Reliability Analysis Technique Comparison, as Applied to the Space Shuttle

AE 8900 OLD – Special Topic

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LIST OF ACRONYMS

APU	Auxiliary Power Unit
EAFB	Edwards Air Force Base
ET	External Tank
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
FTA	Fault Tree Analysis
KSC	Kennedy Space Center
LOV	Loss of Vehicle
MEIDEX	Mediterranean-Israeli Dust Experiment
NASA	National Aeronautics and Space Agency
PRA	Probabilistic Risk Assessment
RCC	Reinforced Carbon-Carbon
RLV	Reusable Launch Vehicle
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TPS	Thermal Protection System

1. Introduction

With the events of the Columbia Space Shuttle accident and all of the investigation and speculation that followed, safety and reliability have become much more focused upon in the space industry. To this day, even with technology growing and advancing as it has, there has not been a single reliability analysis technique developed to perfectly model any advanced system, especially a system as complex as the Space Shuttle. All methods currently used have many advantages, along with several faults inherent in each technique.

Within the reliability community there are several different methods that are used, and there is no consensus of which is the best method to use. Even when determining the best method, there are many criteria that could be used to make this distinction. Whether it be the easiest to use, the most accurate to represent a complex model, the fastest computational tool, the most simplified method, or an array of other measures of which analysis is "best", there is no clear-cut favorite for most of these. The most widely used method of reliability analysis within the Aerospace Engineering community is Fault Tree Analysis (FTA), which is good for modeling complex systems in that it is a relatively simple method. However, many say FTA is too simplified and unable to accurately model complex systems for several reasons.[1]

2. The Space Shuttle

Human space flight began on April 12th, 1961, when cosmonaut Yuri Gagarin was launched into orbit aboard the Vostok 1. This was accomplished in the midst of the space race in which the former Soviet Union and the United States were constantly competing and trying to better one another in the area of human space travel. The space race has often been credited with helping to advance the technologies involved, and propel space travel forward at an incredible rate that would not have been possible otherwise.

Figure 2.1 – Launch of Apollo 11.

The National Aeronautics and Space Agency (NASA) was constantly looking to the future during this time. During the height of the Apollo program in the late 1960s NASA was concurrently probing its next possible major human spaceflight efforts. (Figure 2.1

shows the launch of Apollo 11 aboard a Saturn V booster.) In January 1972, President Richard Nixon declared that NASA would begin development of a Space Transportation System (STS), more commonly known as the Space Shuttle.[2]

The idea behind the Space Shuttle was to provide relatively inexpensive, frequent access to space through the use of a reusable launch vehicle (RLV). NASA had envisioned the use of a fully reusable vehicle in order to keep the trip costs at a minimum, with visions of space stations in orbit around the Earth, as well as in lunar orbit and eventually on the lunar surface. When it was realized that these visions of future use and exploration were infeasible, NASA aimed to justify the Space Shuttle on economic grounds, projecting that through the combination of military, commercial, and scientific payloads, the Space Shuttle could be flown for 50 missions a year. However, many of the commitments made by NASA during the policy process lead to a design aimed at satisfying many conflicting requirements. The goals were a vehicle capable of carrying large payloads and cross-range capability, but with low development costs and an even lower operating cost. The result of all of this conflict within the design requirements has been a vehicle that is very costly and difficult to operate, and is much riskier than was originally anticipated.[3]

Once completed, the Space Shuttle was subjected to a vast array of tests well before its first flight. But unlike with the other spacecraft NASA had operated, the Space Shuttle was tested much differently. The philosophy of the Space Shuttle Program was to ground-test key hardware elements, such as the Solid Rocket Boosters (SRB), the External Tank (ET), the Orbiter, and the Space Shuttle Main Engines (SSME) separately.

Then analytical models were used to certify the integrate Space Shuttle System, as opposed to the flight testing that had been used with previous spacecrafts. Even though crews verified that the Orbiter could successfully fly at low speed and land safely, the Space Shuttle was not flown on an unmanned orbital test prior to its first mission, which was contrary to the philosophy of earlier American spaceflight.[4]

Figure 2.2 – Columbia during re-entry on STS-1.

The Space Shuttle also depended highly on significant advances in technology, which cause the development to run well behind schedule. The original launch date for the Shuttle's first launch was in March of 1978, but due to many delays it was pushed back several times, finally being set for April of 1981. An historian described the problems by attributing one year of delays "to budget cuts, a second year to problems with the main engines, and a third year to problems with the thermal protection system."[5] A review by the White House was taken in order to ensure that the Space Shuttle was still worth continuing in 1979, but this need was reaffirmed and the door was now open to transition from development to flight. In addition, despite the fact that only 24,000 of 30,000 Thermal Protection System (TPS) tiles had been attached, NASA decided to move Columbia to the Kennedy Space Center (KSC) from the manufacturing plant in Palmdale California in order to maintain the image that it would be capable of meeting its scheduled launch date.[4]

The first Space Shuttle mission, STS-1, was successfully launched on April 12, 1981, and returned safely two days later to Edwards Air Force Base (EAFB) in California. It is shown during its re-entry in Figure 2.2. The next 3 missions were all launched over the following 15 months aboard the orbiter Columbia as well, undergoing extensive testing and inspection following each one. At the end of its fourth mission, Columbia landed at EAFB on July 4, 1982, where President Ronald Reagan declared that "beginning with the next flight, the Columbia and her sister ships will be *fully operational*, ready to provide *economical and routine access to space* for scientific exploration, commercial ventures, and for tasks related to national security."[3] From 1982 to early 1986 the Space Shuttle demonstrated its capabilities for space operations. It flew science missions with the European-built Spacelab module in its payload bay, retrieved two communications satellites that had suffered upper-stage misfires, and repaired another communications satellite on-orbit. In 1985, between the four orbiters in use nine missions were launched, and by the end of the year 24 communications satellites had been put into orbit, with a backlog of 44 more orders for future commercial launches. Although it seemed to the public that things were progressing well, the facts were that the system was much more difficult to operate than expected, with more maintenance between flights than anticipated. Rather than requiring the 10 working days projected in 1975, by the end of 1985 it was taking an average of 67 days to process a returned Orbiter for its next flight.[4]

2.1 The Challenger Accident

The image that the Space Shuttle was an operational and safe system was abruptly shattered on the morning of January 28, 1986, when Challenger was destroyed 73 seconds after liftoff during STS-51-L, killing all seven crew members aboard as seen in Figure 2.3. A thirteen member Presidential Commission was appointed immediately to investigate the Space Shuttle Challenger Accident immediately following the disaster that had occurred. Early on in this investigation period of this Presidential Commission, otherwise known as the Rogers Commission after its chairman William P. Rogers, the mechanical cause of the accident was identified to be the failure of the joint (also known as an "O-ring") of one of the SRBs. However, when the Rogers Commission learned that on the eve of the launch of Challenger's last flight, NASA and a contractor had been debating the decision to operate the Space Shuttle in the cold temperature predicted for the next day, it shifted the focus of its investigation to "NASA management practices, Center-Headquarters relationships, and the chain of command for launch commit decisions."[3]

The Rogers Commission stated that the decision to launch the Challenger on that day was flawed, because those who made the decision were unaware of the problems encountered concerning the O-rings and the joint. They also did not know of the written recommendation of the contractor advising against the launch at temperatures below 53 degrees Fahrenheit, as well as the continuing opposition of the engineers after the management reversed its decision. Among the many conclusions of the Rogers Commission was the idea that there was a serious decision making process flaw, and that had there been a "well structured and managed system emphasizing safety" the rising doubts on the SRB

Figure 2.3 – Challenger immediately after the explosion of the SRB.

joint would have been flagged. Had something like this been in place, it seems likely that the launch of STS-51-L would not have occurred when it did. It appeared to the Commission that a waiving of launch constraints had been entirely at the expense of flight safety. The final recommendations of the Commission included suggestions concerning design, landing safety, launch abort and crew escape, and other physical Shuttle characteristics, as well as things like improved communications and the Shuttle management structure.[6]

2.2 The Columbia Accident

After the Challenger disaster, it took NASA 32 months before it was ready and confident enough to launch the next Space Shuttle mission. However, over the next fourteen years, with the completion of 87 successful missions public confidence in the Space Shuttle had returned to a level near what it had been previous to the Challenger accident. Unfortunately everything would change with the 113th mission of the Space Shuttle Program. STS-107 was the 28th flight of Columbia, and was finally launched on January 16, 2003 after more than two years of delays (most of which were attributed to other missions taking higher priority). STS-107 is shown immediately after liftoff in Figure 2.4.

Figure 2.4 – STS-107 being launched from KSC.

As is done with every launch that occurs, the Intercenter Photo Working Group examined video from the tracking cameras used to observe the launch. After obtaining video with higher resolution the day after the launch, a debris strike was noticed that occurred 81.9

seconds after launch. It was seen that a large object from the ET struck the Orbiter, impacting the underside of the left wing, near the reinforced carbon-carbon (RCC) leading edge TPS panels 5 through 9. Since the possible damage that may have resulted was not able to be examined by the views captured by the tracking cameras, a Debris Assessment Team was formed to conduct a review, which resulted in the request for imaging of the wing on-orbit so that better information could be used to base the analysis on. However, these requests were denied by the Johnson Space Center Engineering Management Directorate, and the Team was restricted to the use of a mathematical modeling tool known as

Figure 2.5 – Columbia starts breaking up upon re-entry.

