pressure Line
13. Gas Mass Sensor / Mixture Control Valve (GMS/MCV)
14. Gas Distribution Adapter (Gas Ring)
15. Engine Control Unit (ECU)
16. Wire Harness
17. I / P Switch Assembly
18. Interface Issues

In the first phase of the FMEA, each of the main subsystems and components in the assumed system was reviewed to identify sequences of events or scenarios which could lead to any of the generic failure conditions. These scenarios were defined as potential failure causes. This resulted in a systematic examination of potential failures of each major component in the design which could lead to performance problems or safety issues.

The components in each of the subsystems were examined for their potential to fail or be misused. Events that could result from such failures and eventually lead to any of the generic failure conditions described in Section 3.1 were identified and numerous potential scenarios were developed. Typical failure causes included improper usage, malfunction due to defective components and improper installation or settings, contamination, corrosion, mechanical fatigue effects, and environmental effects such as those caused by dirt, moisture, and cold weather. Since some of the underlying causes were common to several subsystems, actions taken to address them would impact several scenarios.

The next step involved assigning the frequency of occurrence index (OC) to individual scenarios. This index was based on reviewing available evidence about the failure scenarios. Sources of evidence included testing data, published failure data, and non-quantitative historical and anecdotal information. After a review of all the evidence available to quantify this index, the scheme listed in Table 2 was established. Since relatively few specifics were available, only six categories of evidence were defined, although the index still ranged from-a-value of 1 to 10. Armed with knowledge specific to their own designs, readers can change the OC index according to Table 2. It should be noted that this may affect RPNs and subsequent data interpretation.

3.3 Identification of Risk Minimization Measures

The probability that a particular sequence of events leading to failure will be detected or can be mitigated through manufacturing control processes, design changes, or validation testing was quantified by the third index: the risk minimization index (MN). While this scale also ranged from 1 to 10, there was insufficient data to provide such a high degree of resolution for the assumed design. Consequently, three ranges of risk minimization measures were established, as shown in Table 3. Again, readers can adjust the MN to reflect their specific designs and properly consider associated changes in RPNs.

Table 2. Frequency of Occurrence Index

Evidence About the Failure Scenario	Occurrence Index (Scale: 1 to 10)
If documented "frequent" occurrence in this or similar application.	10
If known to have occurred "a few times" with documented evidence.	8
If known to have occurred once with documented or reported evidence in this or similar application.	6
If anecdotal evidence of previous occurrence of this or related failure scenario.	4
If no previous history, but greater potential to occur.	2
If no previous history, but potential to occur.	1

3.4 Risk Priority Number

The product of the three indices, SV, OC, and MN is the Risk Priority Number (RPN). The FMEA tables for each of the subsystems are included in Appendix C. The ID numbers were assigned serially for each of the subsystems identified in Section 3.1. Appendix D lists the failure scenarios in decreasing order of RPN.

Table 3. Risk Minimization Index

Range of Control Measures	Risk Minimization Index (Scale: 1 to 10)
If a high degree of control measures implemented or planned, and assigned a LOW probability index range of 1-3	2
If a moderate degree of control measures implemented or planned, and assigned a MEDIUM probability index range of 4-6	5
If a low degree of control measures implemented or planned, and assigned a HIGH probability index range of 7-l 0	8

4. MAIN FINDINGS

4.1 RPN Distribution Characteristics

It is appropriate to begin the findings section with the caveat that it applies only to the assumed design reviewed in this FMEA. The analysis of RPN distributions for reader specific designs may be different. Nonetheless, useful insight into CNG fuel systems is gained by the analysis below.

Examining the distribution of RPN values of the scenarios developed in the FMEA provides insight into the maturity of the product development. There may be many types of immaturities associated with a product, each of which represent a measure of risk. Conceptually, the relative risks associated with a mature product would be distributed in a decreasing manner. The distribution of risk would be skewed to the left, or lower RPN values. Furthermore, the overall distribution would be non-linear, as shown in Figure 2. In other words, if risk was to be conceived of as a continuous variable, its distribution would decay, such as in an exponential distribution. If the higher-risk tail of this distribution was to be mitigated with a newer version of the product, it would lower the actual levels over which the risks would range. However, the shape of the relative distribution would not change. For a leading edge product, examining the deviations from an exponential-type pattern in its distribution of risks provides indications of its likely types of immaturities.

An FMEA attempts to capture the full qualitative spectrum of risks in a set of scenarios. Depending on the level of detail in them, each scenario represents a certain range in this spectrum. Hence, the scenarios may be considered as discretized representations of what is actually a continuous range of risks. For example, the actual risk associated with a gas release can vary essentially continuously depending on the combination of factors such as the probabilities with which various gas leak mechanisms can occur, the variation in the amount of gas released in each of the mechanisms, the potential for gas dissipation or accumulation in the environment into which it is released, the proximity of ignition sources, and numerous other variables. In practice, it is impossible to define a "function" of all these variables with sufficient detail to capture every possible combination of variables. Hence, discrete classes of combinations are defined in terms of individual FMEA scenarios.

An analysis of the distribution of scenarios is thus representative of the distribution of the overall pattern of risks associated with the product. However, the level of detail in examining the patterns needs to be carefully selected. Treating each potential RPN value in the range of 1 to 800 may show no clear patterns since this may be looking at it in too much detail; the maturity of the system as a whole is overlooked. Stepping back a little further by aggregating scenarios into RPN ranges may bring the pattern into better focus. However, stepping back too far may blur the details too much. Thus, analyzing RPNs can be a somewhat subjective exercise.

Figure 3 shows the distribution of RPN values for this FMEA taken one RPN value at a time. While it reflects a decaying risk pattern, it is difficult to identify general areas of concern. Figure 4 shows the distribution after grouping the FMEA scenarios by RPN values in ranges of 25. For RPN values of less than 300, the distribution is clearly declining, albeit with some scatter in this trend. At higher RPN values, there is no increasing or decreasing trend but there may potentially be some outliers or clusters. The clusters and outliers can be seen more clearly in Figures 5 and 6 where the scenarios are grouped in broader ranges of RPN values. The overall pattern seems to indicate a generally mature product, with a few exceptions represented by three or possibly four higher risk clusters or outliers.

The cluster at the RPN value of 720 in Figure 3, which again appears as a high RPN cluster in Figures 4 through 6, will be addressed in detail in Section 4.2. This is an isolated cluster, and all its scenarios are associated with the same failure mode (i.e., large gas release), indicating that this cluster most likely represents a systemic risk overriding all subsystems. This conclusion is further reinforced by examining the scenarios in the range from 101 to 150 (Figure 5). There are more scenarios in this range than one would expect from a mature product. Once again, they are all associated with this same failure mode. Such risks are typically further mitigated by reviewing the general design strategies of the system and revisiting some of the basic engineering approaches.

There is another apparent cluster at RPN values between 501 and 600 (Figure 6). This is comprised of two scenarios associated with different failure modes and different subsystems. Hence, they are not truly clustered scenarios, but rather two separate outlier Scenarios with similar relative risk. Each of them represents a very specific risk which can be further mitigated by developing **a** specific one-time design fix or **process change.**

There is, arguably, another cluster at RPN values between 301 and 400 (Figure 6). Examining the scenarios comprising this cluster indicates that while these risks represent a variety of modes, they are primarily associated with one subsystem, namely the fuel tank. This indicates that a subsystem level mitigation effort may be warranted.

4.2 Highest RPN Scenarios

As noted in section 4.1, there is a cluster of high risk scenarios occurring at an RPN of 720 (Figure 3). This relatively large cluster of high RPNs dictates that additional scrutiny should be applied to understanding the basis and mitigating the causes of these scenarios.

Due to the significance of this high RPN cluster, it is useful to examine each individual scenario in more detail. The specific scenarios are grouped at the beginning of Appendix D.