Crater to assess any damage that may have been sustained due to the impact. The Debris Assessment Team concluded that some localized heating damage would most likely occur during re-entry, but could not speak to the probability of any structural damage that might be experienced. With these analysis results relayed to the Mission Management Team by a manager who had been given the presentation by the Debris Assessment

Team, it was decided that the debris strike was not worthy of the pursuit of more on-orbit imagery, and was ultimately a "turnaround" issue.[3]

Columbia was in orbit for 17 days, and actually observed a moment of silence to honor the memory of the men and women lost in the Apollo 1 and Challenger accidents on January 28, 2003. The crew also performed several duties, including a joint U.S./Israeli experiment, the Mediterranean-Israeli Dust Experiment (MEIDEX), among many other research duties. At 8:15 a.m. EST on the morning of February 1, 2003, Columbia executed its de-orbit burn and began its reentry into the Earth's atmosphere. Everything was going as planned, and sensors showed no signs of a problem, but when the Orbiter was spotted over California, observers on the ground saw signs of debris being shed when a noticeable streak in the Orbiter's trail. It was caused by the superheated air surrounding the Orbiter, and was witnessed four more times over the next 23 seconds by observers. One example of what was seen is in the amateur photo of Columbia starting to break up in Figure 2.5. The first sign at Mission Control that something might be going wrong was when four hydraulic sensors in the left wing had failed. The last communication with the crew of STS-107 was a broken response at 8:59, and videos by observers on the ground shot at 9:00 a.m. showed that the Orbiter was disintegrating. At 9:16 a.m. EST, NASA executed the Contingency Action Plan that had been established after the Challenger accident. With this, the emergency response was initiated, and a debris search recovery effort was started. When all was said and done 25,000 people from 270 organizations were involved in the debris recovery operations, resulting in the finding of more than 84,900 pounds of debris, representing only 38% of the Orbiter's dry weight.[3]

2.3 Investigation Board Findings and Suggestions

The physical cause of the Columbia disaster and the loss of its crew was a breach in the left wing leading edge TPS, initiated by a piece of insulating foam that separated from the ET and struck the left wing during launch. Upon re-entry, superheated air penetrated the leading edge insulation, progressively melting the left wing aluminum structure and resulting in a weakening of the structure. This increased until resulting aerodynamic forces caused loss of control, failure of the wing, and ultimately breakup of the Orbiter.[3]

The organizational causes for this accident were much more disturbing to the Investigation Board than were the physical ones. They were determined to be rooted in the Space Shuttle Program's history and culture, including compromises required to gain approval for the Shuttle Program more than 30 years before the accident occurred. It was also credited to "years of resource constraints, fluctuating priorities, schedule pressures, mischaracterizations of the Shuttle as operational rather than developmental, and lack of an agreed national vision."[3] Finally, it was stated that the development and acceptance of both cultural traits and organizational practices detrimental to safety and reliability were a main cause of all problems that had been encountered throughout the Space Shuttle Program.[3]

3. Reliability Analysis Techniques

For as long as technology has allowed us to create complex systems, a challenge inherent to these systems is the problem of analyzing and predicting how reliable they are. In the advancement of technology and the modification and improvement of these complex systems, one goal has always been to make them safer and more reliable. But in order to do this we must first understand these systems and find a way to determine which parts contribute the most to the risk involved with their use. For a long time, this was done merely by approximation and use of existing data. However, in recent history many techniques have been developed and refined in order to more accurately represent these complex systems. Both qualitative and quantitative methods have been developed to analyze complex systems, and there are constantly more being researched, especially in the academic community. Some are used more widely than others, while some are developed primarily for one specific application, but all techniques have their advantages and disadvantages.

3.1 Qualitative Techniques

Qualitative reliability analysis methods have always been used to help identify all possible failures that could occur within a system, and the general risks associated with each of those failures. The most widely used qualitative method is failure modes and effects analysis (FMEA), sometimes also known as failure modes, effects and criticality analysis (FMECA). The purpose of FMEA is to review a system in terms of its subsystems, assemblies, and so on, down to the component level, in order to identify all of the causes and modes of failure and the effects of these failures. This is generally done by identifying the five following characteristics: how each part can possibly fail, what might produce these failure modes, what could be the effects of these failures, how can the failures be detected, and what provisions are provided to compensate for this failure in the design.[1]

FMEA can be completed either on an existing system or during the design phase, and its application at different phases fulfills various objectives. For instance, when performed during the design phase, it can help to select design alternatives with high safety and reliability potential. It can also assist in developing early criteria for test planning, which can help provide a basis for any quantitative reliability analysis that would be performed. No matter when it is performed, FMEA ultimately strives to list all potential failures and identify the magnitude of their effects.[1]

3.2 Quantitative Techniques

There are several methods of quantitative reliability analysis techniques, with various theories behind them. The three that are most widely used are fault tree analysis (FTA), reliability block diagrams (RBD), and Markov analysis (MA). As will be discussed, all three of these methods are best for different situations, and all have their inherent pros and cons. Quantitative analysis aims to use knowledge of how a system works, often gained from previously completed qualitative assessments, and apply information about failure rates, probabilities, characteristics, and so on to this knowledge in order to gain more knowledge of subsystems or the system as a whole. The information concerning failure rates, distributions, or probabilities can be gained in a variety of ways, but the most accurate is always through test and flight data. However, when this data is not available, or sufficient data does not exist, a variety of theories can be applied to hypothesize and predict the failure characteristics of a component or subsystem. Then, depending on which analysis method is used, the outcome is some form of failure data of the system, and can be used to perform a range of tasks, the most obvious being to identify the largest risk contributors in a system in order to improve them and consequently reduce the risk the system undergoes.[1]

3.2.1 Fault Tree Analysis

The concept of FTA was developed in 1962 by Bell Telephone Laboratories for the U.S. Air Force for use with the Minuteman system. A fault tree is a logic diagram that shows potential events that might affect system performance, and the relationship between them and the reasons for these events. Failure of one or more components of the system are not the only possible causes however. The reasons also include environmental conditions, human errors, and other factors.[7]

A fault tree helps to illustrate the state of a system, otherwise denoted as the top event, in terms of the states of the system's components, otherwise denoted as basic events. A top event can be connected to lower events through gates. The two gates that form the building blocks for the other (more complicated, less used) gates are the "OR" gate and the "AND" gate. The "OR" gate symbolizes that the output event will occur if any of the input events occur. The "AND" gate means that the output even will occur only if all of the input events occur. These are the only two gates that were originally used when fault

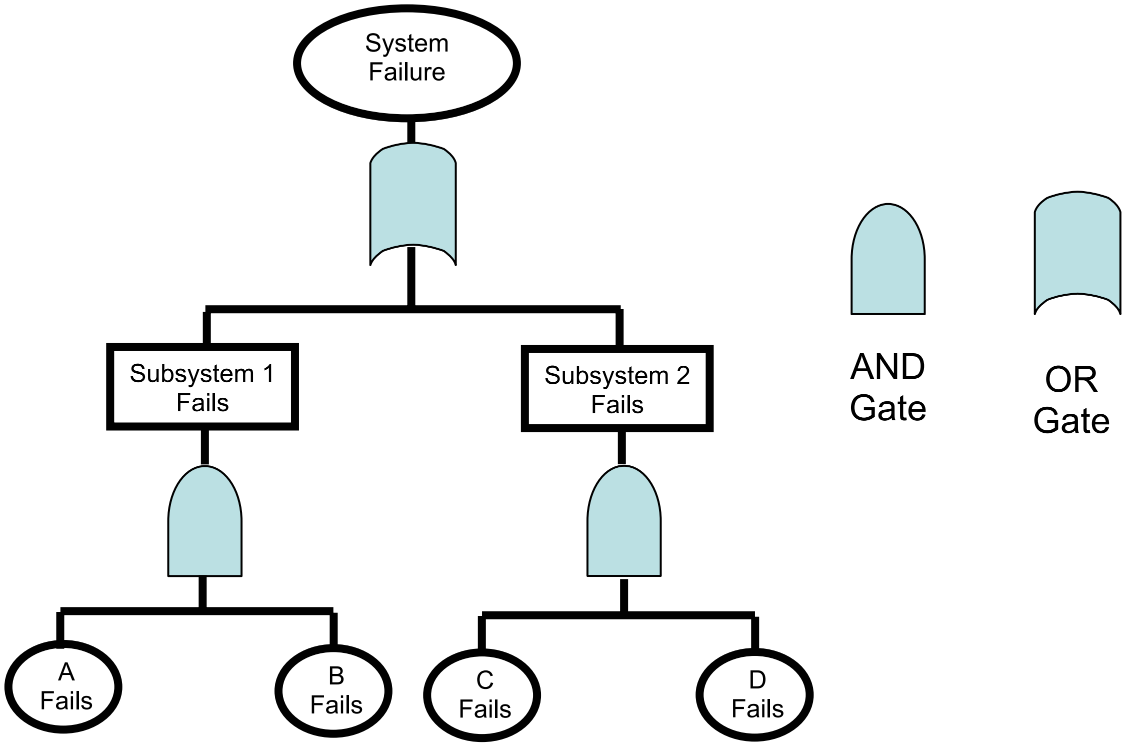


Figure 3.1 – Sample FTA.

trees were developed, but since then many more types of gates have been created to fit specific needs (such as Inhibit gates, Priority AND gates, Exclusive OR gates, and k-out-of-n gates).[1]

3.2.2 Reliability Block Diagram

A system reliability can be predicted by looking at the reliabilities of the components that make up the entire system. In order to do this, a configuration must be predetermined that accurately represents the logic behind the reliability of the system. This action is similar to determining what types of gates to use in a fault tree. However, in the case of RBDs, a top-down approach is used as well, so at the end of this composition the sum of the components must accurately represent the whole system. The two basic structures employed in RBD that coincide with the two gates mostly used in FTA are the series and parallel configurations. A sample RBD can be seen in Figure 3.2. A set of blocks in series is the equivalent of a set of events connected by an "OR" gate, while a set of blocks in parallel is the RBD equivalent of a set of events all under the same "AND" gate. Similarly, just as in FTA, blocks can be connected through sets of series and parallel connections in order to accurately represent a system. In addition, there are many other types of connections (such as the k-out-of-n, or the bridge structure) that can be used to form the block diagrams for more complex systems.[7]

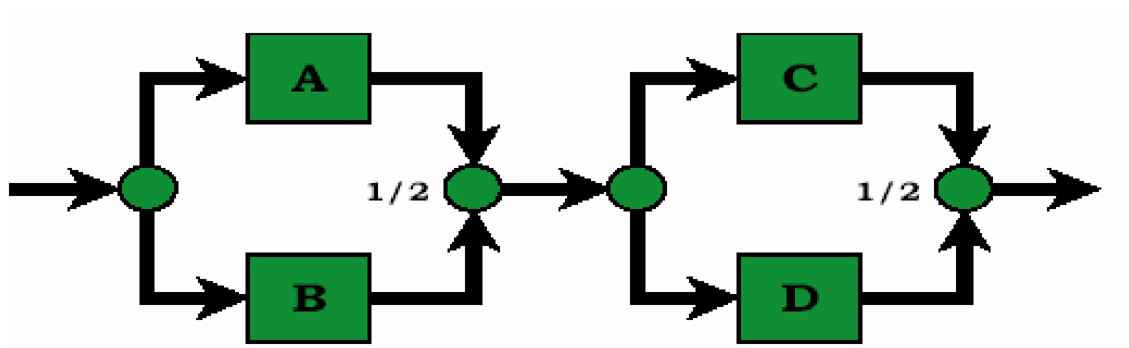


Figure 3.2 – Sample RBD of a series of two sets of two parallel gates.

3.2.3 Markov Analysis

Markov analysis is different from the others described previously in that it is a dynamic, state-space analysis. This means that the state of the system is what is modeled, and not the probability of specific events occurring. Each system state represents a set of local states, meaning that a state can represent when all of the components are functioning, when one specific component has failed, when another has failed, when two have failed, and so on until every possible global state is represented. In addition, there are transitions that exist between many of these states, depending on the nature of the system, and each is given a failure rate that is assumed to be constant. For instance, Figure 3.3 shows a system of two identical components (A and B), both of which can be functioning or failed at any time, independent of what state each other is currently in, with a failure rate of each component of λ and repair rate of α. This means that there can be four possible global states: both are working, A is working and B is failed, B is working and A is failed, and both have failed. As can be seen there is then a failure rate associated with each transition between states. Since this is a repairable system there can also be transitions from failed states back to working states with given constant rates as well. (There is no transition directly from the state where both are working to the state where both have failed because it is theoretically impossible for two independent components to fail simultaneously.)[8]

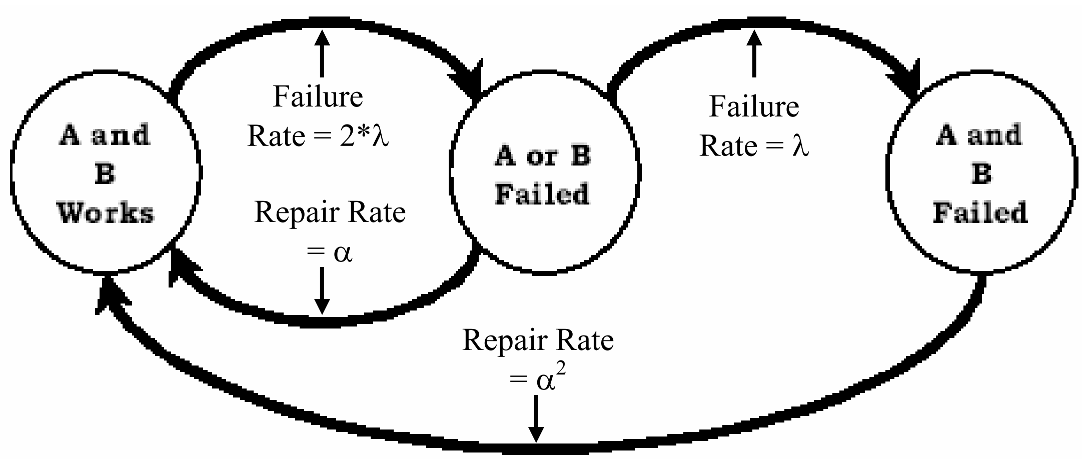


Figure 3.3 – Sample Markov Chain.

The qualities inherent to MA give it many distinct advantages and disadvantages. The major advantage comes from it being a dynamic analysis. This allows MA to be representative of the system at any given time using just one model. It also gives an illustration of the state of every component or subsystem at any given time in the analysis. However, since MA is a state-space analysis as opposed to an event-based analysis (like FTA or RBD) the models can get incredibly large very quickly. This is because when developing a MA model, every single possible state must be considered, which makes the model as well as the analysis very complicated. When modeling a very complex system, this can get completely out of hand very quickly, which is one of the large reasons that MA is not commonly used for very complex systems. Another disadvantage is that MA is limited to the use of constant failure rates for the transitions. Although MA is widely used for systems where constant failure rates can be applied, this does not accurately represent most components or subsystems, and therefore makes the accuracy of the results gained from MA highly questionable.[8]

3.2.4 Petri Nets

A Petri Net is another dynamic method of reliability analysis that is not used nearly as much as the other methods previously discussed. A Petri Net is actually a general-purpose mathematical tool mostly used for describing relations existing between conditions and events, which is the major reason that it is starting to lend itself towards reliability analysis. In the case of reliability analysis, there are a number of places representing all of the possible states that whatever is being modeled could be in. A token, which could represent a number of things (including, but not limited to, a component, assembly, or subsystem) would be located in any one of these places, which would identify the current state of whatever that token represents. In addition, there are transitions (either instant or timed) between many of these places according to the physics of the system, and a token will move from one place to another according to the transitions connecting the many places represented in the Petri Net. Petri Nets, just like any other reliability analysis technique, have had much more details and options added to them that help to more accurately model a larger range of systems, but those are the basics behind the method. Figure 3.4 is an example of a simple Petri net, with a legend denoting the items involved. One can see how this approach might become complicated rather quickly with a growing model.[9]

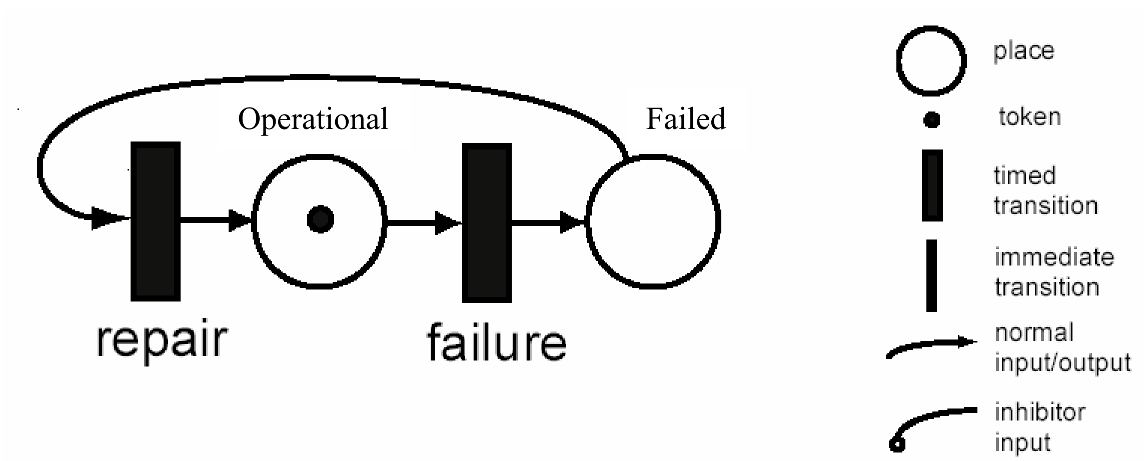


Figure 3.4 – Sample Petri Net.

Similarly to MA, the use of Petri Nets is advantageous because it represents the state of one or many components (or systems), and therefore is more representative of what it is modeling over time. Also, since this method is not limited to constant failure rates, it can sometimes more accurately denote the actions of a system than can MA. However, since it is a state-space analysis, it tends to get incredibly large and hard to work with as the model it represents gets more complex and complicated. Between this and the fact that it is not very well known to begin with, it is rarely used as a reliability analysis method with the exception of its application to simple models.[9]

Table 3.1 shows a comparison of the different approaches to reliability analysis, and a summary of some of the important characteristics of the methods discussed.

Table 3.1 – Comparison of Reliability Analysis Method Characteristics.

Characteristics	FTA	RBD	MA	Petri Nets
Static	X	X		
Dynamic			X	X
Logic-based	X	X		
State-space			X	X
Top-down	X	X		
Variable distributions	X	X		X

4. Space Shuttle Analyses

With such a complex system as the Space Shuttle, there is no technique that can perfectly model the reliability of the entire system. Knowing the advantages and disadvantages of all available techniques, engineers and researchers must sacrifice many things in order to do a complete analysis of the system. After the Challenger disaster in 1986, engineers set out to perform the first complete reliability analysis of the Space Shuttle.