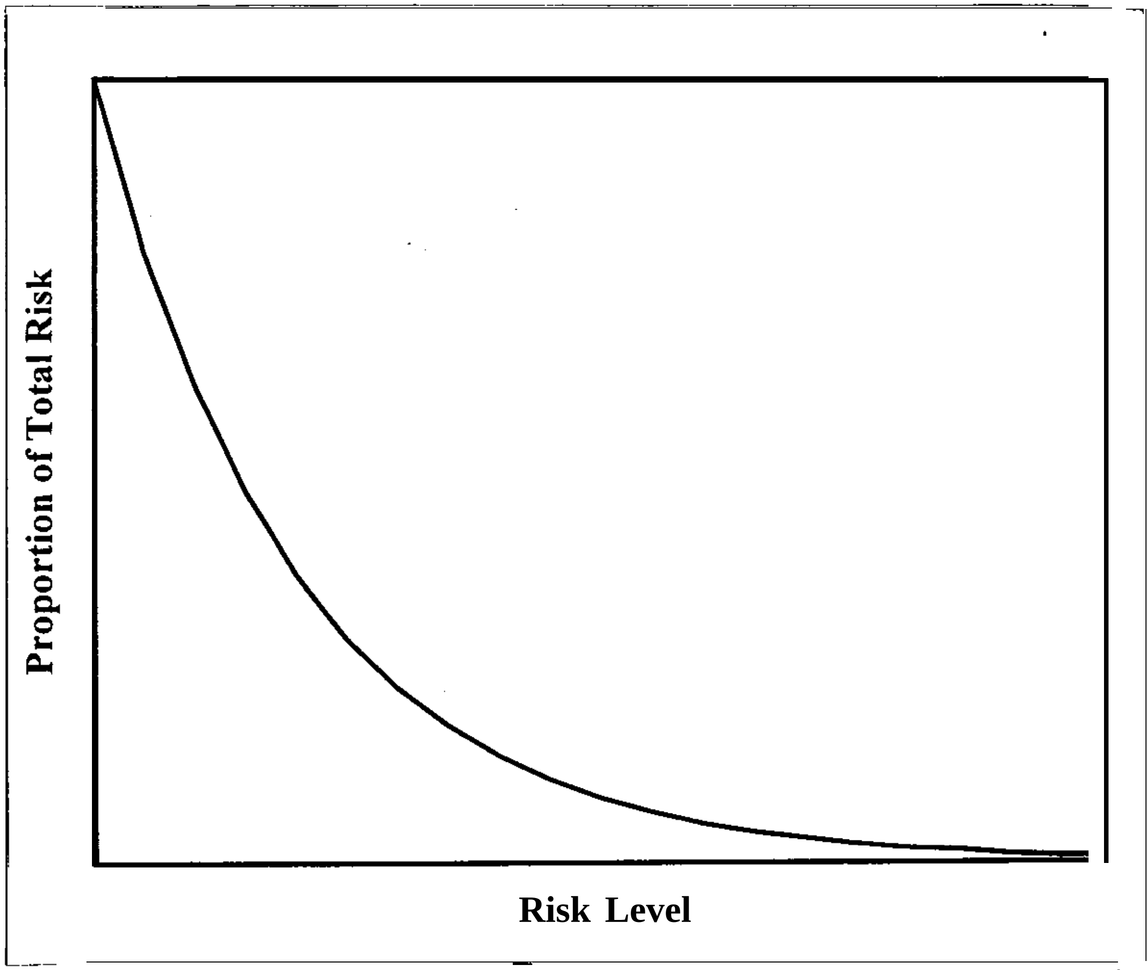

Figure 2. Distribution of Risk in a Mature Product

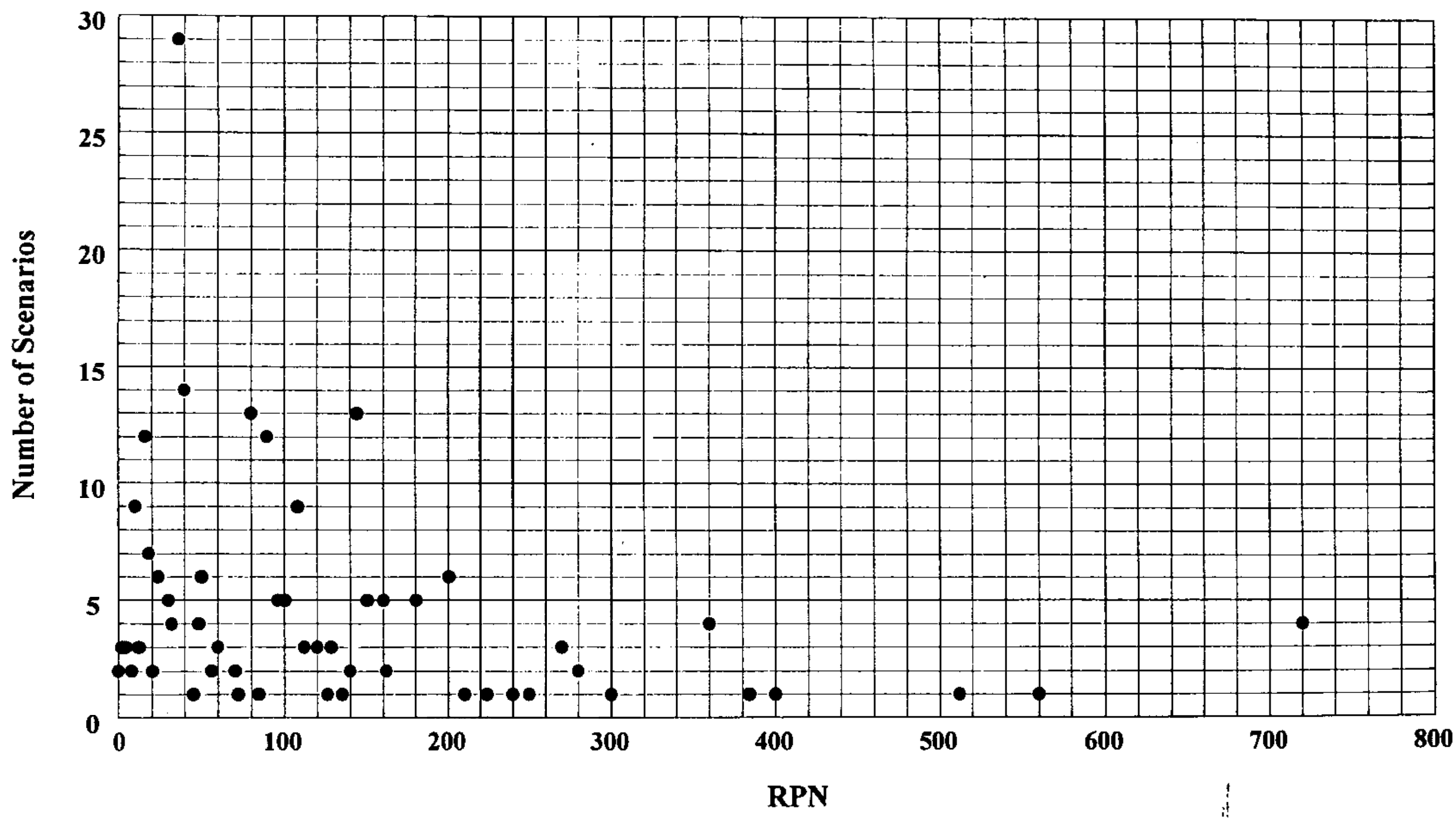

Figure 3. Distribution of RPN Values

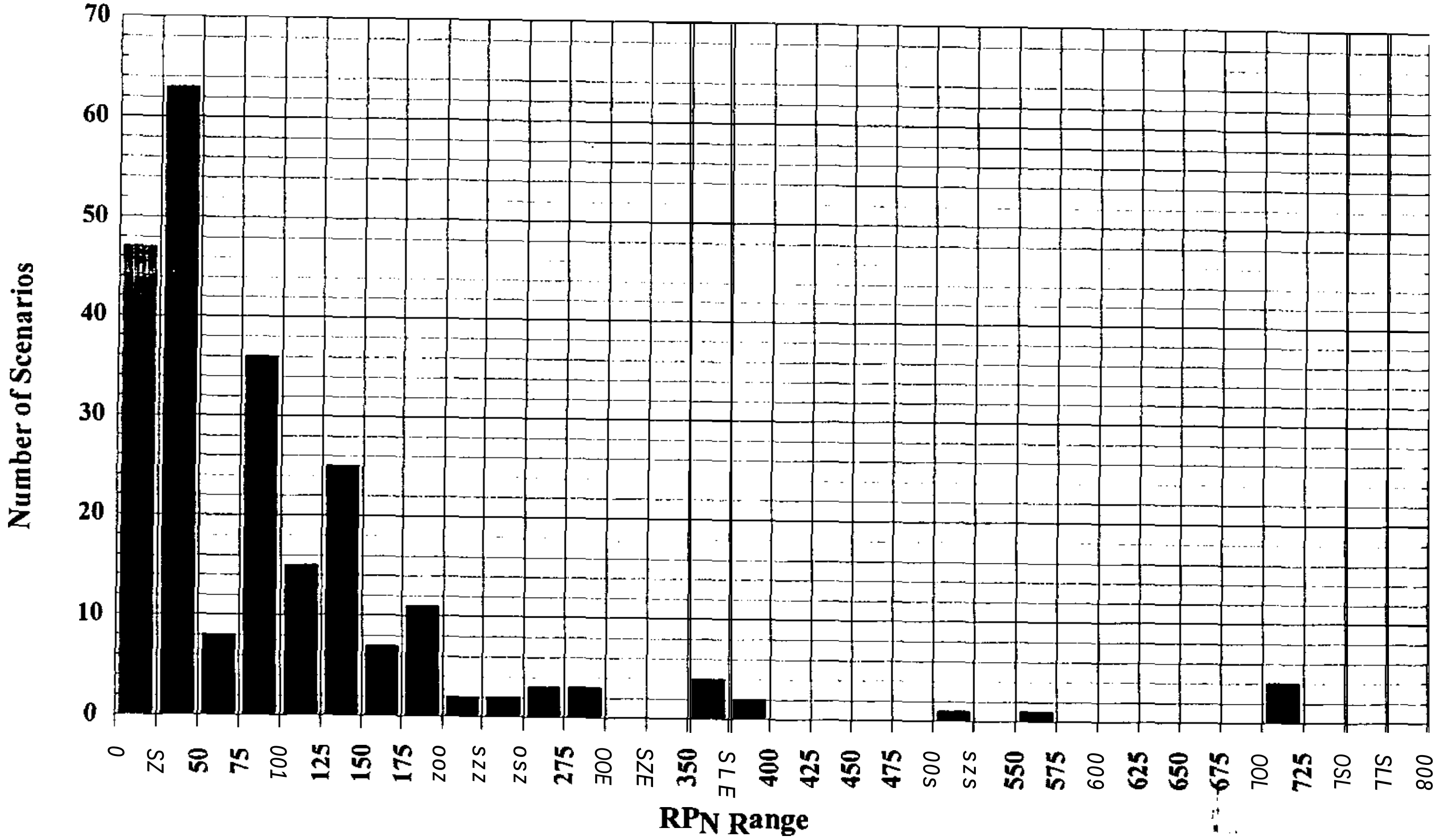

Figure 4. Distribution of RPN Values (Grouped by 25)

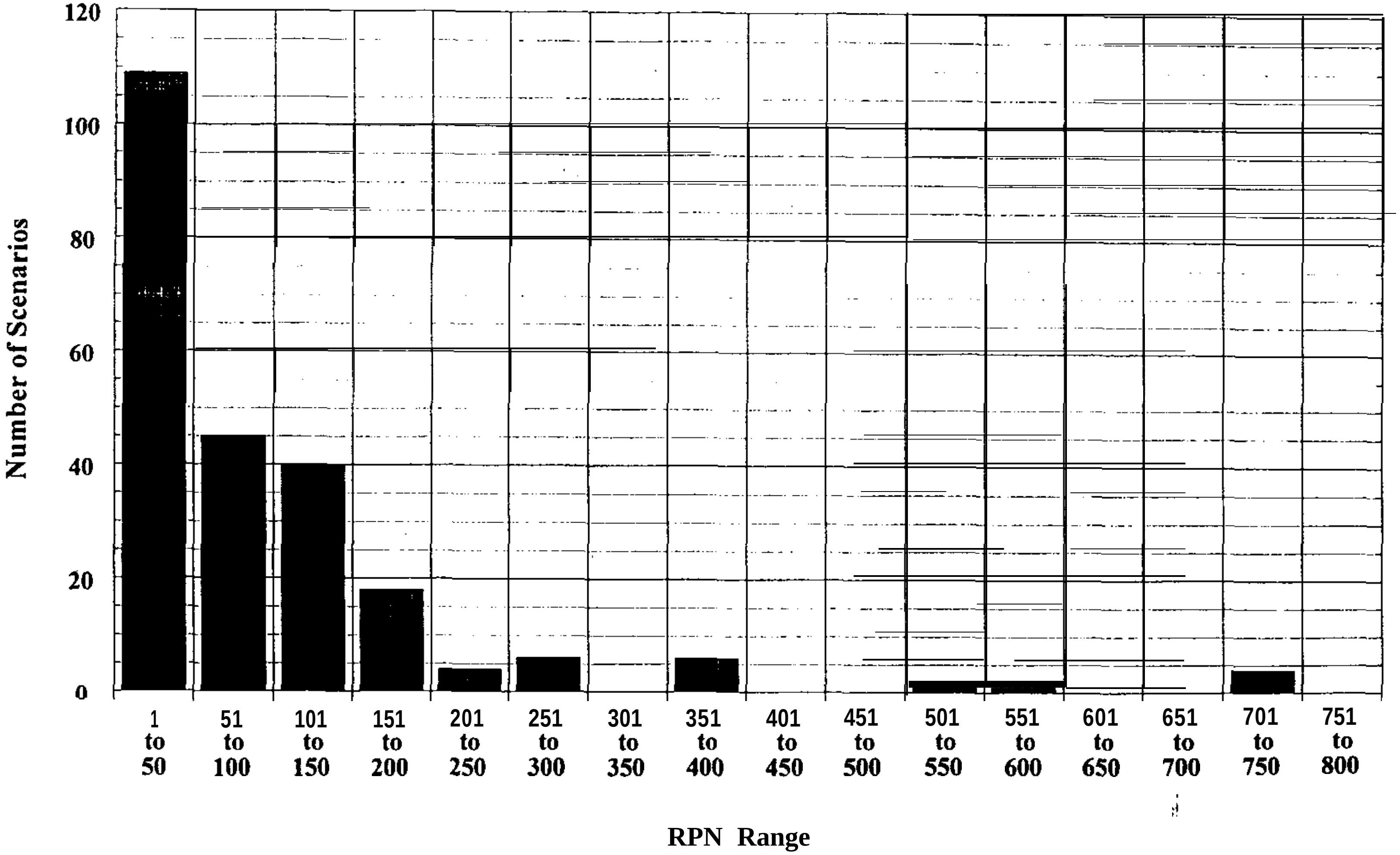

Figure 5. Distribution of RPN Values (Grouped by 50)

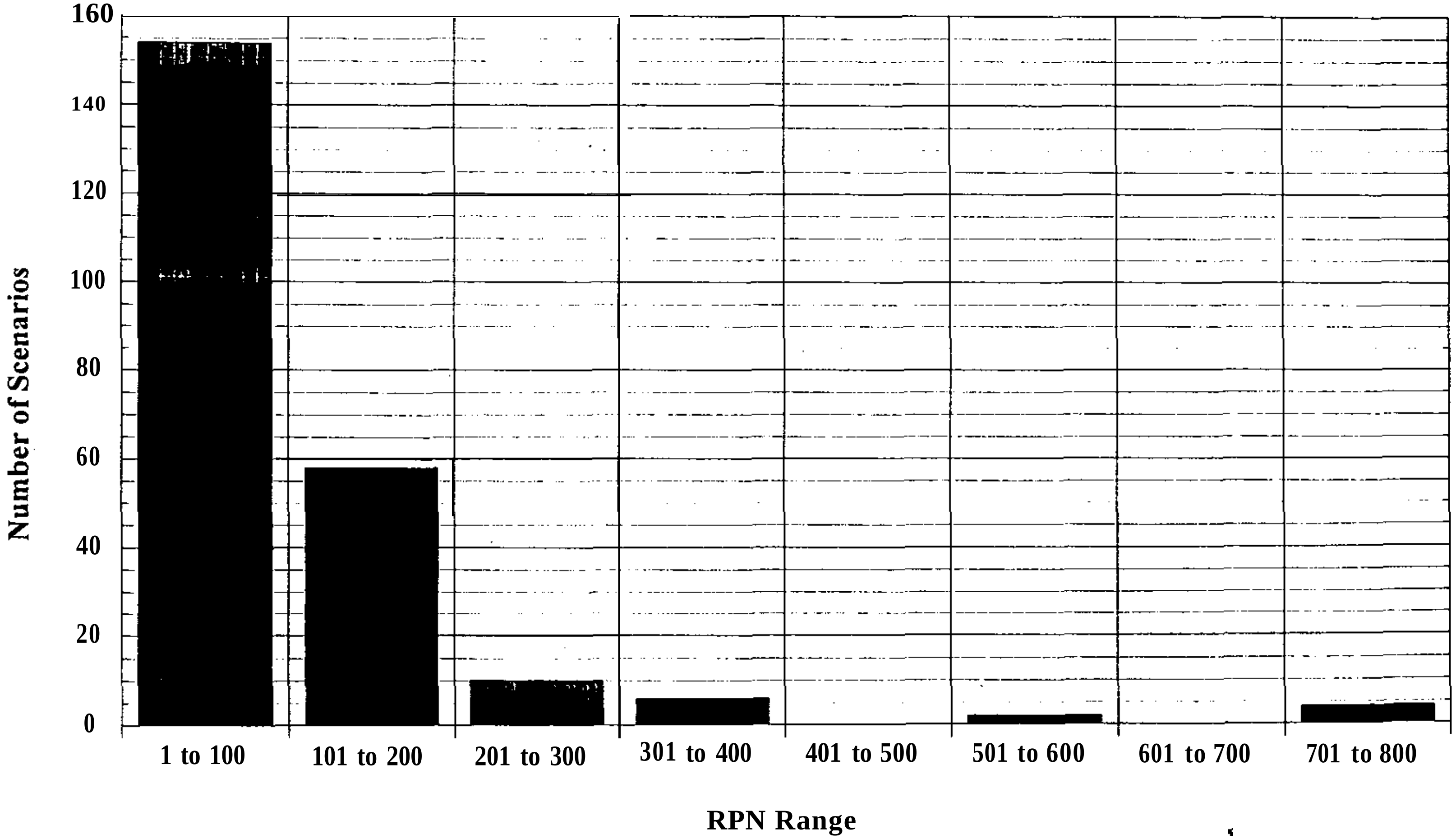

Figure 6. Distribution of RPN Values (Grouped by 100)