4.1 SAIC Probabilistic Risk Assessment (PRA)

When NASA decided to compose a reliability analysis of the Space Shuttle, the first choice was which technique to use. When SAIC was contracted to perform this analysis, the tool they were using was a FTA tool (CAFTA), so the next problem was the break down the functions of the Shuttle to complete this FTA.[10] It was necessary to start at the highest level of complexity, and break each event down into the functions that were necessary to complete that event. From there, each of those functions needed to be broken down, and so on until the entire analysis was dependent upon only basic events that could not be further simplified. The highest level FTA for loss of vehicle (LOV) from this PRA can be seen in Figure 4.1, where the events with circles below them are basic events, and the triangles are references to other pages and other locations in the fault tree. The probability of each event can be seen underneath the box that describes each one, and to the right of the gate/event associated with that event.[10]

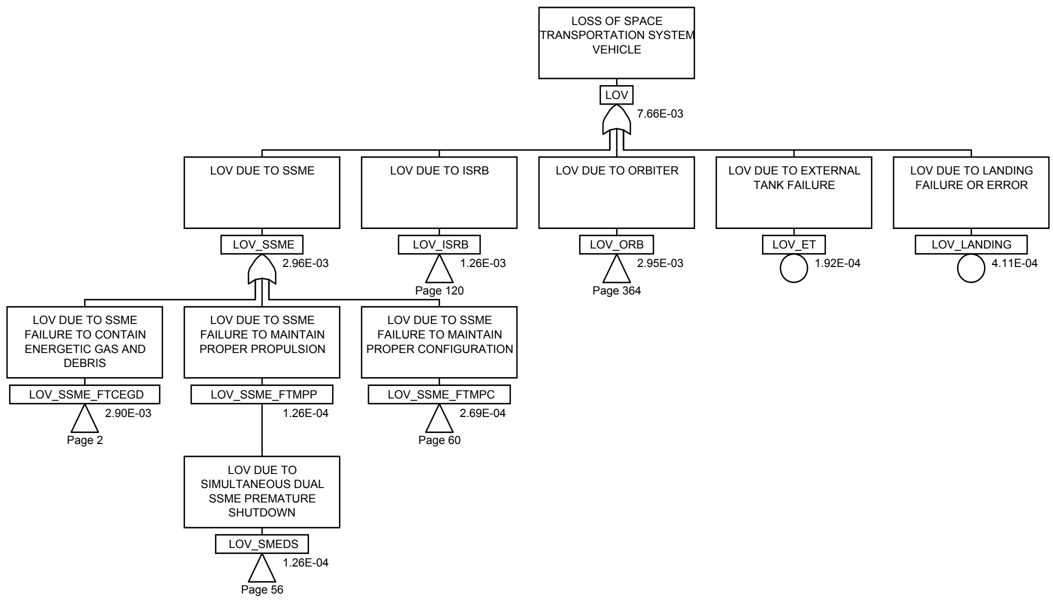


Figure 4.1 – The top event and some subsequent high level events of the LOV PRA completed by SAIC.[10]

Once the basic events had all been identified, it was necessary to come up with failure probabilities for each of these events. This in itself was probably the most difficult part of the compilation of the fault tree. Since there had been so few flights of the Space Shuttle to this point, there was no way that these probabilities could be determined merely from flight data. Therefore it was necessary to go back to a lot of the test data involved with the design and certification of all of the systems of the Space Shuttle. In addition, a lot of theoretical concepts had to be applied in order to predict what the failure rates, probabilities and characteristics of many components would be. Another difficulty that has been brought to the attention of many with the recent Columbia disaster is the identification and modeling involved with the many interactions that occur throughout a flight. Not only are there several interactions and dependencies between individual components of the Space Shuttle, but between different systems as well. When compiling the PRA, SAIC not only had to take these into account, but somehow approximate the effects of each interaction and model them using a method (FTA) that does not do the best job of modeling dependent events.[10]

4.2 Relex FTA (Georgia Tech Assessment)

Considering the size and scale of the PRA performed by SAIC, it was unfortunately not possible to attempt to reproduce the entire analysis using any method. Once this conclusion was reached, it was decided that a smaller, less detailed analysis would be done on the probability of LOV. Given more time, and the full version of the software used (Relex), a complete model of LOV would have been possible. The top levels of a fault tree were identified, and the reliability analysis tool Relex was used to create this fault tree. Values for probability of failure were then taken from the previously completed PRA to use in this analysis as constant failure probabilities.

For the first model assessed for the current research, the LOV was only broken down to a third level of detail, and the analysis was performed using previously obtained values. The results were then compared with the overall LOV probability determined in the SAIC PRA. This was the first time that the PRA was called into question, since the values input into the Relex model were being taken directly from that PRA, and the value for LOV obtained in the Relex model was different from that in the PRA. At this point the PRA was further reviewed, and a few parts of the model were identified that seemed to have major discrepancies. One specific portion of the fault tree that identified to be concentrated on later was the part that modeled the SSME failure probability. It could be seen just by looking at the input and output values that there had been something that made the results inaccurate. There were many possible explanations for this that would later be looked into, but from this observation it was decided that the SSME was one system within the original fault tree that should be further analyzed. After further examination of the PRA, the auxiliary power unit (APU) was identified as another system that would be remodeled using Relex, primarily since it had been previously identified as a major risk contributor in the overall LOV of the Shuttle. In addition, another LOV analysis was completed with the reanalyzed SSME values used instead of those provided in the original PRA.

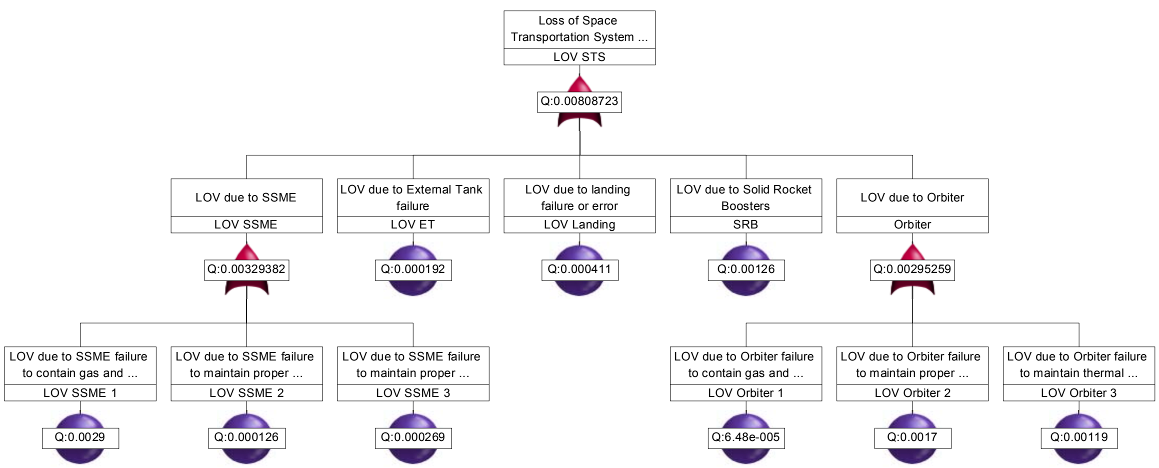


Figure 4.2 – Three-level Relex fault tree of LOV for the Space Shuttle.

With the three-level model, the value obtained for LOV was $8.09\text{x}10^{-3}$ or 1 in 124 flights, which is 5.6% larger than the $7.66\text{x}10^{-3}$ value (or 1/131 flights) that was obtained in the PRA. (All of these values can be seen in Table 4.1.) This fault tree can be seen in Figure 4.2. Then another model was created using another level of detail in the SSME portion of the fault tree, and LOV was calculated again. The value that resulted for LOV was a probability of $9.11\text{x}10^{-3}$ (1/110 flights), which is a total of 18.9% larger than the PRA value. This fault tree is illustrated in Figure 4.3. This primarily implies that there is a problem with the analysis done in the PRA. However, a conclusion that can be hypothesized from this result that may be much more meaningful is that with the addition of more

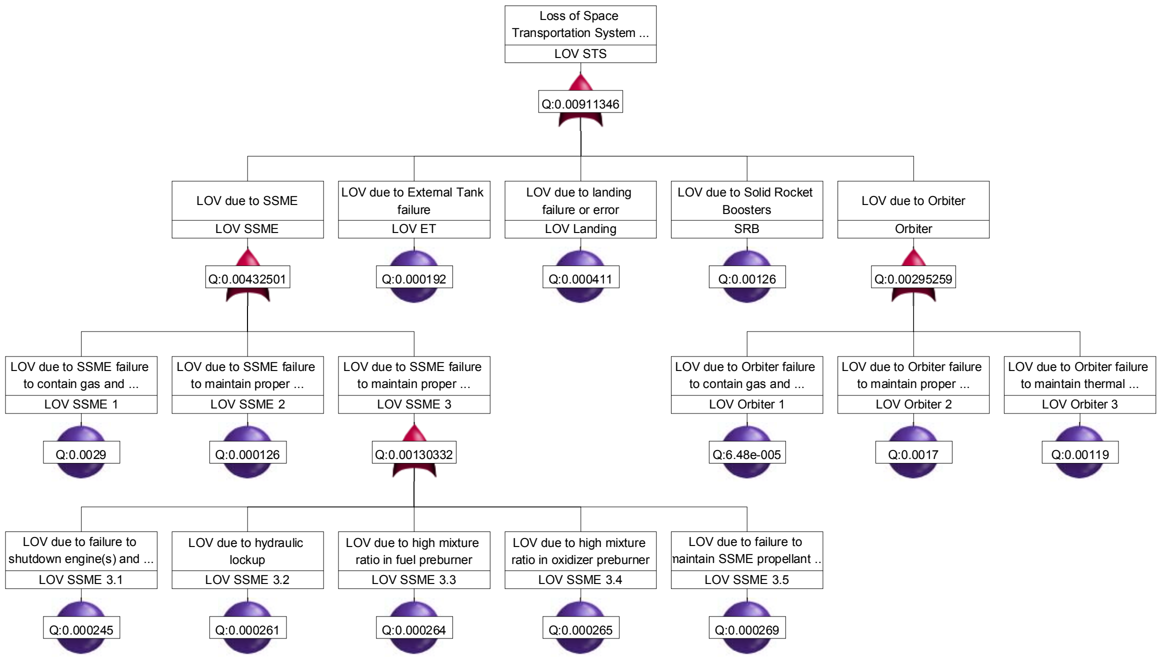


Figure 4.3 – LOV Relex fault tree with added detail under LOV due to SSME.

and more detail to a new model, there will be more and more of a discrepancy between the original PRA values and a more accurate fault tree model. A plot of the difference in top level probability versus level of detail of the model is shown in Figure 4.4, with the x-axis being the LOV probability obtained in the PRA. This is something that can easily be further investigated with the addition of more detail to the model. Unfortunately the demonstration version of Relex used for these analyses limited the size of the model created, and therefore this could not be further analyzed using this fault tree tool.

The discrepancies seen in the SSME portion of the model made it a natural candidate for one of the individual systems to be looked at. It was identified when the probabilities of the five third level events within LOV due to SSME failure to maintain proper configuration, which all had relatively similar probabilities, were noticed to be just slightly less probable than the top level event. For instance, the theory behind FTA shows that for an

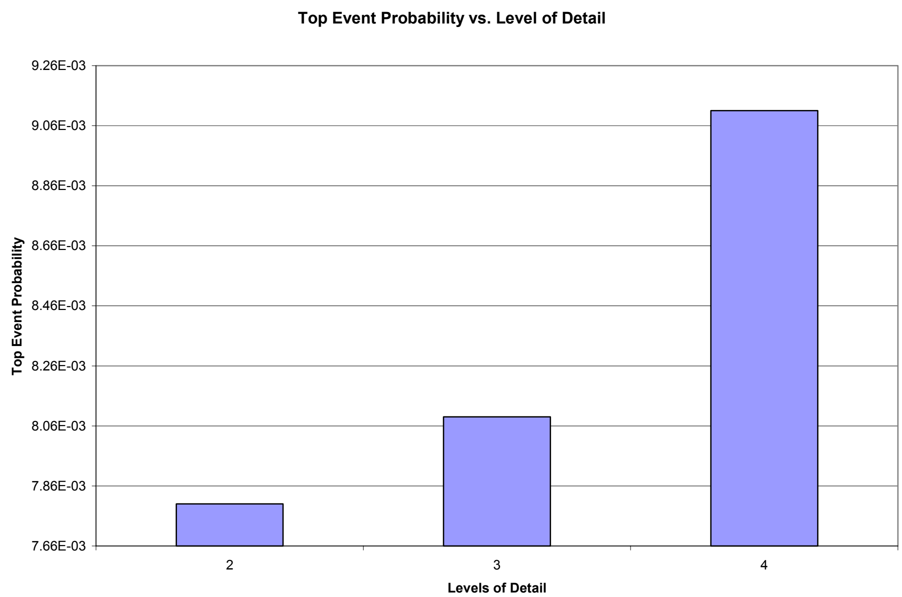


Figure 4.4 – Plot of top event probability versus level of detail.

"OR" gate with two events below it (in this case we will call them "A" and "B") the probability would be the equivalent of the union of those two events (assuming independence):

$$P(\text{top level event}) = P(A) + P(B) - P(A)*P(B)$$

Therefore, simply by using the two most likely third level events within this tree, the probability of the second level event would be $5.34\text{x}10^{-4}$, much lower than its actual value, but already significantly larger than the $2.69\text{x}10^{-4}$ it is given in the original PRA. The top level of the LOV due to SSME failure fault tree was one of the second level events for the overall LOV model. The model was then broken down with that event as the top event, and probabilities were input in the same was as the other fault trees. The result was a value for LOV due to SSME failure of 4.71×10^{-3} (1/212), as compared to the value in the PRA of 2.96×10^{-3} (1/338), which is an incredible overall increase of 59.1%. The Relex fault tree of SSME failure can be seen in Figure 4.5, and the corresponding fault trees for LOV due to SSME failure to maintain proper configuration and LOV due to SSME failure to contain energetic gas and debris from the SAIC PRA can be seen in Figures 4.6 and 4.7 respectively. A larger image of this Relex fault tree can be more easily viewed in Appendix A. One observation that was made concerning this portion of the fault tree was how close many of the values were underneath the gate representing LOV due to SSME failure to maintain proper configuration. If this correlation can be found in other locations of the fault tree it would help to determine the reason for the inaccuracies of the original PRA.

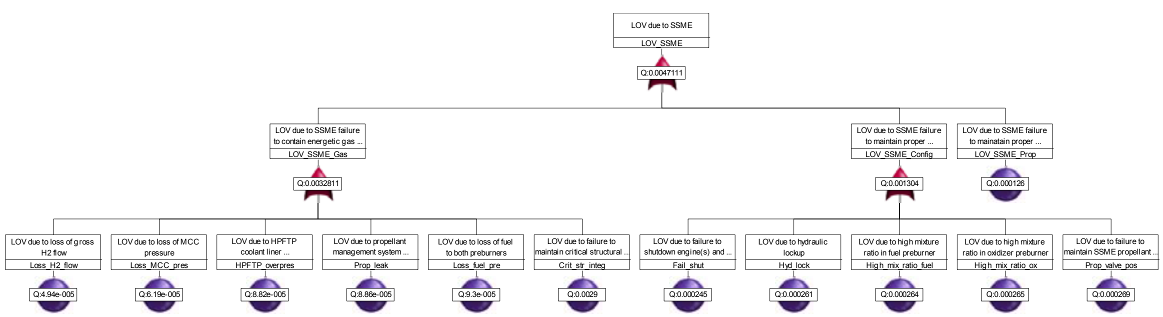


Figure 4.5 – Relex fault tree of LOV due to SSME.

The other system that was modeled was the APU hydrazine turbine overspeed and hub failure, which is located within the LOV due to Orbiter portion of the fault tree as seen in Figure 4.9. The value obtained in the PRA for this probability is 6.18×10^{-5} (1/16181). However, when the fault tree was comprised in Relex (as seen in Figure 4.8), using the same values for this three level model, the top event of LOV due to APU failure to contain energetic gas and debris occurred with a probability of 6.76×10^{-5} (1/14793). This is a difference of 9.4%, and once again would contribute to an even larger difference for the overall LOV probability if it were to be included in the model for LOV.

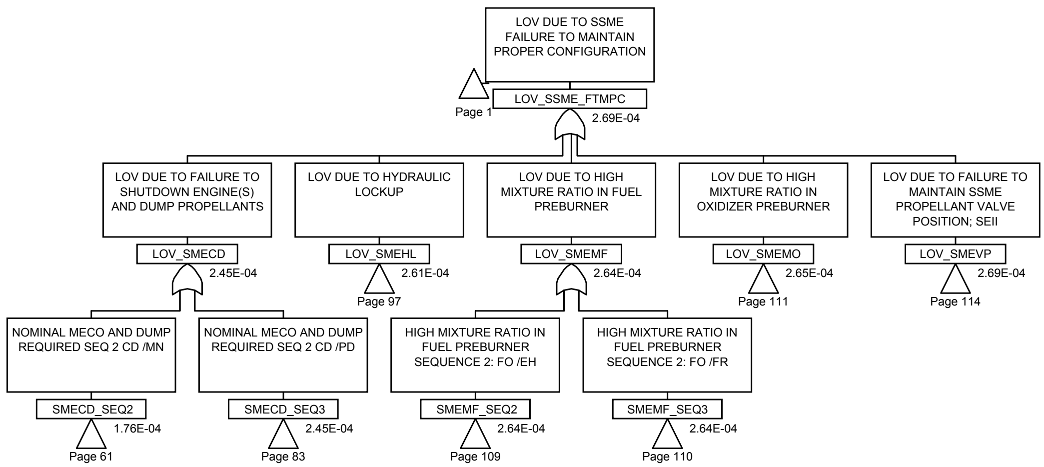


Figure 4.6 – LOV due to SSME failure to maintain proper configuration portion of PRA fault tree.[10]

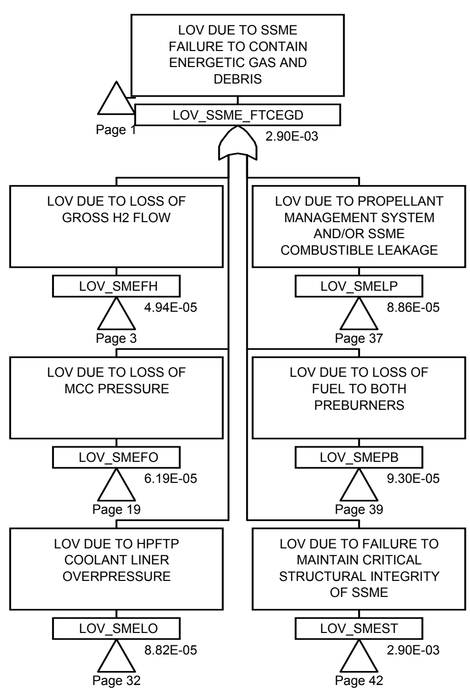


Figure 4.7 – LOV due to SSME failure to contain energetic gas and debris portion of PRA fault tree.[10]

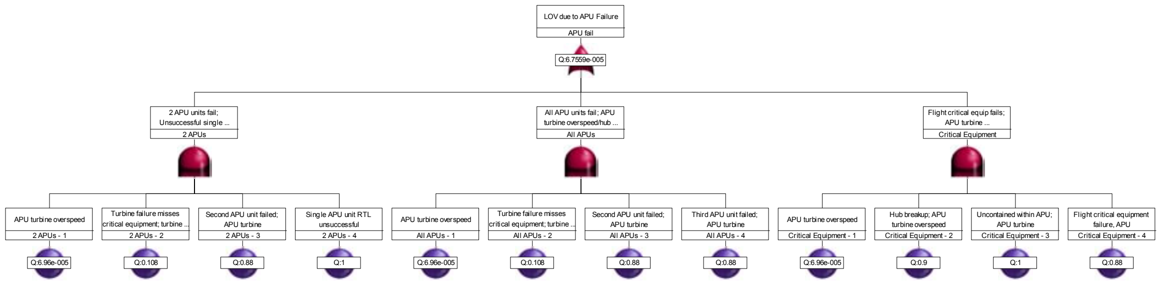


Figure 4.8 – Relex FTA of LOV due to APU failure to contain energetic gas and debris.