4.2.1 Table Entry 1.8

As mentioned in the table entry, this scenario involves a large gas release during the filling operation due to the loss of an O-ring. Specifically, it was mentioned that the loss of the interface O-ring can be caused by a leaking 3-way valve on a Type 2 nozzle. Several potential mitigating actions were discussed, including:

- Use of a higher durometer (90) O-ring. This may help alleviate the problem, but no validation testing has been performed to confirm this.
- Possible use of an O-ring retaining sleeve.
- Consider warning customers to avoid Type 2 nozzles. Implementation of the warning would serve to lower the MN index to 5, but the potential for consumer use of such a nozzle would not be completely avoided.
- Consider notifying relevant agencies. Relevant agencies and safety bureaus might be convinced to require all public filling stations to be equipped with only Type 1 nozzles. However, at this time there are still public tilling stations which utilize Type 2 nozzles.

4.2.2 Table Entry 5.29

This scenario involves a large gas release due to improper venting to the atmosphere, potentially during service. One minimization measure considered involves detailing the proper maintenance procedure in a service manual.

4.2.3 Table Entry 18.10

Table entry 18.10 details a large gas release, coupled with potential customer injury, due to an improper connection of the filling line. Changes could be to design the problem out, coupled with validation testing.

4.2.4 Table Entry 18.32

This scenario involves the ignition of a large gas release due to a missing or broken ground strap. One solution would be to redesign the system with a redundant strap.

Although it seems obvious that a redundant strap will reduce the likelihood of this scenario, it ‘is possible that the reduction in probability will not be large in extent. For instance, there were cases noted where the ground strap was broken. Since the mechanism of this break has not been determined, there is a potential that the cause of a broken ground strap could easily break a redundant ground strap at the same time. Until the ultimate effect of the redundant ground strap is known, through either a detailed understanding of the failure mechanism or statistical field performance data, the RPN will retain its current value.

5. REFERENCES

1 Department of Defense, Procedures for Performing a Failure Mode. Effects, and Criticality Analysis, MIL-STD-I 629A, Global Engineering Documents, 1980.

2 Reprinted with permission from D.H. Stamatis, Failure Mode and Effect Analvsis, FMEA from Theory to Execution, ASQC Quality Press, 1994.

3 J.B. Caldwell in D. Blockley, Engineering Safety, McGraw-Hill Book Company, 1992, pp. 259-262.

Appendix A

Examples of Various FMEA Scales and Applications[2]

Rank*	Mechanical or electromechanical industry	Electronics or semiconductor industry	Medical devices	Automotive industry	General guidelines for severity
= very low	<or = 1 in 10,000	< or = I in I million	< or = 1 in 100,000	< or = 1 in 10,000	None
= low or minor	2–10 in 10,000	2 to 10 in 1 million	2 to 10 in 100,000	<or = 1 in2000	Minor
= moderate or significant	11-25 in 10,000	11 to 25 in I million	11 to 25 in 100.000	< or = I in 500	Significant
= high	26–50 in 10,000	26 to 50 in I million	26 to 50 in 100.000	<or = 1 in 50	High
= very high	>50 in 10,000	>50 in 1 million	>50 in 100.000	>or =..I in 10	Catastroph

Interpretation of RPN = S x 0 x D

90%	95%	99%	Common scale
Minor risk I-13	Minor risk 1–6	Minor risk I-2	Minor risk 1–17
Moderate risk 14-52	Moderate risk 7-24	Moderate risk 3-8	Moderate risk ı 8-63
Major risk 53-125	Major risk 25-125	Major risk 9-125	Major risk 64–125

Where:
s = Severity 0 = Occurrence D = Detection

Table F.1 Numerical guidelines for I-5 scale* in occurrence, detection, ond severity.
*All the above numerical values may he changed to suite specific applications.

Ranking	Probability of occurrence or frequency	Degree of severity	Probability of detection	Likelihood of the defect or defective product reaching the customer
= very low or none	Rare < 1 per 10⁴ to 10⁶	Minor nuisance	Detectable before service is released	Very low to none
= low or minor	Infrequent 2 to 10 per 10⁴ to 10⁶	Product operable at reduced performance	Detectable after release but before production	Low or minor
= moderate or significant	Moderate 11 to 25 per 10⁴ to 10⁶	Gradual performance degradation	Detectable before reaching the customer	Moderate or significant
= h i	Frequent and high 26 to 50 per 10⁴ to 10⁶	Loss of function	Detectable only by customer and/or during service	High
= very high or catastrophic	Very high to catastrophic >50 per 10⁴ to 10⁶	Safety-related catastrophic failures	Undetectable until catastrophe occurs	Very high

Table F.2 Word description of I-5 scale far design FMEA.
Note: This guideline is only a sample. It may be changed to suit specific applications.

Ranking	Probability of occurrence or frequency	Degree of severity	Probability of detection	Likelihood of the defect or defective product reaching the customer
1 = very low or none	Rare < 1 per 10^4 to 10^6 or less than once a year	Minor nuisance; almost no effects on products	Detectable before product is released	Very low to none; outstanding control
2 = low or minor	Infrequent 2 to 10 per 10^4 to 10^6 about once a month	Reduced product performance and slow creeping in of inefficiency	Detectable after release to production	Low or minor; very good control. 90–95 percent of the time action taken when process out of control and parts within spec at all times.
3 = moderate or significant	Moderate 11 to 25 per 10^4 to 10^6 or about once every two weeks	Gradual product degradation; moderate inefficiency; reduced productivity; operator starts to be frustrated	Detectable before reaching the customer	Moderate or significant or mediocre control which is not very effective. Action taken only < or = 50 percent of the time. Increased percentage or above parts out of print
4 = high	Frequent and high 26 to 50 per 10^4 to 10^6 or almost every week	More than 50–70% no build condition. Requires high operator efforts. High inefficiency, low productivity. High scrap; loss of function in field	Detectable only by customer and/or during service	High. Very low control. Action taken infrequently. 90 percent or above parts out of specifications
5 = very high or catastrophic	Very high to catastrophic >50 per 10^4 to 10^6 or every other day or more	No build condition. Line shut down; safety-related or catastrophic.	Undetectable until catastrophe occurs	Very high. No controls. No actions. 100 percent wrong parts built

Table F.3 Word description for 1–5 scale for process FMEA.
Note: This guideline is only a sample. It may be changed to suit specific applications.

Ranking	Probability of occurrence or frequency	Degree of severity	Probability of detection	Likelihood of the defect or defective product reaching the customer
1 = very low or none	Rare < 1 per 10^4 to 10^6 or less than once a year	Minor nuisance; almost no effects on service. Great job	Detectable before service is released	Very low to none; outstanding control
2 = low or minor	Infrequent 2 to 10 per 10^4 to 10^6 about once a month	Reduced service performance; no rework. Minor inspection	Detectable after release	Low or minor, very good control. 90–95 percent of the time action taken when process out of control
3 = moderate or significant	Moderate 11 to 25 per 10^4 to 10^6 or about once every two weeks	Moderate inefficiency; reduced productivity; operator starts to be frustrated; aware of problem. May or may not fix	Detectable before reaching the customer	Moderate, significant, or mediocre control which is not very effective. Action taken only 50 percent of the time
4 = high	Frequent and high 26 to 50 per 10^4 to 10^6 or almost every week	Operator frustration. Great dissatisfaction. Needs to fix it now. No possible repeat business	Detectable only by customer and/or during service	High. Very low control. Action taken infrequently. Tight schedules and outside forces.
5 = very high or catastrophic	Very high to catastrophic >50 per 10^4 to 10^6 or every other day or more	No repeat business. Take it back. Very heavy dissatisfaction level	Undetectable until catastrophe occurs	Very high. No controls. No actions. 100 percent bad service

Table F.4 Word description of 1-5 scale for service FMEA.
Note: This guideline is only a sample. It may be changed to suit specific applications.

Effect	Rank	Criteria
No effect	1	No effect on product or subsequent processes.
Very slight effect	2	Customer more likely will not notice rhe failure. Very slight effect on product/process performance. Nonvital fault noticed *sometimes.*
Slight effect	3	Customer slighdy annoyed. Slight effect on product or process performance. Nonvital fault noticed roost of the rime.
Minor effect	4	Customer experiences minor nuisance. Minor effect on product/process performance. Fault does nor require repair. Nonvital fault always noticed.
Moderate effect	5	Customer experiences some dissatisfaction. Moderate effect on product/process performance. Fault on nonvital part requires repair.
Significant effect	6	Customer experiences discomfort. Product/process performance degraded, but operable and safe. Nonvital part inoperable.
Major effect	7	Customer dissatisfied. Major effect on process; rework/repairs on pan necessary. Product/process performance severely affected but functionable and safe. Subsystem inoperable
Extreme effect	8	Customer very dissatisfied. Extreme effect on process; equipment damaged. Product inoperable but safe. System inoperable.
Serious effect	9	Potential hazardous effect. Able to nop product without mishap; safety-related; time-dependent failure. Disruption to subsequent process operations. Complianc with government regulation is in jeopardy.
Hazardous effect	IO	Hazardous effect. Safety-related—sudden failure. Noncompliance with government regulation.

Resolution

If the numerical value falls between two numbers *always* select the higher number.

If the team has a disagreement in the ranking value the following may help.

1. If the disagreement is an adjacent category, average out the difference. For example, if one member says 5 and someone else says 6, the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6. I I, I 1/2 = 5.5).
2. If the disagreement jumps one category, then consensus must be reached. Even with one person holding out, total consensus must be reached. No average, no majority. Everyone in that ram must have ownership of the ranking. They may not agree *100* percent, but they can live with it.

Table **F.5** Severity guideline for process FMEA* (I-10 qualitative scale).

*All the above guidelines and rankings may be changed to reflect specific situations.

Detection	Rank	C_{pk}	Criteria	CNF/1000
Almost never	1	>1.67	Failure unlikely. History shows no failures.	<.00058
Remote	2	>1.50	Rare number of Failures likely.	.0068
Very slight	3	>1.33	Very few failures likely.	.0063
Slight	4	>1.17	Few failures likely.	.46
Low	5	>1.00	Occasional number of failures likely.	2.7
Medium	6	>0.83	Moderate number of failures likely	12.4
Moderately high	7	DO.67	Frequent high number of failures likely.	46
High	8	>0.51	High number of failures likely.	134
Very high	9	DO.33	Very high number of failures likely.	316
Almost certain	10	co.33	Failure almost certain. History of failures exists fmm previous or similar designs.	>316

Resolution

If the numerical value falls between two numbers *always* select rhc higher number.

If the team has a disagreement in the ranking value the following mry hdp.

t. If the disagreement is an adjacent category, average out the difference. For example, if one member says 5 and someone else says 6. the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6 = 11, 11/2 = 5.5 ≅ 6).

2. If the disagreement jumps one category, then consensus must be reached. Even with one person holding out, total consensus must be reached. No average, no majority. Everyone in that team must have ownership of the ding. They may nor agree 100 percent, but they can live with it.

Table F.6 Occurrence guideline for process FMEA (1-10 qualitative scale).*

*All the above guidelines and rankings may be changed to reflect specific situations.