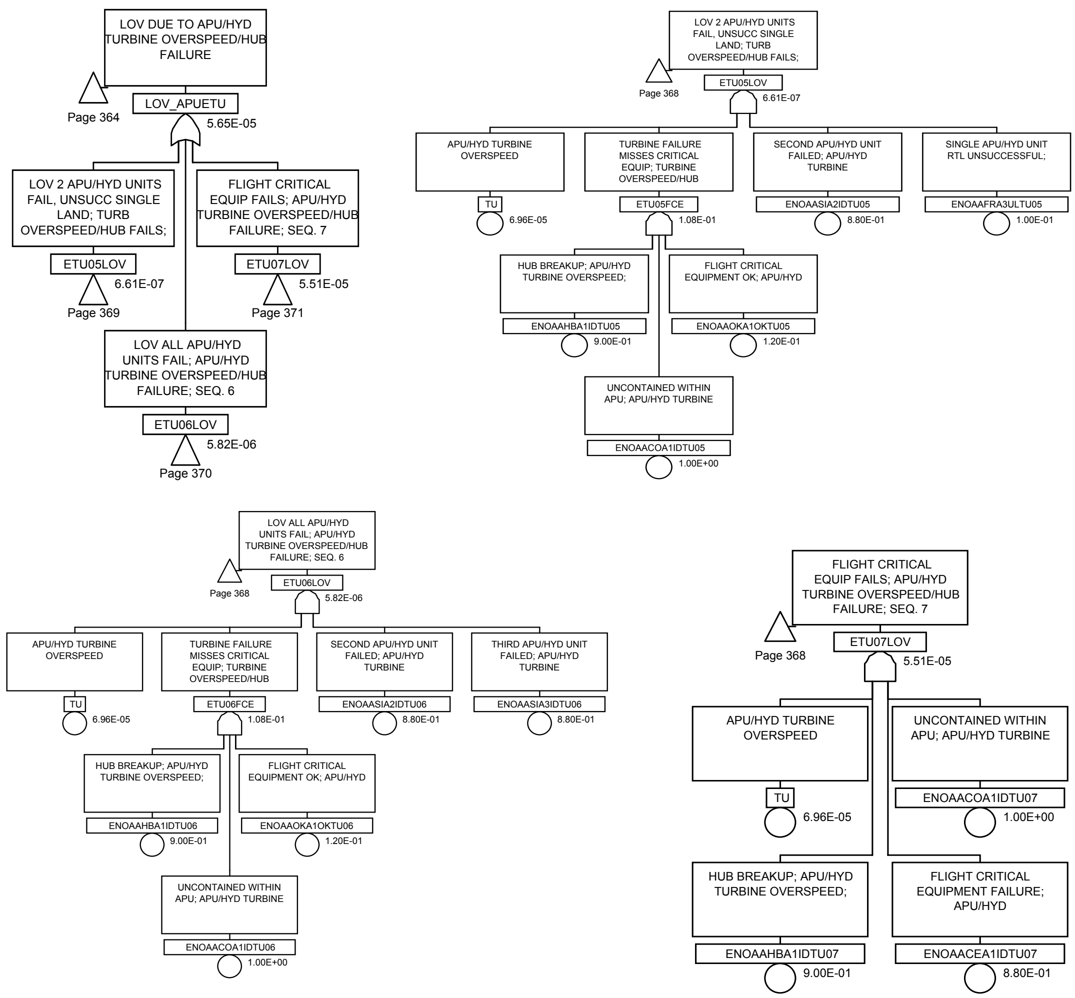


Figure 4.9 – All four parts of the PRA fault tree associated with APU hydrazine turbine overspeed and hub failure.[10]

With all of the discrepancies encountered throughout this study, the most likely explanation would be that the software used for the PRA (CAFTA) used approximations to decrease computation time. However, these compiling approximations, although typically small and sometimes even insignificant for many cases, have proven here to be large enough to make the model much less accurate than initially considered.

4.3 BlockSim RBD

The tool used to create and perform the RBD analyses of systems as well as the overall LOV probability of the Space Shuttle is called BlockSim. BlockSim was first used to create an RBD of the overall LOV, once again using the inputs from the PRA done by SAIC. The same level of detail was used for each model, in order to ensure accuracy when comparing the results of the different models, and the BlockSim RBD modeling LOV can be seen in Figure 4.10. The result of the overall LOV was a failure probability of $8.1x10^{-3}$, which is the same result gained by use of the Relex analysis. This is what was expected, considering that both FTA and RBD are based on the same logic principles.

BlockSim was then used to model the failure of the SSME as a RBD. Since all of the events within the SSME system fault tree that had been modeled were related through "OR" gates, all of the events could simply connected in series in any order to form the RBD. Therefore, all of the third level events (which is the same level of detail used in the fault tree) were connected in series, at which point the probabilities were taken from the

PRA and the analysis was completed. This RBD is shown in Figure 4.11. The result was a probability of failure of 4.7×10^{-3}, which is once again identical to the probability gained through FTA.

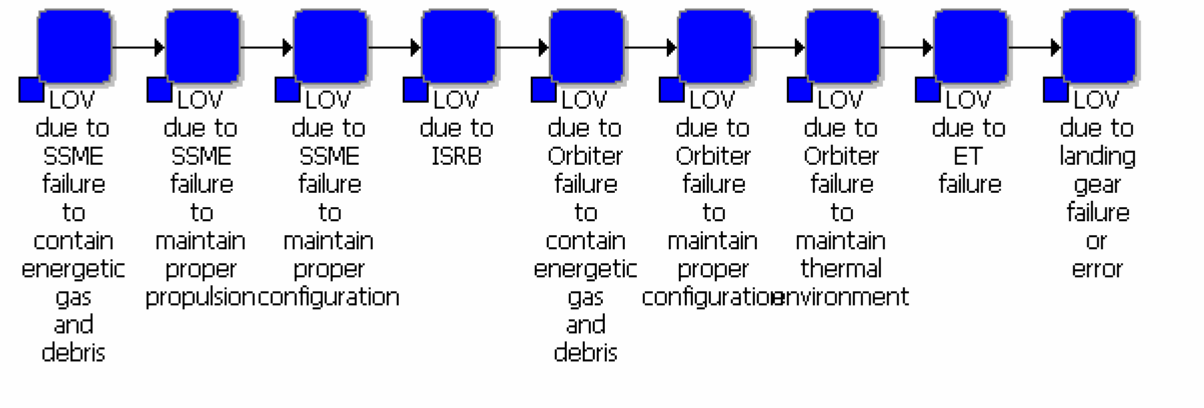


Figure 4.10 – BlockSim RBD of three-level LOV.

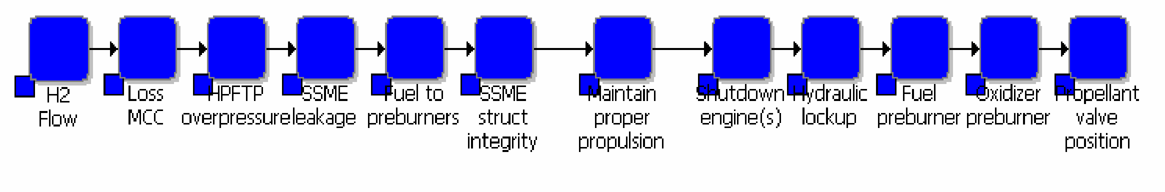


Figure 4.11 – BlockSim RBD of LOV due to SSME.

In order to create a RBD to model APU hydrazine turbine overspeed and hub failure, it involved more than just putting all of the events in series. Since there are three "AND" gates in the FTA (for this level of detail) of this system, the model was created as a series of three sets of four parallel events, because in each case all four events would need to occur to have that particular failure. The RBD representing this model is illustrated in Figure 4.12. The probability of APU hydrazine turbine overspeed and hub failure attained from this RBD is 6.76x10^{-5}, which is once again identical to the results of the associated fault tree as was expected.

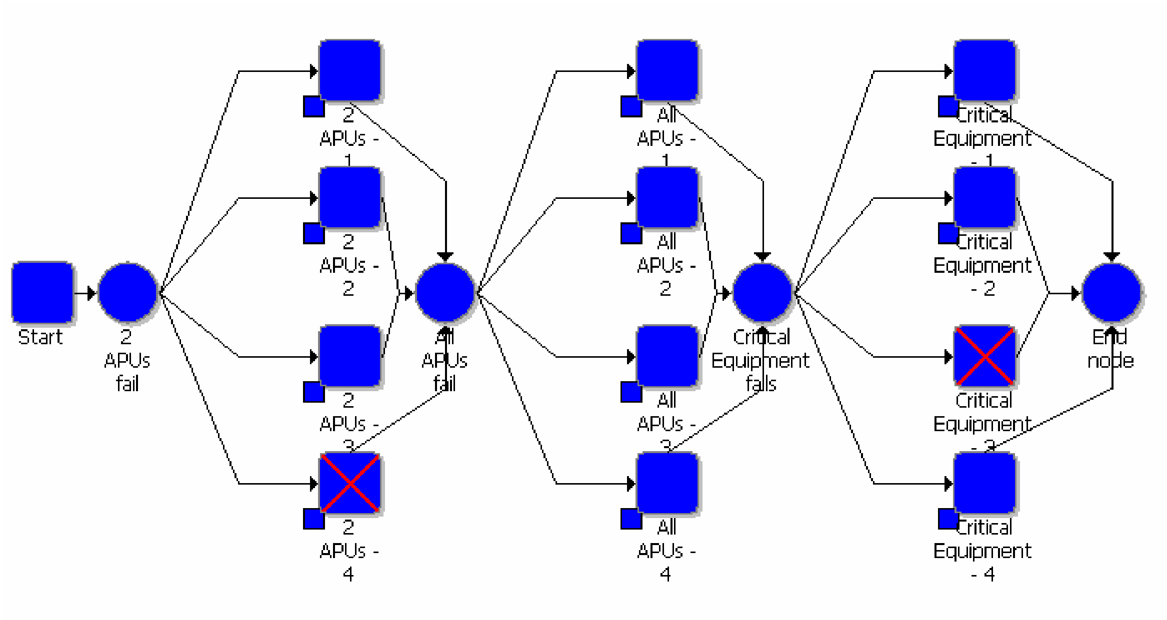


Figure 4.12 – BlockSim RBD of APU hydrazine turbine overspeed and hub failure.

Table 4.1 – Comparison of Reliability Analysis Techniques.