Detection	Rank	Criteria	Resolution
Almost certain	I	Current controls almost always will derecr the failure. Reliable detection controls are known and used in similar processes.	If rhe numerical value falls between two numbers always select the higher number. If the team has a disagreement in the ranking value the following may help. 1. If the disagreement is an adjacent category, average out the difference. For example, if one member says 5 and someone else says 6, the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6 = 11, 11/2 = 5.5 ≅ 6). 2. If the diimcnr jumps one category, then consensus must be reached. Even with one person holding out total consensus must be reached. No average, no majority. Everyone in that rum must have ownership of rhe ranking. They may nor agree 100 percent, but they can live with it.
Very high	2	Very high likelihood current controls will detect the failure.	
High	3	Good likelihood current controls will detect the failure.	
Moderately high	4	Moderately high likelihood current controls will detect the failure.	
Medium	5	Medium likelihood current controls will derecr the failure.	
Low	6	Low likelihood current controls will detect rhc failure.	
Slight	7	Slight likelihood current controls will dctccr the failure.	
Very slight	a	Very slight likdihood current controls will detect the failure.	
Remote	9	Remote likelihood current controls will detect the failure.	
Almost impossible	10	No known controls available to detect the failure.	

Table F.7 Detection guideline for process FMEA (I-10 qualitative scale).'

*All the above guidelines and rankings may be changed to reflect specific situations.

Effect	Rank	Criteria	Resolution
No effect	I	No effect on product or subsequent processes.	If the numerical value falls between two numbers always select the higher number. If the team has a disagreement in the ranking value the following may help. I. If the disagreement is an adjacent category, average out the difference. For example, if one member says 5 and someone else says 6. the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6 = I I, 11/2 = 5.5 ≅ 6). 2. If the disagreement jumps one category, then consensus must bc reached. Even with one person holding out total consensus must be reached. No average, no majority. Everyone in that team must have ownership of the ranking. They may not agree 100 percent. but they can live with it.
Very slight effect	2	Customer more likely will not notice the failure. Very slight effect on product/service performance. Nonvital huh noticed sometimes.	
Slight effect	3	Customer slightly annoyed. Slight effect on product or service performance. Nonvital fault noticed most of the time.	
Minor effect	4	Customer experiences minor nuisance. Minor effect on product/service performance. Fault does not require attention. Nonvital fault always noticed	
Moderate effect	5	Customer experiences some dissatisfaction. Moderate effect on product/service performance. Fault on nonvital part requires repair.	
Significant effect	6	Customer experiences d i i n Product/process performance degraded, but operable and safe. Nonvital service incomplete.	
Major effect	7	Customer dissatisfied. Major effect on service; rework on service necessary. Product/service performance severely affected but functionable and safe. Subsystem incomplete.	
Extreme effect	a	Customer very dissatisfied. Extreme effect on process/service; equipment damaged. Product/service incomplete but safe. System incomplete.	
Serious effect	9	Potential hazardous effect. Able to stop product/service without mishap. Safety-related. Time-dependent failure. Disruption to subsequent process operations. Compliance with government regulation is in jeopardy.	
Hazardous effect	10	Hazardous effect. Safety-related—sudden failure. Noncompliance with government regulation.	

Table F.8 Severity guideline for service FMEA* (I-10 qualitative scale).

'All the above guidelines and rankings may be changed to reflect specific situations.

Detection	Rank	C_{pK}	Criteria	CNF/1000	Resolution
Almost never	1	>1.67	Failure unlikely. History shows no failures.	<.00058	If the numerical value falls between two numbers *always* select the higher number. If the team has a disagreement in the ranking value the following may help. 1. If the disagreement is an adjacent category, average out the difference. Far example, if one member says 5 and someone else says 6, the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6 = 11, 11/2 = 5.5 ≅ 6). 2. If the disagreement jumps one category, then consensus must be reached. Even with one person holding out, total consensus must be reached. No average, no majority. Everyone in that team must have ownership of the ranking. They may not agree 100 percent, but they can live with it.
Remote	2	>1.50	Rare number of failures likely.	.0068	
Very slight	3	71.33	Very few failures likely.	.0063	
Slight	4	>1.17	Few failures likely.	.46	
Low	5	>1.00	Occasional number of failures likely.	1.7	
Medium	6	>0.83	Moderate number of failures likely.	12.4	
Moderately high	7	>0.67	Frequent high number of failures likely.	46	
High	8	>0.51	High number of failures likely.	134	
Very high	9	z-o.33	Very high number of failures likely.	316	
Almost certain	10	co.33	Failure almost certain. History of failures exists from previous or similar designs.	>316	

Table F.9 Occurrence guideline for service FMEA (l-l 0 qualitative scale).*

*All the above guidelines and rankings may be changed to reflect specific situations.

Detection	Rank	Criteria	Resolution
Almost certain	l	Current controls almost always will detect the failure. Reliable detection controls are known and used in similar processes.	If the numerical value falls between two numbers *always* select rhc higher number. If the team has a disagreement in the ranking value the following may help. 1. If the disagreement is an adjacent category, average out the difference. For example. if one member says 5 and someone else says 6. the ranking in this case should be 6 (5 and 6 are adjacent categories. Therefore 5 + 6 = 11. 11/2 = 5.5 ≅ 6). 2. If the disagreement jumps one category, then consensus must be reached. Even with one person holding out total consensus must bc reached. No average, no majority. Everyone in that team must have ownership of the ranking. They may nor agree 100 percent, but they can live with it.
Very high	2	Very high likelihood current controls will detect the failure.	
High	3	Good likelihood current controls will detect the failure.	
Moderately high	4	Moderately higb likelihood current controls will detect the failure.	
Medium	5	Medium likelihood current controls will dcrccr rhc failure.	
Low	6	Low likelihood current controls will detect the failure.	
Slight	7	Slight likelihood current controls will detect the failure.	
Very slight	8	Very slight likelihood current controls will detect the failure.	
Remote	9	Remote likelihood current controls will dcrccr the failure.	
Almost impossible	10	No known controls available to detect rhe failure.	

Table F.10 Detection guideline for service FMEA (1-10 qualitative scale).'

*All the above guidelines and rankings may be changed to reflect specific situations.

Appendix B

List of Workshop Participants

List of Participants
FMEA Workshop I
November 15-17, 1995

Failure Analysis Associates, Inc. (FaAA)

General Motors Corporation

Representatives from the following component and subsystem suppliers:

- Valves
- CNG tanks
- Hose and tubing
- Electronic control systems and parts
- Seals
- Connectors and fittings
- Cables
- Fuel sensors
- Assembly materials for specific systems
- Pressure regulators
- Wiring assemblies
- The system integrator

List of Participants
FMEA Workshop II
February 21-23, 1996

Failure Analysis Associates, Inc. (FaAA)

General Motors Corporation

Representatives from the following component and subsystem suppliers:

- Screens and filters
- Dust and pressure caps
- Springs
- Valves
- CNG tanks
- Hose and tubing
- Electronic control systems and parts
- Seals
- Connectors and fittings
- Systems risk analysis
- Fuel sensors
- Assembly materials for specific systems
- Pressure regulators
- Wiring assemblies
- The system integrator

Appendix C

FMEA Ta hles

Note: The indices assigned in the following tables represent the consensus of a large group of participants and do not necessarily represent the sole opinions of FaAA.

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

I'ill Receptacle / Filter

ID	Equipment Description	ID	Risk I Failure Mode	SV	Failure Scenarios	OC	M N	RPN
1.0	Fill Receptacle / Filter							
1.1	Fill Nozzle	B	Leakage (non-injury)	2	Driving away from tilling station while fill nozzle is still attached.	8	8	128
1.2	Fill Receptacle-O-Ring	B	Leakage (non-injury)	2	Debris in gas contaminates seal.	6	2	24
1.3	Housing - Fill Valve Mounting	B	Leakage (non injury)	2	Potential for failure of part resulting in leakage.	1	5	IO
1.4	Housing - Fill Valve Mounting	A	Customer dissatisfaction	1	Bent mounting causing improper tit with till nozzle.	I	2	2
1.5	Gasket - Fill Valve Housing	-ii-	Leakage (non injury)	2	Damaged gasket and leaking line.	1	5	IO
I.6	Valve - Fill 1/4 Face Seal	G	Large gas release	9	Form ice in the fill process, causing a restriction preventing the valve from closing.	6	5	270
1.7	Valve - Fill 1/4 Face Seal	B	Leakage (non injury)	2	Form ice in the till process, causing a restriction preventing the valve from closing.	6	5	60
1.8	Valve - Fill 1/4 Face Seal	G	Large gas release	9	Loss of nozzle/till receptacle interface O-ring.	10	8	720
I.9	Fill Receptacle - Poppet Seal	B	Leakage (non injury)	2	Damage to poppet seal by gas stream/contaminants.	4	2	16
1.10	Valve-Fill 1/4 Face Seal	A	Customer dissatisfaction	1	Ice blocks the till path, increasing till time.	8	5	40
1.11	Valve -Fill 1/4 Face Seal	F	Loss of crashworthiness	9	Corrosion causes reduced crashworthiness.	1	5	45
1.12	Cap, Dust	A	Customer dissatisfaction	I	Absence of dust cap can cause filter blockage; can be inconvenient to use in winter.	2	5	10

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High *Pressure Fuel Line*

ID	Equipment Description	ID	Risk/ Failure Mode	SV	Failure Scenarios	OC	MN	RPN
2.0	High Pressure Fuel Line							
2.1	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.2	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Corrosion I fatigue of the tubing.	2	2	36
2.3	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.4	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.5	Tube Assembly, Fill Valve to Tank (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.6	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.7	Tube Assemblv. Fill Valve to Tank (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.8	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.9	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.10	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.11	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Corrosion I fatigue of the tubing.	2	2	36
2.12	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2. I3	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High Pressure Fuel Line

2.14	Tube Assembly, Tank to Vent Box (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.15	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.16	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.17	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.18	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.19	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.20	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.21	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.22	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.23	Tube Assembly, Vent Box to FSU Tee	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.24	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.25	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.26	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.27	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.28	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High Pressure Fuel Line

2.29	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.30	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.31	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.32	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.33	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.34	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.35	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.36	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.37	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.38	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.39	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.40	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.41	Tube Assembly, 1/4 Turn Valve to HPR	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.42	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.43	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90

ligh Pressure Fuel Line

2.44	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.45	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.46	1/4" Flex Line	A	Customer dissatisfaction	I	Impurity causes pin hole and resultant small leak.	6	2	12
2.41	1/4" Flex Line	B	Leakage (non injury)	2	Impurity causes pin hole and resultant small leak.	6	2	24
2.48	1/4" Flex Line	G	Large gas release	9	Severed during service.	4	2	72
2.49	1/4" Flex Line	B	Leakage (non injury)	2	Severed during service.	4	2	16

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Ventilation System

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
3.0	**Ventilation System**							
3.1	Enclosure - Ventilation	G	Large gas release	9	Gas is trapped in trunk and if ignited results in combustion.	1	2	18
3.2	Enclosure - Ventilation	B	Leakage (non-injury)	2	Gas is trapped in trunk (no combustion).	6	2	24
3.3	Hose - Vent Tube, Neoprene	B	Leakage (non-injury)	2	Vent tube hose becomes disconnected or torn, resulting in exhaust gas entering the passenger compartment (no combustion).	6	2	24
3.4	Hose - Vent Tube, Neoprene	B	Large gas release	9	Vent tube hose becomes disconnected or torn, resulting in exhaust gas entering the passenger compartment. If ignited, results in combustion.	6	2	108

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High Pressure Valve / PRD

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
4.0	**High Pressure Valve / PRD**							
4.1	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Failure of PRD to open.	8	2	16
4.2	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Failure of PRD to open.	8	2	144
4.3	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Failure to open (electrical cause). CNG system inoperative.	6	8	48
4.4	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	External leak.	10	2	40
4.5	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	External leak.	10	2	180
4.6	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Internal leak (due to freeze-up, due to particulates).	4	5	40
4.7	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Freeze-up, leaving valve open.	8	2	144
4.8	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Corrosion.	1	2	4
4.9	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Corrosion.	1	2	18
4.10	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Freeze-up, causing a restriction or valve closure. CNG system inoperative.	8	2	16
4.11	Electric Tank Valve/Lockoff/PRD	D	Driveability and performance	5	Intermittent function.	6	8	240
4.12	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	10	Slow response of PRD leading to failure to protect tank from overpressurization in a fire.	4	5	200

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High Pressure Valve / PRD

4.13	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	IO	Mechanical binding of PRD leading to failure to protect tank from overpressurization in a fire.	2	5	100
4.14	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Premature activation of PRD.	6	5	270
4.15	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	PRD failure to activate in tire.	3	5	135
4.16	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	IO	PRD failure to activate in tire.	4	5	200
4.17	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	IO	PRD failure to activate as designed during overfilling.	3	5	150
4.18	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Thermal shock, leading to external leak (see tank).	I	5	10

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Fuel Storage Tank

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	O C	M N	RPN
5.0	Fuel Storage Tank							
5.1	Fuel Tank	H	Sudden. high pressure failure	10	Accident, collision.	8	2	160
5.2	Fuel Tank	H	Sudden high pressure failure	IO	Stress corrosion cracking.	8	2	160
5.3	Fuel Tank	G	Large gas release	9	Corrosion, internal.	2	5	90
5.4	Fuel Tank	H	Sudden high pressure failure	IO	Corrosion, internal.	2	5	100
5.5	Fuel Tank	G	Large gas release	9	Corrosion, external.	8	2	144
5.6	Fuel Tank	H	Sudden high pressure failure	IO	Corrosion, external.	8	2	160
5.1	Fuel Tank	G	Large gas release	9	Fire in the system, vehicle tire.	8	2	144
5.8	Fuel Tank	G	Large gas release	9	Fire external to the vehicle.	IO	2	180
5.9	Fuel Tank	G	Large gas release	9	Abrasion.	8	5	360
5.10	Fuel Tank	B	Leakage (non injury)	2	Abrasion.	8	5	80
5.11	Fuel Tank	H	Sudden high pressure failure	IO	Overpressurization.	IO	2	200
5.12	Fuel Tank	F	Loss of crashworthiness	9	Stress corrosion cracking.	8	2	144
5.13	Fuel Tank	H	Sudden high pressure failure	10	UV damage of the composite, leading to degradation.	6	2	120
5.14	Fuel Tank	H	Sudden high pressure failure	10	Handling damage.	10	2	200
5.15	Fuel Tank	F	Loss of crashworthiness	9	UV damage of the composite, leading to degradation.	6	2	108
5.16	Fuel Tank	F	Loss of crashworthiness	9	Handling damage.	10	2	180
5.17	Fuel Tank	F	Loss of crashworthiness	9	Inherent defect in the material and construction.	6	3	162

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Fuel Storage Tank

5.18	Fuel Tank	G	Large gas release	9	Inherent defect in the material and construction.	6	3	162
5.19	Fuel Tank	H	Sudden high pressure failure.	10	Inherent defect in the material and construction.	6	3	180
5.20	Fuel Tank	E	Loss of compliance	7	Inherent defect in the material and construction.	6	3	126
5.21	Fuel Tank	G	Large gas release	9	ESD burns hole in liner.	0	5	0
5.22	Fuel Tank	A	Customer dissatisfaction	1	Water or oil build-up in the tank, leading to reduced range.	10	8	80
5.23	Fuel Tank	E	Loss of compliance	7	Damage to the tank due to vehicle modification.	8	5	280
5.24	Fuel Tank	F	Loss of crashworthiness	9	Damage to the tank due to vehicle modification.	8	5	360
5.25	Fuel Tank	G	Large gas release	9	Damage to the tank due to vehicle modification.	8	5	360
5.26	Fuel Tank	F	Loss of crashworthiness	9	Use beyond service life.	6	5	270
5.27	Fuel Tank	H	Sudden high pressure failure	10	Use beyond service life.	6	5	300
5.28	Fuel Tank	E	Loss of compliance	7	Improper venting / service.	4	8	224
5.29	Fuel Tank	G	Large gas release	9	Improper venting / service.	10	8	720
5.30	Fuel Tank	H	Sudden high pressure failure	10	Thermal shock: hot tank filled with cold fuel.	6	2	120
5.31	Fuel Tank	H	Sudden high pressure failure	10	Loss of tank properties prior to PRD activation, leading to complete loss of contents in an external fire.	4	2	80
5.32	Fuel Tank	H	Sudden high pressure failure	10	Combustible mixture in gas (use of high pressure air to leak test tank, followed by filling).	1	2	20
5.33	Bracket, Tank	H	Sudden high pressure failure	10	Component breakage leading to tank becoming dislodged.	6	2	120

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

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Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Fuel Sending Unit

ID	Equipment Description	ID	Risk I Failure Mode	SV	Failure Scenarios	O C	M N	RPN
6.0	**Fuel Sending Unit**							
6.1	Fuel Sending Unit	G	Large gas release	9	Fatigue, corrosion (external and internal).	1	2	18
6.2	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics.	8	2	16
6.3	Fuel Sending Unit	C	Vehicle inoperative	8	Failure of the electronics.	8	2	128
6.4	Fuel Sending Unit	A	Customer dissatisfaction	1	Mechanical failure / blockage. System defaults to gasoline.	4	2	8
6.5	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics leading to "full" output when empty. Inability to initially use gasoline.	6	5	30
6.6	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics leading to "zero" output when full. System switches to gasoline from CNG prematurely (before complete loss of CNG). Could be due to FSU problem, incorrect fuel level indication or ECU circuit failure (input signal shorted).	6	5	30

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

/4 Turn Valve

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	O C	M N	RPN
7.0	**1/4 Turn Valve**							
7.1	1/4 Turn Valve (Small)	G	Large gas release	9	External leak from valve components, valve breaking off.	2	2	36
7.2	1/4 Turn Valve (Small)	A	Customer dissatisfaction	1	Inadvertent or failure to open I difficult to use or find.	8	5	40
7.3	1/4 Turn Valve (Small)	A	Customer dissatisfaction	1	Inadvertent or failure to close I difficult to use or find.	8	5	40
7.4	1/4 Turn Valve (Small)	E	Loss of compliance	7	Inadvertent or failure to close I difficult to use or find.	8	5	280

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

High Pressure ***Regulator / PRD***

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
8.0	**High Pressure Regulator / PRD**							
8.1	HPR-3600 Assembly	G	Large gas release	9	Rupture.	1	2	18
8.2	HPR-3600 Assembly	A	Customer dissatisfaction	1	Regulator freezing. CNG system inoperative.	8	5	40
8.3	HPR-3600 Assembly	A	Customer dissatisfaction	1	Shut off: filter clogs or sleeve cold flow. CNG system inoperative.	6	2	12
8.4	HPR-3600 Assembly	A	Customer dissatisfaction	1	Blockage due to contaminants in fuel.	8	2	16
8.5	HPR-3600 Assembly	D	Driveability and performance	5	Blockage due to contaminants in fuel.	8	2	80
8.6	HPR-3600 Assembly	G	Large gas release	9	Venting at high pressure under static conditions.	6	2	108
8.7	HPR-3600 Assembly	G	Large gas release	9	Overstressing of regulator body due to excess torque in fittings.	2	2	36

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Low Pressure Line

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
9.0	**Low Pressure Line**							
9.1	Low Pressure Line (Dry Gas Hose)	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections, damaged line.	6	2	24
9.2	Low Pressure Line (Dry Gas Hose)	A	Customer dissatisfaction	1	Severed or disconnected line. CNG system inoperative.	2	8	16
9.3	Low Pressure Line (Dry Gas Hose)	G	Large gas release	9	Gas hose melts in fire, gas continues to be supplied.	0	N/A	0
9.4	Low Pressure Line (Dry Gas Hose)	B	Leakage (non injury)	2	External leak.	2	8	32

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Low Pressure Valve

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
10.0	**Low Pressure Valve**							
10.1	Low Pressure Valve	B	Leakage (non injury)	2	External leakage.	4	2	16
10.2	Low Pressure Valve	D	Driveability and performance	5	External leakage.	4	2	40
10.3	Low Pressure Valve	A	Customer dissatisfaction	1	Seat leakage (internal).	4	2	8
10.4	Low Pressure Valve	D	Driveability and performance	5	Seat leakage (internal).	4	2	40
10.5	Low Pressure Valve	A	Customer dissatisfaction	1	Valve fails to open. CNG system inoperative.	6	5	30
10.6	Low Pressure Valve	A	Customer dissatisfaction	1	Failure to open (electrical cause). CNG system inoperative.	6	8	48
10.7	Low Pressure Valve	B	Leakage (non injury)	2	Corrosion.	1	5	10
10.8	Low Pressure Valve	D	Driveability and performance	5	Intermittent function.	6	5	150

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Low Pressure ***Regulator***

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	O C	M N	RPN
11.0	**Low Pressure Regulator Module**							
11.1	Low Pressure Regulator Assy.	G	Large gas release	9	Rupture.	1	2	18
11.2	Low Pressure Regulator Assy.	A	Customer dissatisfaction	I	Shut off due to primary pin sticking from contamination. CNG system inoperative.	2	2	4
11.3	Low Pressure Regulator Assy.	D	Drivability and performance	5	Pin sticking due to contamination.	2	2	20
11.4	Low Pressure Regulator Assy.	D	Drivability and performance	5	Incorrect output pressure.	6	2	60
11.5	Low Pressure Regulator Assy.	E	Loss of compliance	1	Loss of vehicle emissions compliance due to improper fueling.	6	2	84
11.6	Low Pressure Regulator Assy.	B	Leakage (non injury)	2	External leak.	8	5	80
11.7	Low Pressure Regulator Assy.	G	Large gas release	9	Overstressing of regulator body due to excess torque in fittings.	2	2	36

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Intermediate Pressure Line

ID	Equipment Description	ID	Risk I Failure Mode	S V	Failure Scenarios	O C	M N	RPN
12.0	Intermediate Pressure Line							
12.1	Intermediate Pressure Line	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections.	1	2	4
12.2	Pipe thread fitting	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections.	6	2	24
12.3	Intermediate Pressure Line	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	1	2	18
12.4	Intermediate Pressure Line	G	Large gas release	9	Severed or disconnected line.	1	2	18
12.5	Intermediate Pressure Line	A	Customer dissatisfaction	1	Severed or disconnected line. CNG system inoperative.	1	2	2

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

GMS / MCV

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	O C	M N	RPN
13.0	**Gas Mass Sensor / Mixture Control Valve**							
13.1	GMS/MCV Assy	D	Driveability and performance	5	Internal leak.	6	5	150
13.2	GMS/MCV Assy	A	Customer dissatisfaction	1	Hard failure of sensing element leading to gasoline operation.	10	5	50
13.3	GMS/MCV Assy	D	Driveability and performance	5	Soft failure of sensing element.	10	2	100
13.4	GMS/MCV Assy	E	Loss of compliance	7	Soft failure of sensing element.	10	2	140
13.5	GMS/MCV Assy	A	Customer dissatisfaction	I	Interference of control valve leading to shut off. System defaults to gasoline.	10	5	50
13.6	GMS/MCV Assy	D	Driveability and performance	5	Interference of control valve leading to wide open condition.	2	5	50
13.7	GMS/MCV Assy	B	Leakage (no" injury)	2	External leak.	I	8	16
13.8	GMS/MCV Assy	E	Loss of compliance	7	External leak.	1	8	56
13.9	GMS/MCV Assy	D	Drivability and performance	5	Drift in set point of butterfly valve.	6	2	60

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Gas Distribution Ring / **Adapter**

ID	Equipment Description	ID	Risk I Failure Mode	SV	Failure Scenarios	O C	M N	RPN
14.0	Gas Distribution Ring I Adapter							
14.1	Gas Ring I Adapter	B	Leakage (non injury)	2	External leakage.	6	2	24
14.2	Gas Ring / Adapter	D	Driveability and performance	5	Internal leakage.	6	5	150
14.3	Gas Ring / Adapter	E	Loss of compliance	7	Internal leakage.	6	5	210

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Engine Control Unit

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
15.0	**Engine Control Unit**							
15.1	Engine Control Unit	C	Customer dissatisfaction	1	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open. Mode does not render vehicle inoperative. Vehicle can still be driven in gasoline mode with no problem.	6	5	30
15.2	Engine Control Unit	D	Driveability and performance	5	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open.	6	5	150
15.3	Engine Control Unit	A	Customer dissatisfaction	1	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open.	6	5	30
15.4	Engine Control Unit (Air mass sensor)	A	Customer dissatisfaction	1	Loss of sensors (engine), data. CNG system inoperative.	8	2	16
15.5	Engine Control Unit (Crank, oxygen, coolant, MAT sensors)	D	Driveability and performance	5	Loss of sensors (engine), data.	8	2	80
15.6	Engine Control Unit (Crank, oxygen, air mass, coolant, MAT sensors)	E	Loss of compliance	7	Loss of sensors (engine), data.	8	2	112
15.7	Engine Control Unit	A	Customer dissatisfaction	1	Failure in circuit leading to attempt to use CNG tank when tank is empty. Inability to initially use gasoline.	6	8	48

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

ngine Control Unit

15.8	ECU Assembly	A	Customer dissatisfaction	1	Failure in circuit leadingto switching to gasoline from CNG prematurely (before complete loss of CNG). Could be due to FSU problem, incorrect fuel level indication or ECU circuit failure (input signal shorted).	6	8	48

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Wire Harness

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	OC	MN	RPN
16.0	**Wire Harness**							
16.1	Wire Harness Assembly	A	Customer dissatisfaction	1	Wires are disconnected; improperly connected; misaligned; backed-out connectors. CNG system may be inoperative.	8	5	40
16.2	Wire Harness Assembly	A	Customer dissatisfaction	1	Inadequate circuit protection leading to thermal incident. CNG system inoperative.	6	2	12
16.3	Wire Harness Assembly	A	Customer dissatisfaction	1	Improper routing, wire chafing, or corrosion leading to failure. CNG system inoperative.	8	5	40
16.4	Wire Harness Assembly	C	Vehicle inoperative	8	Short to ground of control wire to VCM which disables gasoline operation. Vehicle inoperative if CNG tank is empty.	6	8	384
16.5	Wire Harness Assembly	A	Customer dissatisfaction	1	Incorrect routing increasing propensity for damage during service, i.e. damage from sheet metal screw. CNG system inoperative.	1	2	2
16.6	Wire Harness Assembly	D	Driveability and performance	5	Voltage spikes. Relays improperly sized.	*	*	*
16.7	Wire Harness Assembly	A	Customer dissatisfaction	1	Voltage spikes. Relays improperly sized.	*	*	*
16.8	Wire Harness Assembly (Fuel gauge relay)	A	Customer dissatisfaction	1	Failure in fuel gauge relay- doesn't indicate fuel level	*	*	*

* Adequate information and associated MN, OC, and RPN indices were not provided by the manufacturer or supplier by the freeze date for this document analysis and production.