Model (Levels of Detail)	Top Event Probability (Relex)	Top Event Failure Rate (Relex)	Top Event Probability (BlockSim)	Top Event Failure Rate (BlockSim)	Top Event Probability (PRA)	Top Event Failure Rate (PRA)	Relative Increase as compared to PRA
LOV (2)	7.80E-03	1/128	7.80E-03	1/128	7.66E-03	1/131	1.8%
LOV (3)	8.09E-03	1/124	8.09E-03	1/124	7.66E-03	1/131	5.6%
LOV (4)	9.11E-03	1/110	9.11E-03	1/110	7.66E-03	1/131	18.9%
LOV due to SSME (3)	4.71E-03	1/212	4.71E-03	1/212	2.96E-03	1/338	59.1%
APU hydrazine turbine overspeed and hub failure (3)	6.76E-05	1/14792	6.76E-05	1/14792	6.18E-05	1/16181	9.4%

5. Conclusions

The most popular technique being used today for quantitative reliability analysis in aerospace engineering is by far FTA. However, it has been argued by many that RBD is a better technique, while just as accurate as FTA. One of the largest points in this argument is that FTA and RBD are based on the same principles of probability, but that RBD is capable of modeling more complicated situations. For instance, an example often used is the "bridge gate" in RBD, which cannot be simply modeled in FTA without some sort of repetitive model representing all of the minimum cut sets. Figure 5.1 shows a simple RBD with a bridge structure, and Figure 5.2 shows the fault tree that would represent the same model. With that in mind, if the same system is modeled in both FTA and RBD, the results of the analysis should be identical in both methods. This phenomenon can be seen by comparing the results of the models completed in both Relex and BlockSim. Therefore if the comparison were merely based on accuracy of the models, both methods would be seen as the same.

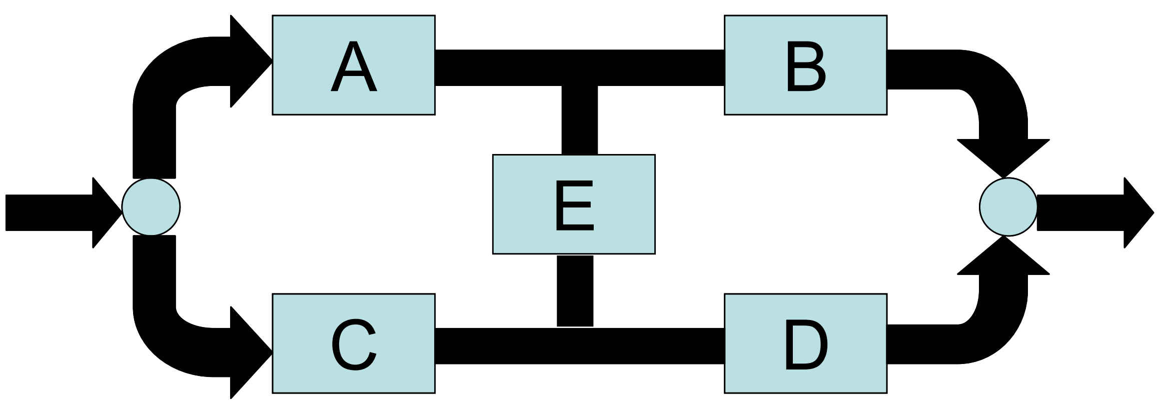


Figure 5.1 – Bridge structure RBD.

Unfortunately there was not sufficient means to create large models in order to compare the analysis times required for each. In addition, those might vary according to the tool used in order to perform each analysis, and would not be specific to each analysis technique. Since the results of the same system being modeled in these two methods do not vary, the process of compiling the models and working with them prior to analysis must be considered for comparison.

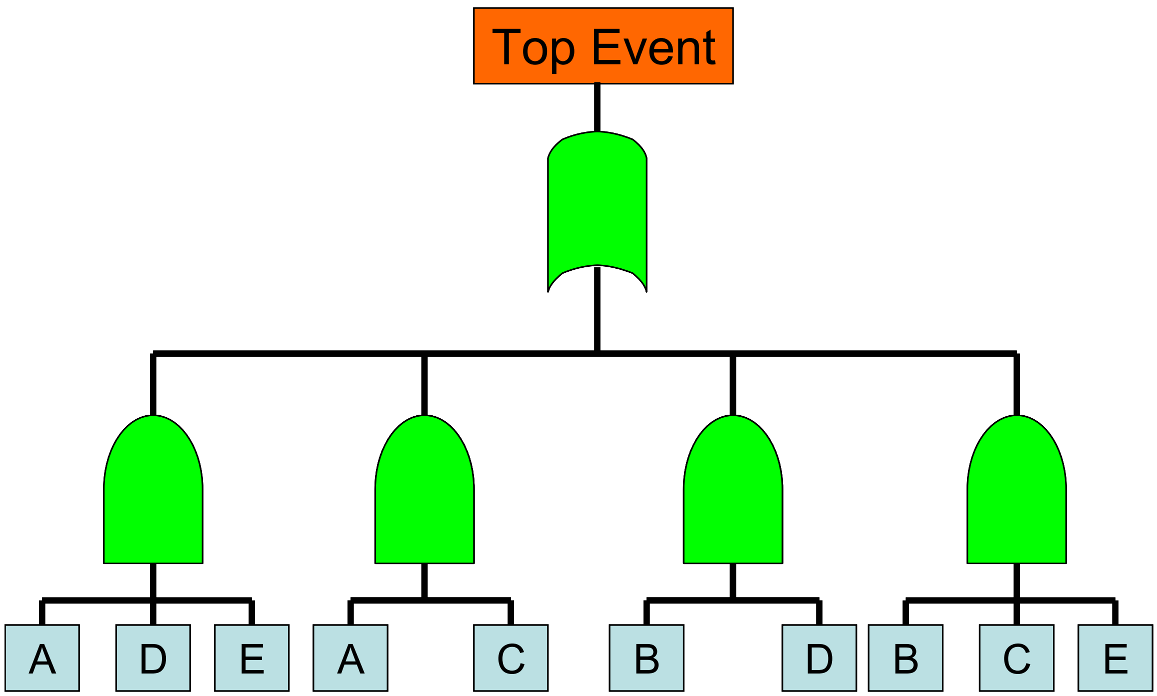


Figure 5.2 – Necessary FTA of a bridge structure.

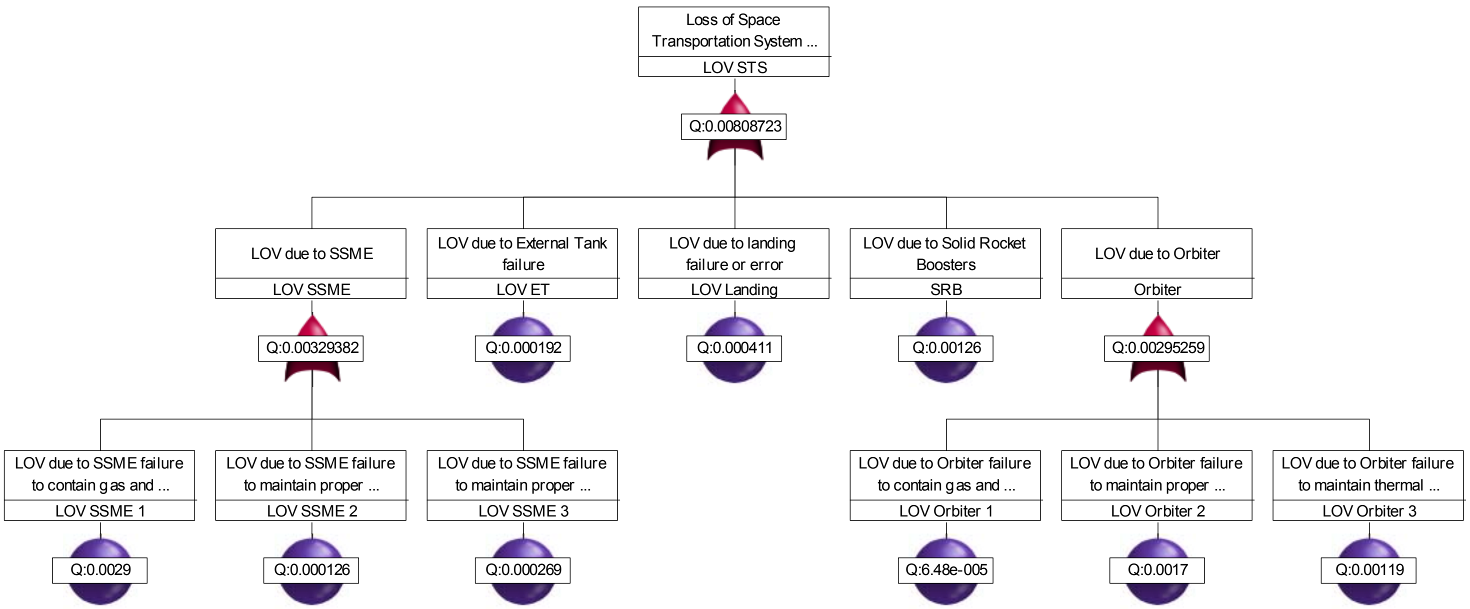
One consideration was how convenient and easy the models would be to create. It was originally hypothesized that the RBD model would be the simplest model to create, since in most cases (especially in modeling the Space Shuttle which has very little redundancy at these high levels) the events would just have to be put in series and defined just as they are in FTA. The surprising conclusion here is that it is the simplicity of this model that makes it somewhat difficult to work with. One of the benefits of the fault tree that was not previously considered is the inherent organization that comes with the creation of a fault tree. The process of creating such a top-down approach model helps to organize all of the events much more than if the same model is created in a bottom-up approach such as RBD. It becomes much easier to find a specific event in a model, or trace the effects of a given event when the model has been broken down from a system level all the way to the component level (and sometimes even to more detail). However, when the outcome of a model is obtained merely by listing every basic event it is very hard to follow and stay aware of which events have already been added when first creating the model.