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Wire Harness

16.9	Wire Harness Assembly (Fuel pump relay)	A	Customer dissatisfaction	I	Failure in fuel pump relay. CNG system inoperative.	*	*	*
16.10	Wire Harness Assembly (Lock-off relay)	A	Customer dissatisfaction	I	Failure in lock-off relay: fails closed. CNG system inoperative.	*	*	*
16.1 I	Wire Harness Assembly (Ignition relay)	C	Vehicle inoperative	8	Failure in ignition relay.	*	*	*

*** Adequate information and associated MN, OC, and RPN indices were not provided by the manufacturer or supplier by the freeze date for this document analysis and production.**

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

I/P Switch Assembly

ID	Equipment Description	ID	Risk I Failure Mode	SV	Failure Scenarios	OC	MN	RPN
17.0	**I/P Switch Assembly**							
17.1	I/P Switch Assembly	C	Vehicle inoperative	8	No fuel mode indication. One could be unaware that the vehicle is running on gasoline. When the gasoline runs out, their is no reserve fuel as expected.	8	8	512

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Interface Issues

ID	Equipment Description	ID	Risk / Failure Mode	SV	Failure Scenarios	O C	M N	RPN
18.0	Interface Issues							
18.1	O-rings/face seal	B	Leakage (non-injury)	2	Surface defects on O-Ring or metal seat, internal corrosion , degradation duet" storage conditions, materials/manufacturing defects, O-Ring is missing, O-Ring extrusion (design dependent), compound does not meet specification, undercured material, incorrect installation, excessive temperature conditions (age dependent).	IO	5	100
18.2	O-rings	B	Leakage (non-injury)	2	Failure of O-Ring due to combination of low temperature (< -65 "C) and stress- directly after HPR.	*	*	*
18.3	O-rings	B	Leakage (non injury)	2	Improper O-Ring (e.g. wrong material or size).	10	5	100
18.4	O-rings/face seal	G	Large Gas Release	9	Improper torque at assembly	4	5	180
18.5	Electrical connectors	A	Customer dissatisfaction	1	Failure to properly mate connections during manufacturing or service. CNG system inoperative.	8	5	40
18.7	Electrical connectors	D	Drivability and performance	5	Failure to properly mate connections during manufacturing or service.	8	5	200

* Adequate information and associated MN, OC, and RPN indices were not provided by the manufacturer or supplier by the freeze date for this document analysis and production.

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Interface *Issues*

18.8	Customer-to-system	A	Customer dissatisfaction	1	Customer fails to properly connect tilling line, hose flies off and causes injury.	10	8	80
18.9	Customer-to-system	E	Loss of compliance	7	Customer fails to properly connect filling line, hose flies off and causes injury.	10	8	560
18. IO	Customer-to-system	G	Large gas release	9	Customer fails to properly connect tilling line, hose flies off and causes injury.	10	8	720
18.11	Customer-to-system	A	Customer dissatisfaction	1	Customer is unable to disconnect fueling line.	IO	5	50
18. I2	Customer-to-system	C	Vehicle inoperative	8	Customer is unable to disconnect fueling line.	10	5	400
18.13	Customer-to-system	A	Customer dissatisfaction	1	Customer fails to cycle gasoline fuel as recommended.	2	5	10
18.14	Customer-to-system	C	Vehicle inoperative	8	Customer fails to cycle gasoline fuel as recommended.	2	5	80
18.15	Customer-to-system	D	Driveability and performance	5	Customer fails to cycle gasoline fuel as recommended.	2	5	50
18.16	Customer-to-system	E	Loss of compliance	7	Customer fails to cycle gasoline fuel as recommended.	2	5	70
18.17	Customer-to-system	C	Vehicle inoperative	8	Customer fails to fill gasoline tank.	10	2	160
18.18	CNG service-to-system	A	Customer dissatisfaction	1	Failure to follow proper procedures for electrical system.	2	8	16
18.19	CNG service-to-system	C	Vehicle inoperative	8	Failure to follow proper procedures for electrical system.	2	8	128
18.20	CNG service-to-system	D	Drivability and performance	5	Failure to follow proper procedures for electrical system.	2	8	80
18.21	CNG service-to-system	E	Loss of compliance	7	Failure to follow proper procedures for electrical system.	2	8	112
18.22	CNG service-to-system	B	Leakage (non injury)	2	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	32

Failure Modes and Effects Analysis for CNG-Fueled Vehicles

Interface Issues

18.23	CNG service-to-system	G	Large gas release	9	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	144
18.24	CNG service-to-system	F	Loss of crashworthiness	9	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	144
18.25	CNG service-to-system	G	Large gas release	9	Failure to follow proper procedures for tank installation.	2	8	144
18.26	CNG service-to-system	H	Sudden high pressure failure	10	Failure to follow proper procedures for tank installation.	2	8	160
18.27	Vehicle service-to-CNG system	G	Large gas release	9	Accidental damage to high pressure system.	8	5	360
18.28	Vehicle service-to-CNG system	A	Customer dissatisfaction	1	Inadvertently render CNG system inoperative.	8	5	40
18.30	Metal-to-metal seals	B	Leakage (non injury)	2	Presence of foreign material.	8	2	32
18.31	Metal-to-metal seals	B	Leakage (non injury)	2	Failure to follow proper procedures.	8	5	80
18.32	Electrical system to CNG fuel system	G	Large gas release (leads to tire)	9	Missing or broken ground strap, causes spark.	10	8	720
IS.33	CNG components to heater	D	Drivability and performance	5	Degradation of engine's coolant affecting heat transfer capacity of the high pressure regulator.	1	2	10
18.34	CNG fuel to engine	A	Customer dissatisfaction	1	Wear of intake valve seats. CNG system inoperative.	10	5	50
18.35	CNG fuel to engine	D	Drivability and performance	5	Wear of intake valve seats.	10	5	250
18.36	CNG fuel to engine	E	Loss of compliance	7	Wear of intake valve seats.	10	2	140
18.37	Threaded connections	B	Leakage (non injury)	2	Failure due to corrosion, fatigue, overtightening; looseness.	8	5	80
18.38	Bracket-to-component	F	Loss of crashworthiness	9	Corrosion.	2	2	36
18.39	Bracket-to-component	G	Large gas release	9	Corrosion /collision effect on tank.'	2	2	36
18.40	Bracket-to-component	H	Sudden high pressure failure	IO	Corrosion /collision effect on tank.	2	2	40
IS.41	Bracket-to-component	G	Large gas release	9	Corrosion /collision effect on valves, regulators.	2	2	36

Interface Issues

18.42	Bracket-to-component	A	Customer dissatisfaction	1	Vibration.	2	5	10
18.43	Bracket-to-vehicle	F	Loss of crashworthiness	9	Corrosion.	2	2	36
18.44	Bracket-to-vehicle	G	Large gas release	9	Corrosion / collision effect on tank.	2	2	36
18.45	Bracket-to-vehicle	H	Sudden high pressure failure	10	Corrosion / collision effect on tank.	2	2	40
18.46	Bracket-to-vehicle	G	Large gas release	9	Corrosion / collision effect on valves, regulators.	2	2	36
18.47	Bracket-to-vehicle	A	Customer dissatisfaction	1	Vibration.	2	5	10
18.48	CNG exhaust to vehicle exhaust system	E	Loss of compliance	7	Deterioration of catalytic converter or oxygen sensor.	4	2	56
18.49	CNG system to OEM components in base vehicle	E	Loss of compliance	7	Effect of CNG system on base vehicle OEM environment (e.g. thermal, salt spray effects).	2	5	70
18.50	Vehicle manufacturer controller to CNG system integrator controller	E	Loss of compliance	7	Loss of fuel mode communication between the two fuel controllers, resulting in DTCs and miscellaneous calibration issues.	8	2	112
18.51	Vehicle manufacturer controller to CNG system integrator controller	A	Customer dissatisfaction	1	Loss of fuel mode communication between the two fuel controllers, resulting in DTCs and miscellaneous calibration issue. CNG system inoperative.	8	2	16
18.52	Vehicle manufacturer electronics to CNG system integrator electronics	C	Vehicle inoperative	8	Loss of ground, transient, results in damage to OEM component.	2	5	80
18.53	CNG system to body structure	F	Loss of crashworthiness	9	Impact of distribution of mass on body structure durability.	2	5	90
18.54	Internal corrosion of components (other than tank)	H	Sudden high pressure failure	IO	Corrosion of internal high pressure components results in unexpected high pressure release.	4	5	200

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Appendix D

FMEA Tables Sorted by RPN

Note: The indices assigned in the following table represent the consensus of a large group of participants and do not necessarily represent the sole opinions of FaAA.

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

ID	Equipment Description	ID	Risk I Failure Mode	SV	Failure Scenarios	OC	MN	RPN
I.8	Valve Fill 1/4 Face Seal	G	Large gas release	9	Loss of nozzle/fill receptacle interface O-ring.	IO	8	720
5.29	Fuel Tank	G	Large gas release	9	Improper venting / service.	IO	8	720
18.10	Customer-to-system	G	Large gas release	9	Customer fails to properly connect tilling line, hose flies off and causes injury.	IO	8	720
18.32	Electrical system to CNG fuel system	G	Large gas release (leads to fire)	9	Missing or broken ground strap, causes spark.	IO	8	720
18.9	Customer-to-system	E	Loss of compliance	7	Customer fails to properly connect tilling line, hose flies off and causes injury.	IO	8	560
17.1	I/P Switch Assembly	C	Vehicle inoperative	8	No fuel mode indication. One could be unaware that the vehicle is running on gasoline. When the gasoline runs out, their is no reserve fuel as expected.	8	8	512
18.12	Customer-to-system	C	Vehicle inoperative	8	Customer is unable to disconnect fueling line.	IO	5	400
16.4	Wire Harness Assembly	C	Vehicle inoperative	8	Short to ground of control wire to VCM which disables gasoline operation. Vehicle inoperative if CNG tank is empty.	6	8	384
5.25	Fuel Tank	G	Large gas release	9	Damage to the tank due to vehicle,: modification.	8	5	360
5.9	Fuel Tank	G	Large gas release	9	Abrasion.	8	5	360
18.27	Vehicle service-to-CNG system	G	Large gas release	9	Accidental damage to high pressure system.	8	5	360

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

5.24	Fuel Tank	F	Loss of crashworthiness	9	Damage to the tank due to vehicle modification.	8	5	360
5.27	Fuel Tank	H	Sudden high pressure failure	10	Use beyond service life.	6	5	300
5.23	Fuel Tank	E	Loss of compliance	7	Damage to the tank due to vehicle modification.	8	5	280
7.4	1/4 Turn Valve (Small)	E	Loss of compliance	7	Inadvertent or failure to close / difficult to use or find.	8	5	280
1.6	Valve - Fill 1/4 Face Seal	G	Large gas release	9	Form ice in the fill process, causing a restriction preventing the valve from closing.	6	5	270
4.14	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Premature activation of PRD.	6	5	270
5.26	Fuel Tank	F	Loss of crashworthiness	9	Use beyond service life.	6	5	270
18.35	CNG fuel to engine	D	Driveability and performance	5	Wear of intake valve seats.	10	5	250
4.11	Electric Tank Valve/Lockoff/PRD	D	Driveability and performance	5	Intermittent function.	6	8	240
5.28	Fuel Tank	E	Loss of compliance	7	Improper venting / service.	4	8	224
14.3	Gas Ring / Adapter	E	Loss of compliance	7	Internal leakage.	6	5	210
4.12	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	10	Slow response of PRD leading to failure to protect tank from overpressurization in a fire.	4	5	200
4.16	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	10	PRD failure to activate in fire.	4	5	200
5.11	Fuel Tank	H	Sudden high pressure failure	10	Overpressurization.	10	2	200
5.14	Fuel Tank	H	Sudden high pressure failure	10	Handling damage.	10	2	200

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

18.54	Internal corrosion of components (other than tank)	H	Sudden high pressure failure	10	Corrosion of internal high pressure components results in unexpected high pressure release.	4	5	200
18.7	Electrical connectors	D	Driveability and performance	5	Failure to properly mate connections during manufacturing or service.	8	5	200
5.19	Fuel Tank	H	Sudden high pressure failure	10	Inherent defect in the material and construction.	6	3	180
4.5	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	External leak.	10	2	180
5.8	Fuel Tank	G	Large gas release	9	Fire external to the vehicle.	10	2	180
18.4	O-rings/face seal	G	Large Gas Release	9	Improper torque at assembly	4	5	180
5.16	Fuel Tank	F	Loss of crashworthiness	9	Handling damage.	10	2	180
5.18	Fuel Tank	G	Large gas release	9	Inherent defect in the material and construction.	6	3	162
5.17	Fuel Tank	F	Loss of crashworthiness	9	Inherent defect in the material and construction.	6	3	162
5.1	Fuel Tank	H	Sudden high pressure failure	10	Accident, collision.	8	2	160
5.2	Fuel Tank	H	Sudden high pressure failure	10	Stress corrosion cracking.	8	2	160
5.6	Fuel Tank	H	Sudden high pressure failure	10	Corrosion, external.	8	2	160
18.26	CNG service-to-system	H	Sudden high pressure failure	10	Failure to follow proper procedures for tank installation.	2	8	160
18.17	Customer-to-system	C	Vehicle inoperative	8	Customer fails to fill gasoline tank.	10	2	160
4.17	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	10	PRD failure to activate as designed during overfilling.	3	5	150

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

10.8	Low Pressure Valve	D	Driveability and performance	5	Intermittent function.	6	5	150
13.1	GMS/MCV Assy	D	Driveability and performance	5	Internal leak.	6	5	150
14.2	Gas Ring / Adapter	D	Driveability and performance	5	Internal leakage.	6	5	150
15.2	Engine Control Unit	D	Driveability and performance	5	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open.	6	5	150
2.18	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.27	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.36	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.45	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
2.9	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Absence of label leads to servicing injury.	8	2	144
4.2	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Failure of PRD to open.	8	2	144
4.7	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Freeze-up, leaving valve open.	8	2	144
5.5	Fuel Tank	G	Large gas release	9	Corrosion, external.	8	2	144
5.7	Fuel Tank	G	Large gas release	9	Fire in the system, vehicle fire.	8	2	144
18.23	CNG service-to-system	G	Large gas release	9	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	144

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

18.25	CNG service-to-system	G	Large gas release	9	Failure to follow proper procedures for tank installation.	2	8	144
5.12	Fuel Tank	F	Loss of crashworthiness	9	Stress corrosion cracking.	8	2	144
18.24	CNG service-to-system	F	Loss of crashworthiness	9	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	144
13.4	GMS/MCV Assy	E	Loss of compliance	7	Soft failure of sensing element.	10	2	140
18.36	CNG fuel to engine	E	Loss of compliance	7	Wear of intake valve seats.	10	2	140
4.15	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	PRD failure to activate in fire.	3	5	135
6.3	Fuel Sending Unit	C	Vehicle inoperative	8	Failure of the electronics.	8	2	128
18.19	CNG service-to-system	C	Vehicle inoperative	8	Failure to follow proper procedures for electrical system.	2	8	128
1.1	Fill Nozzle	B	Leakage (non-injury)	2	Driving away from filling station while fill nozzle is still attached.	8	8	128
5.20	Fuel Tank	E	Loss of compliance	7	Inherent defect in the material and construction.	6	3	126
5.13	Fuel Tank	H	Sudden high pressure failure	10	UV damage of the composite, leading to degradation.	6	2	120
5.30	Fuel Tank	H	Sudden high pressure failure	10	Thermal shock: hot tank filled with cold fuel.	6	2	120
5.33	Bracket, Tank	H	Sudden high pressure failure	10	Component breakage leading to tank becoming dislodged.	6	2	120
15.6	Engine Control Unit (Crank, oxygen, air mass, coolant, MAT sensors)	E	Loss of compliance	7	Loss of sensors (engine), data.	8	2	112
18.21	CNG service-to-system	E	Loss of compliance	7	Failure to follow proper procedures for electrical system.	2	8	112

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

18.50	Vehicle manufacturer controller to CNG system integrator controller	E	Loss of compliance	7	Loss of fuel mode communication between the two fuel controllers, resulting in DTCs and miscellaneous calibration issues.	8	2	112
8.6	HPR-3600 Assembly	G	Large gas release	9	Venting at high pressure under static conditions.	6	2	108
2.15	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.24	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.33	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.42	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
2.6	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Failure of O-Ring.	6	2	108
5.15	Fuel Tank	F	Loss of crashworthiness	9	UV damage of the composite, leading to degradation.	6	2	108
5.34	Bracket, Tank	F	Loss of crashworthiness	9	Component breakage leading to loss of crashworthiness.	6	2	108
3.4	Hose - Vent Tube, Neoprene	B	Large gas release	9	Vent tube hose becomes disconnected or torn, resulting in exhaust gas entering the passenger compartment. If ignited, results in combustion.	6	2	108
4.13	Electric Tank Valve/Lockoff/PRD	H	Sudden high pressure failure	10	Mechanical binding of PRD leading to failure to protect tank from overpressurization in a fire.	2	5	100
5.4	Fuel Tank	H	Sudden high pressure failure	10	Corrosion, internal.	2	5	100

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

13.3	GMS/MCV Assy	D	Drivability and performance	5	Soft failure of sensing element.	IO	2	100
18.1	O-rings/face seal	B	Leakage (non-injury)	2	Surface defects on O-Ring or metal seat, internal corrosion, degradation due to storage conditions, materials/manufacturing defects, O-Ring is missing, O-Ring extrusion (design dependent), compound does not meet specification, undercured material, incorrect installation, excessive temperature conditions (age dependent).	IO	5	100
18.3	O-rings	B	Leakage (non injury)	2	Improper O-Ring (e.g. wrong material or size).	IO	5	100
2.14	Tube Assembly, Tank to Vent Box (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.23	Tube Assembly, Vent Box to FSU Tee	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.32	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.41	Tube Assembly, 1/4 Turn Valve to HPR	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.5	Tube Assembly, Fill Valve to Tank (HP)	B	Leakage (non-injury)	2	Failure of O-Ring.	6	8	96
2.16	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.25	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.34	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

2.43	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
2.7	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Vibration and thermal effects loosen connections.	2	5	90
5.3	Fuel Tank	G	Large gas release	9	Corrosion, internal.	2	5	90
2.17	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.26	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.35	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.44	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
2.8	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	2	5	90
18.53	CNG system to body structure	F	Loss of crashworthiness	9	Impact of distribution of mass on body structure durability.	2	5	90
11.5	Low Pressure Regulator Assy.	E	Loss of compliance	7	Loss of vehicle emissions compliance due to improper fueling.	6	2	84
5.31	Fuel Tank	H	Sudden high pressure failure	10	Loss of tank properties prior to PRD activation, leading to complete loss of contents in an external fire.	4	2	80
18.55	Galvanic corrosion of components	H	Sudden high pressure failure	10	Corrosion of high pressure components results in unexpected high pressure release.	4	2	80
x.5	HPR-3600 Assembly	D	Driveability and performance	5	Blockage due to contaminants in fuel.	8	2	80
15.5	Engine Control Unit (Crank, oxygen, coolant, MAT sensors)	D	Driveability and performance	5	Loss of sensors (engine), data.	8	2	80

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

18.20	CNG service-to-system	D	Driveability and performance	5	Failure to follow proper procedures for electrical system.	2	8	80
18.14	Customer-to-system	C	Vehicle inoperative	8	Customer fails to cycle gasoline fuel as recommended.	2	5	80
18.52	Vehicle manufacturer electronics to CNG system integrator electronics	C	Vehicle inoperative	8	Loss of ground, transient, results in damage to OEM component.	2	5	80
5.10	Fuel Tank	B	Leakage (non injury)	2	Abrasion.	8	5	80
11.6	Low Pressure Regulator Assy.	B	Leakage (non injury)	2	External leak.	8	5	80
18.31	Metal-to-metal seals	B	Leakage (non injury)	2	Failure to follow proper procedures.	8	5	80
18.37	Threaded connections	B	Leakage (non injury)	2	Failure due to corrosion, fatigue, overtightening; looseness.	8	5	80
5.22	Fuel Tank	A	Customer dissatisfaction	1	Water or oil build-up in the tank, leading to reduced range.	10	8	80
18.8	Customer-to-system	A	Customer dissatisfaction	1	Customer fails to properly connect filling line, hose flies off and causes injury.	10	8	80
2.48	1/4" Flex Line	G	Large gas release	9	Severed during service.	4	2	72
18.16	Customer-to-system	E	Loss of compliance	7	Customer fails to cycle gasoline fuel as recommended.	2	5	70
18.49	CNG system to OEM components in base vehicle	E	Loss of compliance	7	Effect of CNG system on base vehicle OEM environment (e.g. thermal, salt spray effects).	2	5	70
11.4	Low Pressure Regulator Assy.	D	Driveability and performance	5	Incorrect output pressure.	6	2	60
13.9	GMS/MCV Assy	D	Driveability and performance	5	Drift in set point of butterfly valve.	6	2	60
1.7	Valve - Fill 1/4 Face Seal	B	Leakage (non injury)	2	Form ice in the fill process, causing a restriction preventing the valve from closing.	6	5	60

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

13.8	GMS/MCV Assy	E	Loss of compliance	7	External leak.	1	8	56
18.48	CNG exhaust to vehicle exhaust system	E	Loss of compliance	7	Deterioration of catalytic converter or oxygen sensor.	4	2	56
13.6	GMS/MCV Assy	D	Driveability and performance	5	Interference of control valve leading to wide open condition.	2	5	50
18.15	Customer-to-system	D	Driveability and performance	5	Customer fails to cycle gasoline fuel as recommended.	2	5	50
13.2	GMS/MCV Assy	A	Customer dissatisfaction	1	Hard failure of sensing element leading to gasoline operation.	10	5	50
13.5	GMS/MCV Assy	A	Customer dissatisfaction	1	Interference of control valve leading to shut off. System defaults to gasoline.	10	5	50
18.11	Customer-to-system	A	Customer dissatisfaction	1	Customer is unable to disconnect fueling line.	10	5	50
18.34	CNG fuel to engine	A	Customer dissatisfaction	1	Wear of intake valve seats. CNG system inoperative.	10	5	50
4.3	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Failure to open (electrical cause). CNG system inoperative.	6	8	48
10.6	Low Pressure Valve	A	Customer dissatisfaction	1	Failure to open (electrical cause). CNG system inoperative.	6	8	48
15.7	Engine Control Unit	A	Customer dissatisfaction	1	Failure in circuit leading to attempt to use CNG tank when tank is empty. Inability to initially use gasoline.	6	8	48
15.8	ECU Assembly	A	Customer dissatisfaction	1	Failure in circuit leading to switching to gasoline from CNG prematurely (before complete loss of CNG). Could be due to FSU problem, incorrect fuel level indication or ECU circuit failure (input signal shorted).	6	8	48