Another benefit of FTA is that when analyzing a complicated model, one can obtain the probabilities associated with failure of a subsystem within that model without creating an entirely new model for it. If a complex system is being considered, the failure probability of any subsystem within the model must be calculated in order to then be used in calculation of the failure probability of the next level up from that. However, in RBD the subsystems are not necessarily identified, and since it is merely the accumulation of all of the basic events, in order to get the failure probability of a subsystem, one would need to create a new model to obtain this value. The only down side to this is that FTA must perform more calculations in order to get the system failure probability, and in a very large and complex model such as the one compiled to analyze the Space Shuttle, this can be a significant amount of analysis time. But since analysis techniques, as well as computer technology have come a long way in the last several years, this has become a less important factor to consider when deciding on which analysis technique to use.

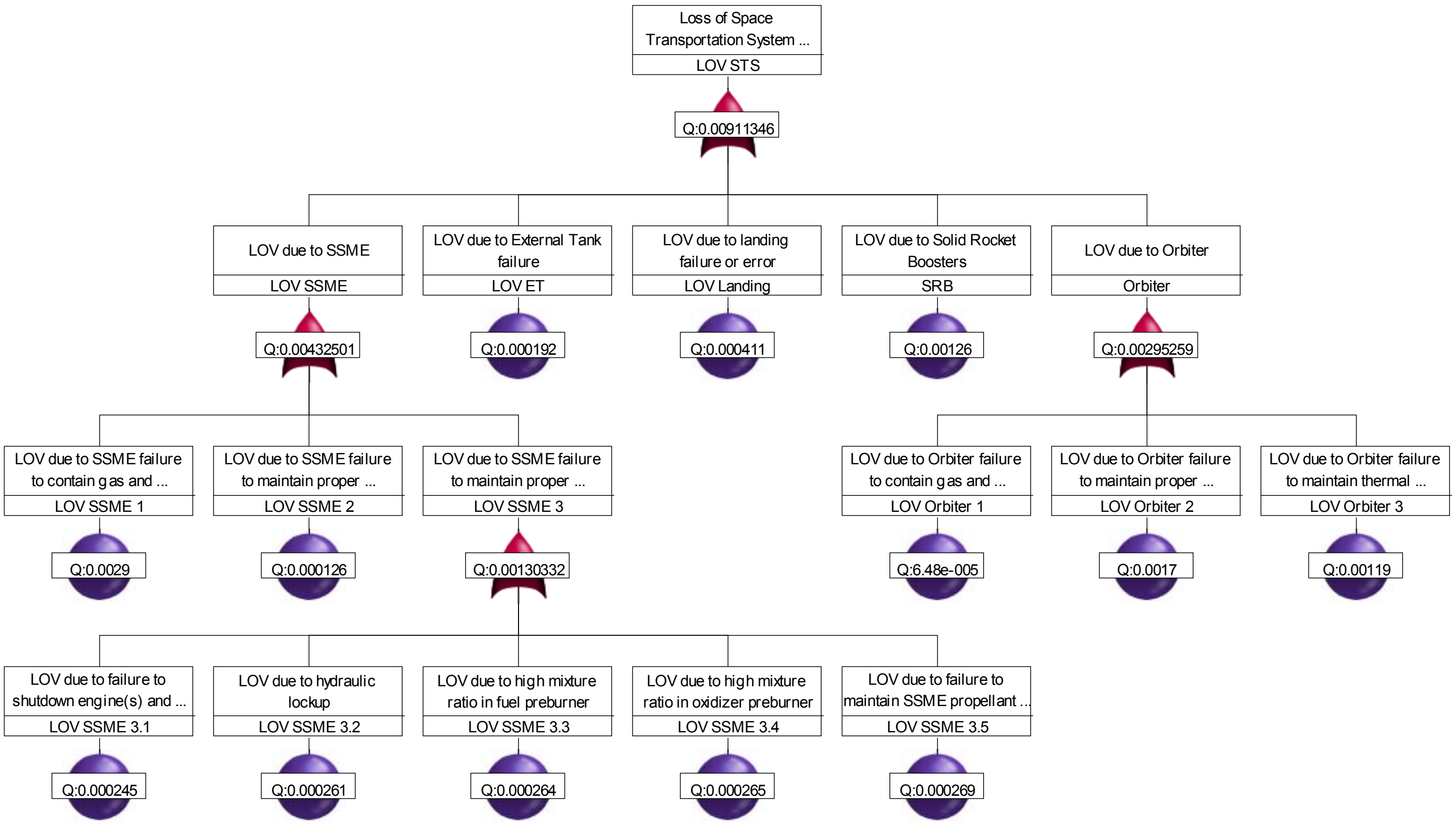
The time it took to set up and execute the different models was also initially hypothesized to be a factor in which technique was better overall. However, through the completion of this work that factor has not come into play. The time to set up the same model in either a FTA software package or a RBD software package (assuming the user is an experienced one) is very similar. For the models created in this study, the time to set one up should be on the order of several hours to a day for an experienced user. This is the same for both software packages used. And due to the constant improvement of computation time of both software packages and computers in general, computation time for these models was on the order of seconds. Given, models of the size of the PRA would take significantly longer to compile and compute, but computation time should not be any different for the two techniques here, and the time to set up the same model in each should be comparable.

In summary, there are of course advantages and disadvantages to all methods being considered. There is no one analysis technique that is superior to all others for every case, and decisions on which technique is to be used to analyze a given system should always be made on a case by case basis. However, when it comes to a system that will not necessarily be modeled most accurately by a specific method, sometimes it is the user's needs and preferences that are responsible for this choice. Depending on the application of the results that are to be obtained, this may be the best way to choose an analysis method in some cases since the majority of the time involved in an analysis is the time associated with the compilation of the model.

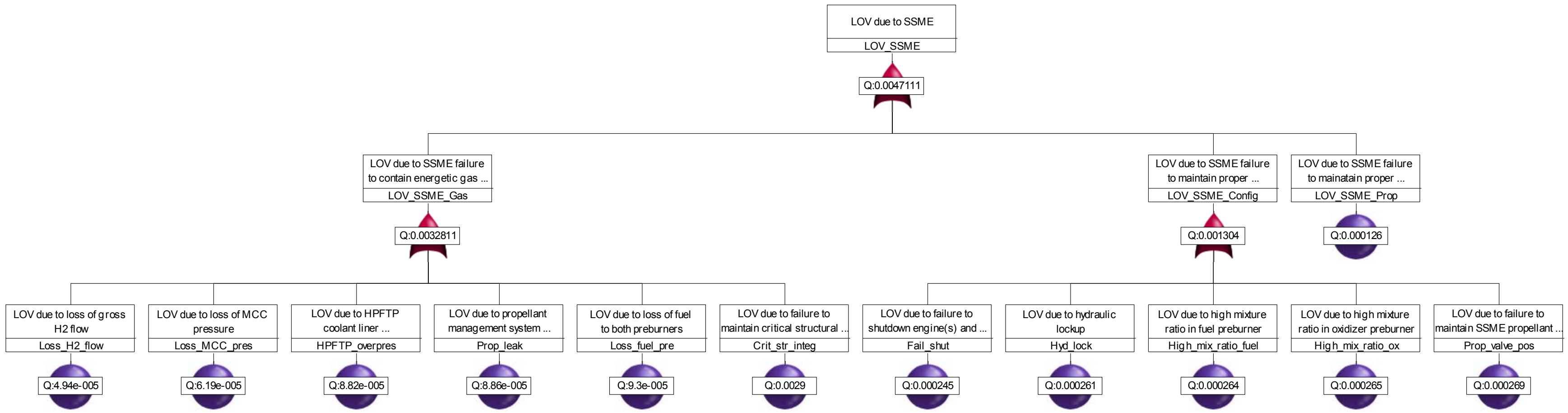
Appendix A – Relex Fault Trees



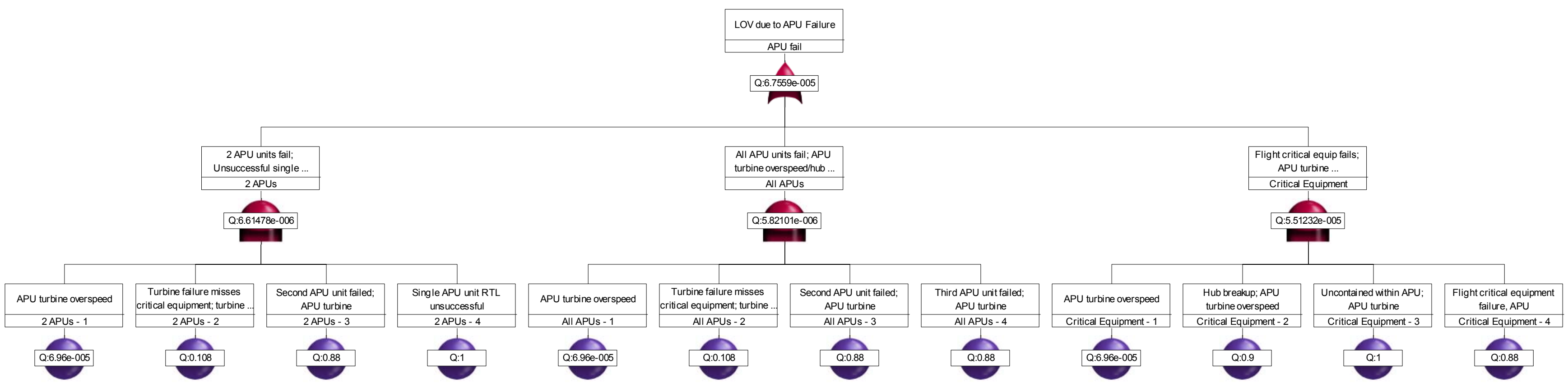
Relex fault tree of LOV with three levels of detail.



Relex fault tree of LOV with three levels of detail, and additional detail under LOV due to SSME failure to maintain proper configuration.



Relex fault tree of LOV due to SSME with three levels of detail.



Relex fault tree of APU hydrazine turbine overspeed and hub failure with three levels of detail.

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