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
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1.11	Valve - Fill 1/4 Face Seal	F	Loss of crashworthiness	9	Corrosion causes reduced crashworthiness.	1	5	45
18.40	Bracket-to-component	H	Sudden high pressure failure	10	Corrosion / collision effect on tank.	2	2	40
18.45	Bracket-to-vehicle	H	Sudden high pressure failure	10	Corrosion / collision effect on tank.	2	2	40
10.2	Low Pressure Valve	D	Driveability and performance	5	External leakage.	4	2	40
10.4	Low Pressure Valve	D	Driveability and performance	5	Seat leakage (internal).	4	2	40
4.4	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	External leak.	10	2	40
4.6	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Internal leak (due to freeze-up, due to particulates).	4	5	40
1.10	Valve - Fill 1/4 Face Seal	A	Customer dissatisfaction	1	Ice blocks the fill path, increasing fill time.	8	5	40
7.2	1/4 Turn Valve (Small)	A	Customer dissatisfaction	1	Inadvertent or failure to open / difficult to use or find.	8	5	40
7.3	1/4 Turn Valve (Small)	A	Customer dissatisfaction	1	Inadvertent or failure to close / difficult to use or find.	8	5	40
8.2	HPR-3600 Assembly	A	Customer dissatisfaction	1	Regulator freezing. CNG system inoperative.	8	5	40
16.1	Wire Harness Assembly	A	Customer dissatisfaction	1	Wires are disconnected; improperly connected; misaligned, backed-out connectors. CNG system may be inoperative.	8	5	40
16.3	Wire Harness Assembly	A	Customer dissatisfaction	1	Improper routing, wire chafing, or corrosion leading to failure. CNG system inoperative.	8	5	40

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

18.28	Vehicle service-to-CNG system	A	Customer dissatisfaction	1	Inadvertently render CNG system inoperative.	8	5	40
18.5	Electrical connectors	A	Customer dissatisfaction	1	Failure to properly mate connections during manufacturing or service. CNG system inoperative.	8	5	40
2.1	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.10	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.12	Tube Assembly, Tank to Vent Box (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.19	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.21	Tube Assembly, Vent Box to FSU Tee	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.28	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.3	Tube Assembly, Fill Valve to Tank (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.30	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
2.37	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Corrosion / fatigue of the tubing.	2	2	36
2.39	Tube Assembly, 1/4 Turn Valve to HPR	G	Large gas release	9	Failure of braze joint results in large leakage.	2	2	36
7.1	1/4 Turn Valve (Small)	G	Large gas release	9	External leak from valve components, valve breaking off.	2	2	36
8.7	HPR-3600 Assembly	G	Large gas release	9	Overstressing of regulator body due to excess torque in fittings.	2	2	36

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11.7	Low Pressure Regulator Assy.	G	Large gas release	9	Overstressing of regulator body due to excess torque in fittings.	2	2	36
18.39	Bracket-to-component	G	Large gas release	9	Corrosion / collision effect on tank.	2	2	36
18.41	Bracket-to-component	G	Large gas release	9	Corrosion / collision effect on valves, regulators.	2	2	36
18.44	Bracket-to-vehicle	G	Large gas release	9	Corrosion / collision effect on tank.	2	2	36
18.46	Bracket-to-vehicle	G	Large gas release	9	Corrosion / collision effect on valves, regulators.	2	2	36
2.11	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.13	Tube Assembly, Tank to Vent Box (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.2	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.20	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.22	Tube Assembly, Vent Box to FSU Tee	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.29	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.31	Tube Assembly, FSU Tee to 1/4 Turn Valve (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.38	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Corrosion / fatigue of the tubing.	2	2	36
2.4	Tube Assembly, Fill Valve to Tank (HP)	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
2.40	Tube Assembly, 1/4 Turn Valve to HPR	F	Loss of crashworthiness	9	Failure of braze joint results in large leakage.	2	2	36
18.38	Bracket-to-component	F	Loss of crashworthiness	9	Corrosion.	2	2	36
18.43	Bracket-to-vehicle	F	Loss ofcrashworthiness	9	Corrosion.	2	2	36

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
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9.4	Low Pressure Line (Dry Gas Hose)	B	Leakage (non injury)	2	External leak.	2	8	32
18.22	CNG service-to-system	B	Leakage (non injury)	2	Failure to follow proper procedures for fuel transfer system (e.g. failure to torque a line, leading to problem).	2	8	32
18.30	Metal-to-metal seals	B	Leakage (non injury)	2	Presence of foreign material.	8	2	32
15.1	Engine Control Unit	C	Customer dissatisfaction	1	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open. Mode does not render vehicle inoperative. Vehicle can still be driven in gasoline mode with no problem.	6	5	30
6.5	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics leading to "full" output when empty. Inability to initially use gasoline.	6	5	30
6.6	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics leading to "zero" output when full. System switches to gasoline from CNG prematurely (before complete loss of CNG). Could be due to FSU problem, incorrect fuel level indication or ECU circuit failure (input signal shorted).	6	5	30
10.5	Low Pressure Valve	A	Customer dissatisfaction	1	Valve fails to open. CNG system inoperative.	6	5	30
15.3	Engine Control Unit	A	Customer dissatisfaction	1	Failure (wire between VCM and ECU) causing both CNG and gasoline to run at the same time: NGV enable circuit- open.	6	5	30

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1.2	Fill Receptacle - O-Ring	B	Leakage (non-injury)	2	Debris in gas contaminates seal.	6	2	24
2.47	1/4" Flex Line	B	Leakage (non injury)	2	Impurity causes pin hole and resultant small leak.	6	2	24
3.2	Enclosure - Ventilation	B	Leakage (non-injury)	2	Gas is trapped in trunk (no combustion).	6	2	24
3.3	Hose - Vent Tube, Neoprene	B	Leakage (non-injury)	2	Vent tube hose becomes disconnected or torn, resulting in exhaust gas entering the passenger compartment (no combustion).	6	2	24
9.1	Low Pressure Line (Dry Gas Hose)	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections, damaged line.	6	2	24
12.2	Pipe thread fitting	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections.	6	2	24
14.1	Gas Ring / Adapter	B	Leakage (non injury)	2	External leakage.	6	2	24
5.32	Fuel Tank	H	Sudden high pressure failure	10	Combustible mixture in gas (use of high pressure air to leak test tank, followed by filling).	1	2	20
11.3	Low Pressure Regulator Assy.	D	Driveability and performance	5	Pin sticking due to contamination.	2	2	20
3.1	Enclosure - Ventilation	G	Large gas release	9	Gas is trapped in trunk and if ignited results in combustion.	1	2	18
4.9	Electric Tank Valve/Lockoff/PRD	G	Large gas release	9	Corrosion.	1	2	18
6.1	Fuel Sending Unit	G	Large gas release	9	Fatigue, corrosion (external and internal).	1	2	18
8.1	HPR-3600 Assembly	G	Large gas release	9	Rupture.	1	2	18
11.1	Low Pressure Regulator Assy.	G	Large gas release	9	Rupture.	1	2	18
12.4	Intermediate Pressure Line	G	Large gas release	9	Severed or disconnected line.	1	2	18
12.3	Intermediate Pressure Line	F	Loss of crashworthiness	9	Vibration and thermal effects loosen connections.	1	2	18

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
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1.9	Fill Receptacle - Poppet Seal	B	Leakage (non injury)	2	Damage to poppet seal by gas stream/contaminants.	4	2	16
2.49	1/4" Flex Line	B	Leakage (non injury)	2	Severed during service.	4	2	16
IO.1	Low Pressure Valve	B	Leakage (non injury)	2	External leakage.	4	2	16
13.7	GMS/MCV Assy	B	Leakage (non injury)	2	External leak.	1	8	16
4.1	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Failure of PRD to open.	8	2	16
4.10	Electric Tank Valve/Lockoff/PRD	A	Customer dissatisfaction	1	Freeze-up, causing a restriction or valve closure. CNG system inoperative.	8	2	16
6.2	Fuel Sending Unit	A	Customer dissatisfaction	1	Failure of the electronics.	8	2	16
8.4	HPR-3600 Assembly	A	Customer dissatisfaction	1	Blockage due to contaminants in fuel.	8	2	16
9.2	Low Pressure Line (Dry Gas Hose)	A	Customer dissatisfaction	1	Severed or disconnected line. CNG system inoperative.	2	8	16
15.4	Engine Control Unit (Air mass sensor)	A	Customer dissatisfaction	1	Loss of sensors (engine), data. CNG system inoperative.	8	2	16
18.18	CNG service-to-system	A	Customer dissatisfaction	1	Failure to follow proper procedures for electrical system.	2	8	16
18.51	Vehicle manufacturer controller to CNG system integrator controller	A	Customer dissatisfaction	1	Loss of fuel mode communication between the two fuel controllers, resulting in DTCs and miscellaneous calibration issue. CNG system inoperative.	8	2	16
2.46	1/4" Flex Line	A	Customer dissatisfaction	1	Impurity causes pin hole and resultant small leak.	6	2	12
8.3	HPR-3600 Assembly	A	Customer dissatisfaction	1	Shut off: filter clogs or sleeve cold flow. CNG system inoperative.	6	2	12

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

16.2	Wire Harness Assembly	A	Customer dissatisfaction	1	Inadequate circuit protection leading to thermal incident. CNG system inoperative.	6	2	12
18.33	CNG components to heater	D	Driveability and performance	5	Degradation of engine's coolant affecting heat transfer capacity of the high pressure regulator.	1	2	10
1.3	Housing - Fill Valve Mounting	B	Leakage (non injury)	2	Potential for failure of part resulting in leakage.	1	5	10
1.5	Gasket - Fill Valve Housing	B	Leakage (non injury)	2	Damaged gasket and leaking line.	1	5	10
4.18	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Thermal shock, leading to external leak (see tank).	1	5	10
10.7	Low Pressure Valve	B	Leakage (non injury)	2	Corrosion.	1	5	10
1.12	Cap, Dust	A	Customer dissatisfaction	1	Absence of dust cap can cause filter blockage; can be inconvenient to use in winter.	2	5	10
18.13	Customer-to-system	A	Customer dissatisfaction	1	Customer fails to cycle gasoline fuel as recommended.	2	5	10
18.42	Bracket-to-component	A	Customer dissatisfaction	1	Vibration.	2	5	10
18.47	Bracket-to-vehicle	A	Customer dissatisfaction	1	Vibration.	2	5	10
6.4	Fuel Sending Unit	A	Customer dissatisfaction	1	Mechanical failure / blockage. System defaults to gasoline.	4	2	8
10.3	Low Pressure Valve	A	Customer dissatisfaction	1	Seat leakage (internal).	4	2	8
4.8	Electric Tank Valve/Lockoff/PRD	B	Leakage (non injury)	2	Corrosion.	1	2	4

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
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12.1	Intermediate Pressure Line	B	Leakage (non injury)	2	Vibration and thermal effects loosen connections.	1	2	4
11.2	Low Pressure Regulator Assy.	A	Customer dissatisfaction	1	Shut off due to primary pin sticking from contamination. CNG system inoperative.	2	2	4
1.4	Housing - Fill Valve Mounting	A	Customer dissatisfaction	1	Bent mounting causing improper fit with fill nozzle.	1	2	2
12.5	Intermediate Pressure Line	A	Customer dissatisfaction	1	Severed or disconnected line. CNG system inoperative.	1	2	2
16.5	Wire Harness Assembly	A	Customer dissatisfaction	1	Incorrect routing increasing propensity for damage during service, i.e. damage from sheet metal screw. CNG system inoperative.	1	2	2
5.21	Fuel Tank	G	Large gas release	9	ESD bums hole in liner.	0	5	0
9.3	Low Pressure Line (Dry Gas Hose)	G	Large gas release	9	Gas hose melts in fire, gas continues to be supplied.	0	N/A	0
16.6	Wire Harness Assembly	D	Driveability and performance	5	Voltage spikes. Relays improperly sized.	*	*	•
16.11	Wire Harness Assembly (Ignition relay)	C	Vehicle inoperative	8	Failure in ignition relay.	*	*	[illegible]
18.2	O-rings	B	Leakage (non-injury)	2	Failure of O-Ring due to combination of low temperature (< -65 "C) and stress- directly after HPR.	*	*	[illegible]
16.10	Wire Harness Assembly (Lock-off relay)	A	Customer dissatisfaction	1	Failure in lock-off relay: fails closed. CNG system inoperative.	*	*	[illegible]
16.7	Wire Harness Assembly	A	Customer dissatisfaction	1	Voltage spikes. Relays improperly sized.	*	*	[illegible]

* Adequate information and associated MN, OC, and RPN indices were not provided by the manufacturer or supplier by the freeze date for this document analysis and production.

Failure Modes and Effects Analysis for CNG-Fueled Vehicles
Risk Scenarios Sorted by Risk Priority Number (RPN)

16.8	Wire Harness Assembly (Fuel gauge relay)	A	Customer dissatisfaction	I	Failure in fuel gauge relay- doesn't indicate fuel level	*	*	*
16.9	Wire Harness Assembly (Fuel pump relay)	A	Customer dissatisfaction	1	Failure in fuel pump relay. CNG system inoperative.	*	*	*

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